Coordinated Research Project

On

Uncertainty Analysis of Engineering and Environmental Systems

At

Indian Institute of Science, Bangalore

in collaboration with

Board of Research in Nuclear Sciences, Mumbai

&

Bhabha Atomic Research Centre, Mumbai
(Department of Atomic Energy)

IISc

BRNS

BARC

FEBRUARY 2012

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1.0 Persons involved

Programme Coordinator (IISc)

Dr C S Manohar
Professor
Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

Programme Coordinator (BRNS)

Dr. Debanik Roy
Scientist (Robotics) & Programme officer,
Professor Faculty, Homi Bhabha National Institute (HBNI),DAE
Board of Research in Nuclear Sciences (BRNS), DAE,
Mumbai 400085

PI-s and CI-s of the Project (IISc)

Professor C S Manohar

Professor Ananth Ramaswamy

Professor J M Chandra Kishen

Dr Debraj Ghosh

Professor M Sekhar

Professor G L Sivakumar Babu

Dr K Sajeev

PC-s and Co-PC-s (DAE)

Shri Rohit Rastogi, RSD, BARC
Dr. D. Datta, HPD, BARC
Shri Akanshu Sharma, RSD, BARC
Shri Tarvinder Singh, RSD, BARC
Dr. M.K. Samal, RSD, BARC
Shri Manish Chopra, EAD, BARC
Dr. R.R. Rakesh, PSDD, BARC
Dr. V. Phanikant, A&CED, BARC

2.0 **Proposed areas of research**

Quantitative modeling of uncertainties in safety-critical engineering systems such as nuclear power plants is of fundamental importance. Over the past several years, the Department of Civil Engineering at the Indian Institute of Science has been actively involved in R&D and education activities in the areas of stochastic analysis of engineering system. This has led to a host of publications in leading international journals, development of several graduate courses (covering probabilistic modeling, random vibration analysis, structural reliability analysis, seismic risk analysis of engineering systems, stochastic finite element methods, stochastic calculus, probabilistic system identification, and Monte Carlo simulation methods), research training of masters and doctoral students, successful execution of several sponsored research projects, interactions with industries on problems of safety analysis, and contributions to continuing education programmes. Through the present suite of proposed collaborative research programmes, a group of faculty members from the Department aims to focus their energies on addressing wide ranging problems that are of relevance to nuclear power plant engineering programmes of the Country. Various themes of research that have been developed in collaboration with scientists from BARC/BRNS include the following:

1. Safety and global sensitivity analyses of structures with alternative uncertainty models (Investigators: C S Manohar and M Sekhar)
2. Stochastic Modeling of Hydration Process in Concrete: Investigation into Creep and Shrinkage (Investigators: Ananth Ramaswamy, K Sajeev, and C S Manohar)
3. Petrographical, Chemical and Computational Studies on Concrete at High Temperature (Investigators: K Sajeev, Ananth Ramaswamy, and C S Manohar)
4. Studies on Fatigue Crack Growth in Graphite (Investigators: J M Chandra Kishen and C S Manohar)
5. Uncertainty quantification in multiscale analysis of nanocomposite materials (Investigators: Debraj Ghosh and J M Chandra Kishen)
6. Stochastic modeling of groundwater flow and contaminant transport modeling at the proposed uranium tailings pond (Investigators: M Sekhar and C S Manohar)
7. Development of probabilistic design and analysis procedures in radioactive waste disposal in NSDF and design of NSDF closure (Investigators: G L Sivakumar Babu and M Sekhar)

Each of these themes is elaborated in the ensuing sections of this document along with the details of deliverables from the proposed activities.

3.0 Signatures

As per the suggestions given by the TPDM committee, BRNS, the project proposals listed in the preceding section are being submitted for approval for funding.

Programme Coordinator (IISc)

Dr C S Manohar
Professor
Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

Principal Investigators of the Project

Project-1 Professor C S Manohar

Project-2 Professor Ananth Ramaswamy

Project-3 Professor J M Chandra Kishen

Project-4 Dr Debraj Ghosh

Project-5 Professor M Sekhar

Project-6 Professor G L Sivakumar Babu

4.0 Mode of Execution

A Program Monitoring Committee (PMC) will ensure speedy implementation and proper monitoring of the project. The composition and terms of reference of these committees will be as follows:

Program Monitoring Committee (PMC)

The PMC will consist of the following members:

Chairman TSC-4, NRFCC, BRNS	**Chairman**
Programme Coordinator (IISc.)	**Member***
PI & Co-PI of each project (IISc.)	**Member**
PC and Co-PC of each project (BARC)	**Member**
Programme Officer (BRNS)	**Convener**
Technical Experts	**Invitees**

BARC: Bhabha Atomic Research Centre
BRNS: Board of Research in Nuclear Sciences
IISc.: Indian Institute of Science
[*: Dr. C.S. Manohar, Professor, Dept. of Civil Engg., IISc.]

The terms of reference of PMC will be as follows:

(i) To approve plans for the laboratories, offices, working & sitting spaces and also equipments and software, with their specifications and costs, required for the programme and obtain financial approval of PRC.
(ii) To help identify projects & PIs and get the projects formulated for approval by NRFCC, BRNS
(iii) To coordinate all technical programmes to ensure smooth running of the programme.
(iv) To monitor the performance of the projects and report progress to TSC-4, NRFCC every six months.

Chairman PMC may co-opt additional experts for specific projects. PMC will meet every three months. To speed up the work, PMC will appoint sub-committees for specific tasks. The sub-committees of the PMC are expected to meet more frequently depending on the requirements.

CRP on Uncertainty Analysis of Engineering and Environmental Systems

Project-1

Safety and global sensitivity analyses of structures with alternative uncertainty models

A project proposal submitted to

BOARD OF RESEARCH IN NUCLEAR SCIENCES
Department of Atomic Energy
Government of India

By

Professor C S Manohar (PI)
Professor M Sekhar (Co-I)

Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

August 2011

SECTION-A

PART I – PROJECT OVERVIEW

100. Advisory Committee Code Number: 36 [NRFC]

101. Title: Safety and global sensitivity analyses of structures with alternative uncertainty models

102.

- **Keywords:** Probabilistic models; interval analysis; convex models; fuzzy sets; reliability analysis; global sensitivity analysis.
- **Names of referees:**

Professor S Narayanan Department of Mechanical Engineering Indian Institute of Technology Madras Chennai 600 036 Email: narayans@iitm.ac.in Telephone: 044 2257 4668	Professor Baidurya Bhattacharya Department of Civil Engineering Indian Institute of Technology Kharagpur 721 302 Email: baidurya@iitkgp.ac.in Telephone: 09434739650 +91 3222 283422 (W) +91 3222 282254(F)
Professor T K Datta Dogra Chair Professor Department of Civil Engineering Indian Institute of Technology New Delhi 110 016 Email: tkdatta@civil.iitd.ac.in Phone: 09818582445	Professor Armen Der Kiureghian Taisei Chair in Civil Engineering Department of Civil & Environmental Engineering University of California at Berkeley 723 Davis Hall Berkeley, CA 94720-1710 USA Phone: (510) 642-2469; Fax: (510) 643-8928 Email: adk@ce.Berkeley.edu.

103 Project Summary

It is proposed to develop mathematical models (based on theories of probability, interval analysis, convex modeling and fuzzy sets) for uncertainties in the specification of loads and system parameters for externally loaded engineering structures and subsequently evaluate measures of structural safety and global sensitivity using finite element modeling, Monte Carlo simulations, and optimization tools. Furthermore, the tools thus developed are proposed to be integrated with professional finite element analysis packages such as NISA and Abaqus.

104 PI's Name and address Professor C S Manohar Department of Civil Engineering Indian Institute of Science, Bangalore 560 012 Email: manohar@civil.iisc.ernet.in Telephone: 080 2293 3121 Fax: 080 2360 0404	**105 CI's Name and address** Professor M Sekhar Department of Civil Engineering Indian Institute of Science Bangalore 560 012 Email: muddu@civil.iisc.ernet.in Telephone: 080 2293 2245 Fax: 080 2360 0404

106 PC's Name and address

PC: Shri Rohit Rastogi, RSD, BARC
Co-PC: Dr D Datta, HPD, BARC

107 Total budget (amount in lakhs of Rupees): 38.45

108. Detailed Project Proposal Report Enclosed: Yes, see annexure-1.

Part II Project Objectives, Research Plan and Deliverables

200 Objectives

1. To develop a suite of unified computational methods for assessment of safety of structures when the underlying uncertainties are modeled using interval analysis, convex functions, fuzzy sets, and (or) probabilistic models. Examine the inter-relation between alternative models of safety. Tackle forward and inverse reliability problems and questions on system reliability.
2. To develop simulation based methods for evaluation of variance based global sensitivity factors for structural engineering applications taking into account the non-Gaussian distributions and mutual dependence of the basic random variables. Examine relations between these sensitivity factors and those obtained in reliability analysis. Explore the nature of global sensitivity measures when uncertainties are modeled using non-probabilistic tools.
3. Interface the algorithms developed in (a) and (b) above with FE based models for structures created on professional packages (such as NISA and Abaqus).
4. Illustrate the procedures developed on case studies involving broad ranging structural engineering problems encompassing structural nonlinearities, static/dynamic loads, and thermo-mechanical effects.

210 Research Plan and Deliverables

The activities envisaged in the project are divided into following work packages (WP-s):

- WP1: Preparation of a state-of-the-art report on uncertainty modeling using alternative tools (viz., interval analysis, convex functions, fuzzy sets, and (or) probabilistic models) and literature on global sensitivity analysis.
- WP2: Development of algorithms for computation of structural safety based on optimization and Monte Carlo simulation tools.
- WP3: Development of algorithms for computation of global sensitivity indices using Monte Carlo simulation tools.
- WP4: Interface the computational tools developed in WP2 and WP3 with finite element models for structures residing in professional finite element packages.
- WP5: Illustrate the methods developed on a suite of case studies.

A Activities at PI's Institution

I Year	• A review of literature and a state of art report on uncertainty modeling using alternative tools (viz., interval analysis, convex functions, fuzzy sets, and (or) probabilistic models) and literature on global sensitivity analysis. • Hire staff and purchase equipment • Development and implementation of algorithms for computation of structural safety based on optimization and Monte Carlo simulation tools for alternative uncertainty representations. • Illustrate the methods developed on simple structural models developed on Matlab platform. • Submission of the I annual report
II Year	• Development and implementation of algorithms for computation of variance based global sensitivity factors using Monte Carlo simulations by taking into account non-Gaussian distributions and mutual dependence of underlying random variables. • Illustrate the methods developed on simple structural models developed on Matlab platform. • Examine relations between sensitivity measures obtained in reliability analysis and the global sensitivity indices. • Examine issues arising when uncertainties are treated using non-probabilistic or hybrid tools. • Submission of II annual report
III Year	• Interface the safety assessment and global sensitivity tools with Abaqus/NISA based finite element structural models. • Conduct a suite of case studies on structural engineering examples of practical interest including static/dynamic/thermo-mechanical loading. • Submission of final project report

Deliverables

- Development of a unified set of computational tools for safety assessment of structures when the uncertainties are modeled using alternative tools such as interval analysis, convex functions, fuzzy sets and (or) probabilistic models.
- Development of a set of tools for computing global sensitivity factors for structural responses.
- A Matlab-Abaqus/NISA interface for implementing the above tools so that wide ranging class of problems of practical interest could be tackled.
- Research publications and technical reports based on the above research.

B Activities at the PC's Institution

211. Infrastructure facilities related to the project activity available at the PI/CI's Institute:

Softwares such as Matlab and NISA (FE analysis software) are available at the Department and these would be utilized for executing the present project.

212. Facilities available at the PC's institution that would be useful to this project:

Part III- Budget Estimates

300 Details of the budget requirements (amount in lakhs of Rs)

No	Particulars	I year	II year	III year	Total
310	Equipment & software	5.00	0.25	0.25	5.50
320	Salary for SRFs (2 nos.) 30% HRA	4.32 1.30	4.32 1.30	4.80 1.44	13.44 4.04
330	Technical assistance	1.50	1.50	1.50	4.50
340	Consumables	0.75	0.75	0.75	2.25
350A	Travel for PI /CI	0.80	0.80	0.80	2.40
350B	Travel for PC /DC	-	-	-	-
360	Contingencies	0.50	0.50	0.50	1.50
370	Overheads @15%	2.05	1.34	1.43	4.82
380	Total	16.22	10.76	11.47	38.45

BUDGET DETAILS

310. Details of the budget for equipment to be procured by the PI (amount in lakhs of rupees)

Sl.No.	Item	I year	II year	III year	Total
Local:	Desk top computers and accessories (2 nos) Abaqus License (one)	1.50 3.50	0.25 -	0.25 -	2.00 3.50
Imported:	None	-	-	-	-
Total					5.50

340. Details of budget for consumables to be procured by the PI (amount in lakhs of rupees):

Sl. No.	Item	I year	II year	III year	Total
1	Computer peripherals, stationery, printing expenses for reports, maintenance.	0.75	0.75	0.75	2.25
	Total	0.75	0.75	0.75	2.25

350. Details of travel:

Amount in lakhs of ⇨ Rupees	Ist year	IInd year	IIIrd year	Total
351. Proposed number of visits of **PC/DC** to **PI's** Institute	3	3	3	9
351A. Duration of stay (no. of days) during each visit	~3	~3	~3	~9
351B. Total funds required (lakhs of rupees)	0.80	0.80	0.80	2.40
352. Proposed number of visits of **PI to PC/DC's** institute				
352A. Duration of stay (No. of days) during each visit				
352B. Total funds required				
353. Funds required by **PI** for travel to attend conferences within India.	-	-	-	-
354. Funds for Other visits (please give details)	-	-	-	-

Budget Justifications

310 Equipment

The computational facilities (in terms of two desktop PC-s) are needed for focusing on dedicated efforts towards realizing the objectives of the proposed project. These PC-s would be made available to the two SRF-s. A multi-license Abaqus software is being proposed to be procured for four projects under the present CRP. The present proposal (project-1) budgets for cost of one license. The tools for structural safety and global sensitivity analyses would be developed on the Matlab platform and would be interfaced with structural models developed on the Abaqus software. The Abaqus software is being preferred for it s wide ranging capabilities to treat structural nonlinearities.

320 Staff

Given the advanced nature of the modeling techniques proposed to be used in the proposed work (probabilistic and possibilistic modeling & global sensitivity analysis) the service of a project associates with at least ME /M Tech/MSc (Engg) qualification are needed. The service of the project associate is needed for the entire project duration. The salary is as per the Institute norms. The number of staff requested is the minimum required to execute the project.

330 Technical assistance

This is required to support software development needed to interface Matlab and Abaqus softwares, to support visits of short term student trainees, assistance for FE model development, for engaging laboratory attender on temporary basis, and for secretarial/administrative assistance.

340 Consumables

The funds are required to meet expenses towards stationery, electronic storage media, printer cartridges, report preparation, technical literature, etc.

350 Travel

The travel grants requested are for visits of project investigators and PC-s to each other's institutions and also for the cost of travel of PI for attending review meetings.

360 Contingencies

To meet expenditure towards cost of advertising project positions, purchase of books relevant to the project subject, defray expenses towards tuition fees for SRF-s towards their PhD studentship, and for any other unforeseen expenditures related to the project.

PART IV - OTHER PROJECTS

410. List all previous projects that are supported by BRNS or any other funding agency in which PI is actively participating (either as PI or as CI):

No	Title of the project	Total cost	Agency	Present status
1	Vibration based condition assessment and reliability analysis of existing engineering structures	Rs 28.4 lakhs	BRNS	Ongoing 2010-2013 Duration: 3 years
2	Fire resistance and repair of earthquake damaged structures	£146000=00	United Kingdom-India Education and Research Initiative.	Ongoing 2007-2011 Duration: 4 years
3	Aseismic structural reliability analysis of nuclear core support structure	Rs 3.0 lakhs	IGCAR	Ongoing Duration: 1 year

The PI has completed several other funded research projects and a list of these projects is provided in section 500.

411. List all projects submitted during the current financial year by PI to BRNS or any other agency for funding**.** Give details on the present status of the application:

Asif Usmani and C S Manohar (PI-s), Making performance based structural engineering for fire resistance attainable, A collaborative proposal submitted to the UKIERI Innovative partnerships 2011 with participation from IISc and University of Edinburgh and also four industrial partners from India and the UK (total funds requested: £40000.00).

412. Brief description of the project(s) submitted/sanctioned by/to PI by other agencies.

The project proposal mentioned in item 411 has the following objectives:

- To develop a simple and clearly defined performance based structural engineering (PBSE) framework for structures subjected to fire including easy to use software tools that will encourage its wider adoption.
- To incorporate a more explicit treatment of uncertainty in the above framework.

The funding available here mainly supports expenses towards international travel and exchange of research students and does not provide funds for equipment/project staff.

413. List all previous projects that are supported by BRNS or any other funding agency in which CI is actively participating (either as PI or as CI):

No	Title	Total cost	Agency	Status
1.	Near surface soil moisture retrieval using RISAT SAR data and its assimilation for root zone soil moisture estimation at watershed scale.	Rs. 21,60,000	ISRO	Ongoing 1-4-2010, Duration: 3 years
2.	Validation of MT rain rate products and its application in hydrology in the Kabini river basin.	Rs. 21,60,000	ISRO	Ongoing 1-1-2010, Duration: 3 years
3.	Assimilation of remote sensing data for modeling the land surface fluxes at watershed scale using a distributed hydrological	Rs. 7,46,500	ISRO-STC	Ongoing 1-4-2010, Duration: 2 Years

	model.			
4.	Sustainable groundwater management in an urban environment	Rs. 25,00,000	Arghyam (NGO)	Ongoing (with extension) 1-6-2008 Duration: 3 years

414. List all projects submitted during the current financial year by CI to BRNS or any other agency for funding. Give details on the present status of the application:

No	Title	Total cost	Agency	Status
1.	Assessing groundwater storage changes and sustainability due to climate change in the semi-arid watersheds of south India	Rs. 15,00,000	CSIR (under the COPEC project)	Ongoing 1-2-2011 Duration: 3 years

415. Brief description of the project(s) submitted/sanctioned by/to CI by other agencies.

The projects that are currently active are in the areas of climate change impacts on groundwater systems, urban groundwater modeling, calibration of soil moisture for the upcoming RISAT satellite, calibration of rainfall for the upcoming MT satellite and ET modeling.

PART IV - FACILITIES

416. List of facilities that will be extended to the investigators by the implementing institution for the project

A. Infrastructure facilities

Sr. No.	Item Name	Yes/No/ NR*	Sr. No.	Item Name	Yes/No/ NR*
1.	Workshop	NR	7.	Telecommunication	Yes
2.	Water & Electricity	Yes	8.	Transportation	NR
3.	Standby power supply	Yes	9.	Administrative support	Yes
4.	Laboratory space & furniture	Yes	10.	Library facilities	Yes
5.	AC room for equipment	NR	11.	Computational facilities	@
6.	Refrigerator	NR	12.	Animal/Glass house	NR
	NR*: Not Required				

@: Computational facilities required have been budgeted for.

B. Equipment and accessories available within the Investigator's group/Dept. which can be utilized for the project.

Softwares such as Matlab and NISA (FE analysis software) are available at the Department and these would be utilized for executing the present project.

SECTION-B

500 CV of the PI

C S Manohar
Professor and Chairman
Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012 INDIA

Born : 11th May 1959, Hubli (Karnataka)
Indian National
Phone: +91 80 2293 3121 Fax: +91 80-23600 404
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Web: http://civil.iisc.ernet.in/fac/~manohar

Education

- BE (Civil Engg.), 1982, Karnatak University, India, First Class with Distinction.
- ME (Civil Engg.), 1984, Indian Institute of Science, First Class with Distinction.
- PhD (Faculty of Engineering), 1989, Indian Institute of Science, Bangalore.

Work Experience

Academic positions held at the Indian Institute of Science

- Professor, May 2005-present, Department of Civil Engineering.
- Associate Professor, May 1999-May 2005, Department of Civil Engineering.
- Assistant Professor, May 1993-May 1999, Department of Civil Engineering.

Other positions held at the Indian Institute of Science

- Chairman, December 2010- present, Department of Civil Engineering.
- Chairman, July 2007- December 2010, Centre for Earth Sciences.
- Associate Faculty Member, 2007-present, Centre for Earth Sciences.
- Member Secretary, IISc-IGCAR R & D Cell, 2011-present

Positions held outside the Indian Institute of Science

- Visiting Professor, October 2011, Carleton University, Ottawa, Canada.
- Visiting Scientist, May 2003, Dept. of Civil Engineering, University of Delaware, USA.
- Visiting Associate Professor, June-July, 2003, Dept. of Civil Engineering, The Johns Hopkins University, USA.
- Research Assistant, May 1991-May 1993, Dept. of Engineering Sciences, University of Oxford, UK.
- Scientist, Oct 1990-May 1991, Structural Engineering Research Centre, Chennai, India

Honors

- Member, Editorial Board, Probabilistic Engineering Mechanics (Elsevier)
- Member, Editorial Board, Structural Control and Health Monitoring (Wiley)
- Associate Editor (Structural Dynamics), ISET Journal of Earthquake Technology, (since 2007).
- Associate Editor, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation (Serial Publications).
- Session organizer and Chair, Indo-US Frontiers in Engineering Symposium,
- Member, Editorial Board, Earthquakes and Structures (from 2010) (Techno Press).
- Sir C V Raman award for young scientists for the year 1999, Instituted by Government of Karnataka, India.
- Member, Technical Committee of Dynamics, Engineering Mechanics Division, American Society of Civil Engineers, 2003-2007.
- Invitations to IUTAM symposia on Nonlinear Stochastic Mechanics, 1995, 2001, 2009.

Research interests

- Structural dynamics: modeling of nonlinearity and uncertainties; computational and experimental methods; inverse problems: structural system identification and damage detection using measured vibration data; statistical energy analysis.

- Stochastic structural mechanics: stochastic FEM; random vibrations; Bayesian filtering; Monte Carlo simulations & variance reduction schemes; structural reliability modeling.
- Earthquake engineering: seismic safety of large scale structures; science of earthquake simulations: hybrid test methods; real time substructuring; fire following earthquakes.

Papers in refereed journals (last ten years)

1. B Radhika and C S Manohar, 2011, Updating response sensitivity models of nonlinear vibrating structures using particle filters, Computers and Structures, 89(11-12), 901-911.
2. H A Nasrellah and C S Manohar, 2011, Finite element method based Monte Carlo filters for structural system identification, Probabilistic Engineering Mechanics, 26 (2011) 294–307.
3. H A Nasrellah and C S Manohar, 2011, Particle filters for structural system identification using multiple test and sensor data: a combined computational and experimental study, Structural Control and Health Monitoring, 18, 99–120.
4. B Radhika and C S Manohar, 2010, Reliability models for existing structures based on dynamic state estimation and data based asymptotic extreme value analysis, Probabilistic Engineering Mechanics, 25, 393-405.
5. H A Nasrellah and C S Manohar, 2010, A particle filtering approach for structural system identification in vehicle-structure interaction problems, Journal of Sound and Vibration. 329(9), 1289-1309.
6. R Sajeeb, C S Manohar and D Roy, 2010, A semi-analytical particle filter for identification of nonlinear oscillators, Probabilistic Engineering Mechanics, 25, 35-48
7. R Sivaprasad, S Venkatesha, and C S Manohar, 2009, Identification of dynamical systems with fractional derivative damping models using inverse sensitivity analysis, Computers, Materials and Continua, 9 (3), 179-207.
8. R Tipireddy, H A Nasrellah and C S Manohar, 2009, A Kalman filter based strategy for linear structural system identification based on multiple static and dynamic test data, Probabilistic Engineering Mechanics, 24, 60-74.
9. R Sajeeb, C S Manohar and D Roy, 2009, A Conditionally linearized Monte Carlo filter in nonlinear structural dynamics, International Journal of Nonlinear Mechanics, 44(7), 776-790
10. R Sajeeb, C S Manohar and D Roy, 2009, Rao-Blackwellization with substructuring for state and parameter estimations of a class of nonlinear dynamical systems, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation, 1(1-2) 2009.
11. S Venkatesha, R Rajender, and C S Manohar, 2008, Inverse sensitivity analysis of singular solutions of FRF matrix in structural system identification, CMES: Computer Modeling in Engineering and Science, 37(2), 113-152.
12. V Namdeo and C S Manohar, 2008, Force state maps using reproducing kernel particle method and kriging based functional representations, CMES: Computer Modeling in Engineering and Science, 32(3), 123-160.
13. S S Panda and C S Manohar, 2008, Applications of meta-models in finite element based reliability analysis, CMES: Computer Modeling in Engineering and Sciences, 28, N0. 3, 161-184.
14. B Radhika, S S Panda and C S Manohar, 2008, Time variant reliability analysis using data based extreme value analysis, CMES: Computer Modeling in Engineering and Sciences, 27(1-2),79-110.
15. S Ghosh, C S Manohar and D Roy, 2008, Sequential importance sampling filters with a new proposal distribution for parameter identification of structural systems, Proceedings of Royal Society of London, A, 464, 25-47.
16. V Namdeo and C S Manohar, 2007, Nonlinear structural dynamical system identification using adaptive particle filters, Journal of Sound and Vibration, 306, 524-563.
17. R Sajeeb, C S Manohar and D Roy, 2007, Control of Nonlinear Structural Dynamical Systems with Noise Using Particle Filters, Journal of Sound and Vibration, 306, 25, 111-135.
18. S Ghosh, D Roy and C S Manohar, 2007, New forms of extended Kalman filter via transversal linearization and applications to structural system identification, Computer Methods in Applied Mechanics and Engineering, 196, 5063-5083.

19. M Manjuprasad and C S Manohar, 2007, Adaptive random field mesh refinements in stochastic finite element reliability analysis of structures, CMES: Computer Modeling in Engineering and Sciences, 19(1), 23-54.
20. R Sajeeb, D Roy and C S Manohar, 2007, Numerical aspects of a real-time substructuring technique in structural dynamics, International Journal of Numerical Methods in Engineering, 72, 1261-1313.
21. A M Abbas and C S Manohar, 2007, Critical vector random earthquake loads for parametrically excited structures, Structural Safety, 29(1), 32-48.
22. Sayan Gupta and C S Manohar, 2006, Reliability analysis of randomly parametered linear vibrating systems subjected to stochastic excitations, Journal of Sound and Vibration, 297(3-5), 1000-1024.
23. C S Manohar and D Roy, 2006, Nonlinear structure system identification using Monte Carlo filters, Sadhana, Academy Proceedings in Engineering, Indian Academy of Science, 31(4), 399-427.
24. Sayan Gupta and C S Manohar, 2005, Extreme value distribution of von Mises stress in randomly vibrating structures, Journal of Vibration and Acoustics, Transaction of ASME, 127 (6), 547-555.
25. Sayan Gupta and C S Manohar, 2005, Development of multivariate extreme value distributions for random vibration applications, Journal of Engineering Mechanics, ASCE. 131(7), 712-720.
26. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part I: Linear structures, Journal of Sound and Vibration, 287, 865-882.
27. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part II: Nonlinear structures, Journal of Sound and Vibration, 287, 883-900.
28. C S Manohar and R Ghanem, 2005, Multivariate probability distribution of ordered peaks of vector Gaussian random processes, Probabilistic Engineering Mechanics, 20, pp 87-96.
29. Saikat Saha and C S Manohar, 2005, Inverse reliability design of structures subjected to partially specified earthquake loads, Probabilistic Engineering Mechanics, 20, 19-31.
30. Sayan Gupta and C S Manohar, 2004, Response surface method for time variant reliability analysis of nonlinear random structures under nonstationary excitations, 36, 267-280, Nonlinear Dynamics.
31. Sayan Gupta and C S Manohar, 2004, Improved response surface method for structural reliability analysis, 123-139, Structural safety.
32. S Ammanagai, S Venkatesha, and C S Manohar, 2004, Analytical and experimental investigations of structural damages in beams and built-up structures using vibration data, 31(1), 73-84, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
33. Luna Majumder and C S Manohar, 2003, A time domain approach for damage detection in bridge structures using vibration data with moving vehicle as an excitation source, 268, 699-716, Journal of sound and Vibration.
34. C S Manohar, S Venkatesha and S Sadasivan, 2003, Finite element analysis of vehicle-structure interactions during launching of remotely piloted air-vehicles, 30(1), 1-6, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
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4. C S Manohar and K Venkatraman, 2006-2008, Analytical prediction of squeak and rattle noise intensity in a seat belt retractor system, Funded by Delphi Automotive Systems, India.
5. C S Manohar, 2006-2008, Structural Reliability Under Seismic Loads, Funded by Cranes Software India Limited.
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8. C S Manohar and K Venkatraman, 2006, Acoustic vibration of sodium to air heat exchangers, Funded by IGCAR.
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15. C S Manohar, 2001-2004, Structural damage detection using vibration data and probabilistic health assessment, Funded by Council of Scientific and Industrial Research, Government of India.
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610 CV of the CI

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Experience:

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12/1996-12/2007	Assistant Professor, Indian Institute of Science, Bangalore, India
5/2010-8/2010 & 5/2009-7/2009	Visiting Scientist Fellowship of INRA, France.
4/2006-12/2006	Poste Rouge fellowship of CNRS, France
5/2005-7/2005	Visiting Scientist, University of Paul Sabatier, Toulouse, France.
6/2004-7/2004	Visiting Scientist, LMTG, Observatoire Midi-Pyrenees, Toulouse.
7/2002	Visiting Scientist, University of California, San Diego, USA
3/2001-5/2001	Visiting Scientist, Department of Mathematics and Computing Science, Technical University of Eindhoven, The Netherlands.
12/1993-12/1996	Lecturer, Indian Institute of Science, Bangalore, India.
2/1993-11/1993	Project Leader, Transoft International, Paris & Bangalore, India. (Developed "*Pollusol*" – a *Fluidyn* code)

Awards & Felowships

1. Visiting scientist fellowship of INRA, France (2009, 2010 & 2011).
2. Poste Rouge fellowship of CNRS, France.
3. Research fellowship of Indian Institute of Science for Ph.D (1987-1992).
4. Distinction, B.Tech, National scholarship of government of India for M.E. (1985-1987).
5. State recognition award for outstanding academic performance of the Government of Andhra Pradesh, India (1980-1984).

Recognitions

1. Invited by the National Academy of Engineering, USA as a speaker at the Second Indo-American Frontiers of Engineering Meeting, 28th February – 1st March, 2008, Irvine, USA.
2. Member, Central level Expert group for overall reassessment of groundwater resources of the country, 2010, Ministry of Water Resources.
3. Member of the Working group on Water Database Development and Management, Planning Commission, 2010.
4. Nominated as Executive Committee Member, Karnataka State Natural Disaster Monitoring Center, Government of Karnataka, India – May 2004.

Areas of Research

I work in the research areas including groundwater hydrology, numerical modeling, and environmental engineering. My interests include analysis of flow and reactive transport in groundwater systems, field-scale experiments in watershed hydrology, geospatial & geophysical methods and optimization & inverse problems

List of Relevant Publications

1. B. Siva Soumya, B., Sekhar, M., Riotte, J., Audry, S., Lagane, C., Braun, J. J. (2011). Inverse models to analyze the spatiotemporal variations of chemical weathering fluxes in a granito-gneissic watershed: Mule Hole, South India. Geoderma (In Press).
2. Suresh Kumar, G., Sekhar, M. and Misra, D. (2011). Spatial and temporal moment analyses of decaying solute transport in a single fracture with matrix diffusion. Journal of Petroleum and Geosystems Science and Engineering (In Press).
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4. Sat Kumar, Sekhar, M., Bandyopadhyay, S. (2009). Assimilation of remote sensing and hydrological data using adaptive filtering techniques for watershed modeling. Current Science, Vol.97(8), pp.1196-1202 (Invited article in Section: Civil engineering Research).
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12. Kumar, G. S., Sekhar, M., Misra, D. (2008). Time-dependent dispersivity of linearly sorbing solutes in a single fracture with matrix diffusion. Journal of Hydrological Engineering (ASCE), Vol.13(4), pp. 250-257.
13. Chaudhuri, A. and Sekhar, M. (2007) Analysis of biodegradation in a 3-D heterogeneous porous medium using nonlinear stochastic finite element method. Advances in Water Resources, V. 30, pp.589-605.
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620 Curriculum Vitae of the Principal Collaborator (PC)

Annexure-1 Detailed project proposal (See item 108)

1 Summary

It is proposed to develop mathematical models (based on theories of probability, interval analysis, convex modeling and fuzzy sets) for uncertainties in the specification of loads and system parameters for externally loaded engineering structures and subsequently evaluate measures of structural safety and global sensitivity using finite element modeling, Monte Carlo simulations, and optimization tools. . Furthermore, the tools thus developed are proposed to be integrated with professional finite element analysis packages such as NISA and Abaqus.

2 Aims of the project

- To develop a suite of unified computational methods for assessment of safety of structures when the underlying uncertainties are modeled using interval analysis, convex functions, fuzzy sets, and (or) probabilistic models. Examine the inter-relation between alternative models of safety. Tackle forward and inverse reliability problems and questions on system reliability.
- To develop simulation based methods for evaluation of variance based global sensitivity factors for structural engineering applications taking into account the non-Gaussian distributions and mutual dependence of the basic random variables. Examine relations between these sensitivity factors and those obtained in reliability analysis. Explore the nature of global sensitivity measures when uncertainties are modeled using non-probabilistic tools.
- Interface the algorithms developed in (a) and (b) above with FE based models for structures created on professional packages (such as NISA and Abaqus).
- Illustrate the procedures developed on case studies involving broad ranging structural engineering problems encompassing structural nonlinearities, static/dynamic loads, and thermo-mechanical effects.

3 Background

3.1 Uncertainty models and safety measures

The repertoire of tools available in the existing literature to model uncertainties in engineering systems is vast and includes models based on probability, interval analysis, convex modeling, fuzzy logic, and hybrid approaches (Madesn *et al*., 1986, Elishakoff and Ben-Haim 1990, Ben-Haim 1996, Rao and Berke 1997, Elishakoff 1998, Sawyer and Rao 2000, Langley 2000).

In models based on probability, the uncertainties are typically modeled as a *n*-dimensional vector X of random variables with specified joint probability density function $p_X(x)$. The computation of structural reliability entails the evaluation of a multi-fold integral over an implicitly defined irregular region in the *n*-dimensional space spanned by X. The merits of this approach are many:
(a) the axiomatic basis of the probability provides systematic framework for calculus of probability to be incorporated into mechanistic modeling of structures, (b) the theory of statistics offer a rational means to link data with probabilistic models, (c) generalization to include spatiotemporal variation of uncertainties via theory of random processes is possible, (d) availability of various limit theorems to model sums, products, extremes, and rare events, (e) availability of well developed theory based on Bayes' theorem to combine mathematical modeling with experimental observations, (f) availability of powerful tools based on Markov process theory to model stochastic dynamical systems, and (g) availability of powerful tools based on Monte Carlo simulations to simulate uncertain systems on computers. Probabilistic models for uncertainties have been extensively combined with finite element analysis (FEA) for structural analysis and with optimization tools for structural system response and reliability analysis (Kiureghian and Ke 1998, Ellingwood 2006). These models have also provided rational basis for structural design code development (Ditlevsen and Madsen 1996).

In spite of their wide spread usage, the probabilistic models do suffer from a few limitations: (a) sensitivity of probability of failure to details of $p_X(x)$ near its tails and the attendant difficulty in modeling the tail regions due to paucity of empirical data, (b) difficulties in modeling of rare events that might occur during the envisaged life of the structure, (c) difficulties in modeling human interfaces (for example, modeling of loads due to terrorist attack, operation of complex systems, human errors in design and construction), (d) numerical difficulties in evaluation of structural reliability when structure is large, nonlinear, and subject to time variant loads, and (e) general lack of experience in modeling and transformations of multi-variate non-Gaussian quantities. Attempts to develop alternative approaches for modeling uncertainties have lead in recent years to the development of a new body of tools which are collectively termed as possibilistic analysis tools. These include the models based on interval analysis, convex modeling, and fuzzy set theory.

In interval modeling the basic variables $\left(x_i\right)_{i=1}^n$ are taken to lie within a hypercube such that $\underline{x}_i \le x_i \le \overline{x}_i; i = 1, 2, \cdots, n$. Consequently, the response variables also get represented as intervals and characterized either using optimization tools or interval algebra (Rao and Berke 1997). Convex models offer a generalization of the interval modeling by considering $\left(x_i\right)_{i=1}^n$ to lie within a convex region instead of just a hypercube [for example, $x = \left(x_i\right)_{i=1}^n$ can be taken to be such that $x^t \Omega x \le a$ where Ω is a $n \times n$ positive definite matrix and *a* is a scalar]. Here again the response is characterized via optimization tools (Ben-Haim 1996, 2006). Fuzzy sets can be viewed as a further generalization of intervals and convex models. Here the variable *x* is characterized by a membership function $\mu(x)$ such that $0 \le \mu(x) \le 1$ and a confidence level α with $0 \le \alpha \le 1$ (Sawyer and Rao 1997). Thus, for a given α, the variable *x* can be shown to be such that $\underline{\mu}(\alpha) \le x \le \overline{\mu}(\alpha)$. This would mean that *x* can be viewed here as a parameterized interval. In the same vein, one could also conceive fuzzy variables as being parameterized convex models.

In the context of structural safety analysis, by using possibilistic analysis tools one can determine quantitatively if a failure is possible or not. The reliability analysis aims to determine the greatest value of a metric of input uncertainties that is consistent with no failure of the structure. The study by Langley (2000) provides valuable insights into these issues and outlines a suite of optimization problems to characterize safety which are eminently applicable for structural engineering applications. No matter which uncertainty modeling approach is used, it is shown in this study that the problem of evaluation of structural safety can be posed as a problem in constrained nonlinear optimization.

3.2 Global sensitivity analysis

In the context of analysis of structures with random parameters and (or) forcing, the objective of global sensitivity analysis is to decompose the variance of a specified response variable into contributions from uncertainties in the individual input variables. The analysis covers entire range of values assumed by the input variables and, unlike the gradient based local sensitivity analyses, does not limit the variations to be small nor to take place one variable at a time. This leads to quantification of the relative importance of different input variables in a model, thereby enabling ranking of input variables according to their relative importance. Major contributions to the theoretical development of this concept have been made by Sobol and his associates (Sobol 1993, 2001, 2003a,b, Sobol and Levitan 1999, Sobol *et al.,* 2007, Sobol and Kucherenko 2009, 2010). The study by these authors considers model input parameters $\left\{x_i\right\}_{i=1}^n \in K^n = \left\{x \middle| 0 \le x_i \le 1 \forall i = 1, 2, \cdots, n\right\}$ which are transformed nonlineary through a square integrable function $y = f\left(x_1, x_2, \cdots, x_n\right)$. A study of the works of Sobol and associates reveals the following facts. An unique and convergent representation of the form

$$y(x_1, x_2, \cdots, x_n) = f_0 + \sum_{1 \le i \le n} f_i(x_i) + \sum_{1 \le i < j \le n} f_{ij}(x_i, x_j) + \sum_{1 \le i < j < m \le n} f_{ijm}(x_i, x_j, x_m) + \cdots + f_{123\cdots n}(x_1, x_2, \cdots, x_n) \tag{1}$$

is possible where the summands satisfy the following properties:

$$f_0 = \int_{K^n} f(x_1, x_2, \cdots, x_n) \prod_{1 \le i \le n} dx_i$$

$$\int_0^1 f_i(x_i)\, dx_i = 0; 1 \le i \le n$$

$$\int_0^1 \int_0^1 f_{ij}(x_i, x_j) dx_i dx_j = 0; 1 \le i < j \le n \tag{2}$$

$$\vdots$$

$$\int_{K^n} f_{12\cdots n}(x_1, x_2, \cdots, x_n) \prod_{1 \le i \le n} dx_i = 0$$

It can be shown that the summands possess the orthogonality properties

$$\int_{K^k} f_{i_1, i_2, \cdots, i_s}(x_{i_1}, x_{i_2}, \cdots, x_{i_s})\, f_{j_1, j_2, \cdots, j_s}(x_{j_1}, x_{j_2}, \cdots, x_{j_s}) \prod_{l=1}^{k} dx_l = 0 \tag{3}$$

whenever at least one of the subscripts on the two functions differs and the functions can be evaluated using the relations

$$\int f(x)\, dx = f_0; \int f(x) \prod_{\substack{j=1 \\ j \ne i}}^{k} dx_j = f_0 + f_i(x_i)$$

$$\int f(x) \prod_{\substack{j=1 \\ j \ne i}}^{k} dx_j = f_0 + f_i(x_i) + f_j(x_j) + f_{ij}(x_i, x_j) \cdots \tag{4}$$

$$f(x_1, x_2, \cdots, x_k) = f_0 + \sum_{i=1}^{k} f_i(x_i) + \sum_{1 \le i < j \le k} f_{ij}(x_i, x_j) + \sum_{1 \le i < j < m \le k} f_{ijm}(x_i, x_j, x_m) + \cdots + f_{12\cdots k}(x_1, x_2, \cdots, x_k)$$

By interpreting the variables $\{x_i\}_{i=1}^{n}$ as a set of independent random variables distributed identically in the unit interval, it can further be shown that the variance of output *y* is given by

$$\mathrm{Var}[y] = D = \int_{K^k} f^2(x)\, dx - f_0^2 = \sum_{1 \le i \le k} D_i + \sum_{1 \le i < j \le k} D_{ij} + \cdots + D_{1,2,\cdots,k}$$

$$D_i = \int_0^1 f_i^2(x_i)\, dx_i\,; \quad D_{ij} = \int_0^1 \int_0^1 f_{ij}^2(x_i, x_j)\, dx_i dx_j \cdots \tag{5}$$

(5)

This leads to the definition of Sobol's indices

$$S_i = \frac{D_i}{D} \quad [\text{First order indices}]; S_{ij} = \frac{D_{ij}}{D} \quad [\text{Second order indices}]$$
$$S_{ijm} = \frac{D_{ijm}}{D} \quad [\text{Third order indices}]\cdots \tag{6}$$

with

$$\sum_{1\le i\le n} S_i + \sum_{1\le i<j\le n} S_{ij} + \sum_{1\le i<j<m\le n} S_{ijm} + \cdots + S_{1,2,\cdots,n} = 1 \tag{7}$$

The number of these indices can be shown to be equal to $2^n - 1$ with the evaluation of each of the integrals requiring a *k*-fold integration to be performed. Various methods for determination of Sobol's indices including Monte Carlo simulations and polynomial chaos expansions have been developed (Tarantola 2006, Sudret 2007, Blatman and Sudret 2010, Xu and Gertner 2008, Kucherenko *et al.*, 2009, Mara 2009, Aptelli et al., 2010, Plischke 2010). The notion of total sensitivity factor which evaluates the total effect of a specified input variable on the response variance. For the i^{th} variable x_i, this index is given by (Homma and Saltelli 1996)

$$T_i = S_i + \sum_{\substack{j=1 \\ j\neq i}}^{k} S_{ij} + \sum_{\substack{j,m=1 \\ j\neq i, m\neq i}}^{k} S_{ijk} + \cdots$$
$$= 1 - \frac{\text{Var}\left[\text{E}\left(Y \middle| X_{-i}\right)\right]}{\text{Var}\left(Y\right)} = \frac{\text{E}\left[\text{Var}\left(Y \middle| X_{-i}\right)\right]}{\text{Var}\left(Y\right)}; \quad \left[X_{-i} = \text{vector } X \text{ excluding } X_i\right] \tag{8}$$

The calculation of the Sobol's indices can also be done by grouping variables and determining the contributions of various of groups of input variables to the response variance (Sobol 1993, Patelli *et al,* 2010).

The application of global sensitivity analysis to problems of structural engineering is not wide spread. Some of the studies that have been reported include the works of Arwade *et al*., (2010) who have considered Gaussian models for input variables and considered the problem of collapse of a structural frame; Blatman and Sudret (2010) have employed polynomial chaos expansion based method to analyse global sensitivity of a laterally loaded building frame; Mukherjee *et al*., (2011) study the response of an un reinforced masonry shear wall.

3.3 Recent research at IISc by the PI and his group

Combined experimental and analytical studies which employ inverse sensitivity analysis of system natural frequencies, mode shapes and frequency response functions (FRF-s) have been conducted by Ammanagi *et al.,* (2004), Venkatesha *et al.,* (2008), and Sivaprasad *et al.,* (2009). The study by Venkatesha *et al.,* (2008) considered the inverse sensitivity analysis of the singular solutions of the measured FRF-matrix. Sivaprasad *et al.,* (2009) considered identification of parameters of fractionally ordered damped models based on inverse eigensensitivity and FRF-senstivity analyses and highlighted the importance of the studies in structures involving rubber like material. Manohar and Roy (2006) applied particle filtering strategies to identify parameters of nonlinear dynamical systems. Their study also discussed the application of discretization methods as applied to stochastic differential equations using the Ito-Taylor expansions. Namdeo and Manohar (2007) developed a bank of particle filtering approach to estimate parameters of nonlinear dynamical systems. The same authors (Namdeo and Manohar 2008) also explored the application of reproducing kernel particle method to model the restoring force characteristics of nonlinear dynamical systems based on measured time histories of system response. Tipireddy *et al.,* (2009) and Nasrellah and Manohar (2010a,b, 2011) have discussed methods for fusing data from different sensors and from different test scenarios via a common pseudo-time parameter in the context of particle filter based system identification tools for nonlinear structural systems. These studies have involved substantial illustrations that include examples drawn from synthetic data, laboratory data and field data on existing railway bridges.

A suite of programs that interface finite element modeling (using commercial softwares) and particle filtering strategies (with relevant codes developed on the Matlab platform) with measurements from existing structures has been developed. The study by Ghosh *et al.,* (2008) have extended the scope of sequential importance sampling based particle filtering to include nonlinear measurement models and non-Gaussian noises in the context of identification of nonlinear structural systems. Sajeeb *et al.,* (2009a,b, 2010) have considered substructuring schemes based on Rao-Blackwell theorem to develop time domain tools for identification and control of nonlinear dynamical systems. Their study also includes validation of tools developed using measurements on nonlinear frame models in laboratory conditions. Radhika *et al.,* (2008) have considered statistical tools for identification of basin of attraction of extremes of peaks in random time series and have demonstrated how these tools can be employed to estimate the time variant reliability of dynamical systems under random excitations using Monte Carlo simulation techniques. A further study by Radhika and Manohar (2010) has extended this approach to study the reliability of existing structures by combining results from asymptotic extreme value theory with dynamic estimation tools. Radhika and Manohar (2011a) have used nonlinear state estimation methods to update local sensitivities of nonlinear system response when data on measured responses become available. Sundar and Manohar (2011) have developed a simulation based strategy to update reliability models when data on measured response to ambient loads become available. Radhika and Manohar (2011b) have investigated procedures to affect probabilistic substructuring in problems of dynamic state estimation and model updating. Their study includes illustrations on sensitivity model updating of hysteretic systems using substurcturing concepts.

3.4 Discussion

Based on the brief review of literature presented in the preceding sections, we identify the following questions as requiring further research attention:

- While methods of structural reliability analysis based on probabilistic models for structural uncertainties have been integrated with finite element analysis methods, the treatment of other forms of uncertainties in this context still require further development. Some of the specific issues here include: strategies to arrive at uncertainty models based on data; treatment of simultaneous presence of alternative forms of uncertainties in a given problem; analysis of system level safety with alternative uncertainty models; development of methods for time varying safety analysis; generalization of concept of design point and reliability based structural design when alternative uncertainty models are employed; and, updating of safety measures when data on measured response of existing structures become available.
- The application of global sensitivity analysis to problems of structural systems, including dynamic and nonlinear behavior, requires further research attention. There exists wide scope to improve methods for computing Sobol's indices using the recently developed simulation strategies which employ Markov Chain Monte Carlo and subset simulations. The generalization of Sobol's indices to include dependent and non-Gaussian random input variables needs to be developed. The opportunity to determine global sensitivities with respect to groups of random variables has not been utilized in structural engineering applications. Thus, in an earthquake response analysis of a large structure, the grouping of variables into those associated with loads, material constitutive laws, inertial properties, geometric properties, and boundary conditions would afford valuable insights into characterizing output uncertainties. The question on how to update global sensitivity measures when data on measured response become available has not been explored in the existing literature. Similarly, questions on characterization of global response sensitivity measures when inputs are characterized using alternative uncertainty models have not been explored.

4.0 Deliverables

- Development of a unified set of computational tools for safety assessment of structures when the uncertainties are modeled using alternative tools such as interval analysis, convex functions, fuzzy sets and (or) probabilistic models.
- Development of a set of tools for computing global sensitivity factors for structural responses.

- A Matlab-Abaqus/NISA interface for implementing the above tools so that wide ranging class of problems of practical interest could be tackled.
- Research publications and technical reports based on the above research.

5.0 Importance of the proposed work to DAE

Quantitative treatment of uncertainties and analysis of safety of engineering structures is central to the risk analysis of large infrastructure. The studies proposed herein bring a host of powerful computational tools, namely, finite element analysis, advanced Monte Carlo simulation strategies, numerical optimization tools, and uncertainty modeling using probability, fuzzy logic, interval analysis, and convex functions, to develop state-of-the-art strategies for dealing with uncertainties. The wide ranging power of these tools ensures that the strategies developed herein are not limited to the study of idealized low-dimensional systems but can tackle systems of practical interest to the nuclear industry.

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Section C CERTIFICATE-1

Certificate from the Head of the Institution of the Principal Investigator (PI) and Co-Investigator (CI) from Non-DAE Institution (Please see Instruction - Sr. No.4-6)

...

Project Title: Safety and global sensitivity analyses of structures with alternative uncertainty models

(1) Certified that this Institution agrees to the participation of

Principal Investigator:
Professor. C.S. Manohar
Department of Civil Engineering
Indian Institute of Science,
Bangalore 560 012

Co- Investigator:
Professor M Sekhar
Department of Civil Engineering
Indian Institute of Science,
Bangalore 560 012

for the above project which is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS).

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) Certified that the management takes the responsibilities for the timely submission of audited (by external Chartered Accounted or Statutory Government Auditor) statement of account (SA), utilisation certificate (UC), details of staff recruited and equipment purchased for each year as well as the audited (by external Chartered Accounted or Statutory Government Auditor) consolidated SA and UC for the final year.

(4) **Particulars of University Bank A/c are as follows (Please see Instruction - Sr. No.7):**

a) **Name of Account Holder:**
b) **Account No.:**
c) **Bank Name and Branch Address:**
d) **Branch code:**
e) **IFS Code: (16 digits)**

Date:

Place:

Name & signature of the
Head of the institution
or his authorised nominee

Seal:

Note: For Multi-Centre projects, similar certificate is needed from all the participating institutions.

CERTIFICATE-2 (Submit single hard copy only**)**

Certificate from the Head of the Institution of Principal Collaborator (PC) /Departmental Coordinator (DC) from DAE Institution

(Please see Instruction - Sr. No.7)

....

Project Title:

(1) Certified that this Institution agrees to the participation of Prof./Dr. _____ Department/Address _____ as Principal Collaborator (PC)/ Departmental Coordinator (DC) for the above project that is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS) by Prof./Dr. _____ Department/Address _____ as Principal Investigator (PI) .

The PC/ DC shall coordinate for timely submission of yearly progress reports and financial documents towards meaningful conclusion of the project as scheduled.

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) This institution assures to undertake the financial and other management responsibilities of the part of the project work that will be conducted in this institution.

(4) This Certificate is being issued with approval of the Group Board or the Group Board approval shall be taken, after the project is sanctioned by BRNS.

Date:

Place:

Name & signature of the
Head of the DAE institution/
Head of the Group

Seal:

ACKNOWLEDGEMENT (Please Submit Three Copies only)
(TO BE FILLED IN BY THE APPLICANT)

…

Government of India
Department of Atomic Energy (DAE)
Board of Research in Nuclear Sciences (BRNS)

BRNS Secretariat Phone: 022-25590813, 25593329
Central Complex, 1st Floor FAX: 022-25505151, 25519613
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TITLE OF THE PROJECT: Safety and global sensitivity analyses of structures with alternative uncertainty models

NAME AND ADDRESS OF THE
PRINCIPAL INVESTIGATOR (PI)
Professor C S Manohar
Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

----------(Do not write below this line)----------

Application No: Received on:

Dear

This is to acknowledge the receipt of your application for grant of financial assistance by BRNS. Your application will take at least 4 months for processing. Kindly quote the above application No. and date in queries on status of your application.

Thanking you,

Yours sincerely,
Programme Officer, BRNS

CRP on Uncertainty Analysis of Engineering and Environmental Systems

Project-2

"Stochastic Modeling of Hydration Process in Concrete: Investigation into Creep and Shrinkage"

A project proposal submitted to

BOARD OF RESEARCH IN NUCLEAR SCIENCES
Department of Atomic Energy
Government of India

By

Professor Ananth Ramaswamy (PI)
Dr Sajeev Krishnan (CI)
Professor C S Manohar (CI)

Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

February 2012

SECTION-A

PART I – PROJECT OVERVIEW (Please see Instruction - Sr. No. 8)

100. Advisory Committee Code Number (Please see Instruction - Sr. No. 9): **36**

101. Title: **"Stochastic Modeling of Hydration Process in Concrete: Investigation into Creep and Shrinkage"**

102. Key Words & Name of 3 Referees (Please see Instruction - Sr. No. 10) Hydration of cement in concrete; uncertainty in physical process parameters; Mechanical Properties of Concrete; Time dependent deformation in concrete;

103. **Project Summary** (Please see Instruction - Sr. No. 11):

The proposed study aims to develop a hydration based hygro-thermo-chemo-mechanical model for predicting mechanical properties of concrete. The short and long term predictions of time dependent deformations are sensitive to both material parameters of the mix, the ambient environmental conditions and the uncertainties in hydration and related gradient driven processes. The influence of parameter uncertainties will be accounted for in the model development. Time dependent deformations in concrete, both creep and shrinkage, play a critical role in prestressed concrete structures, such as bridge girders, nuclear containment vessels, etc. These strains result in losses, through release of prestress, and thereby influence the safety of these structures. Data on the effects of ambient humidity and temperature on time dependent deformations in normal and heavy density concrete obtained experimentally in an earlier study together with other reported information in the literature will be employed in the present study for model validation. Predictions of creep and shrinkage in structural elements, such as beams and slabs using this model will also be undertaken as a validation of the modeling features.

Personal Details:

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	Co-PC	Shri Tarvinder Singh		tarvindr@barc.gov.in; tarvindersinghs@gmail.com	022-25591554	

107. Total Budget Rs. 36,73,040/-

108. Detailed Project Proposal Report Enclosed: Yes

Detailed Project Proposal

Background:

Predicting delayed strains (creep and shrinkage) in concrete proves to be critical to a large number of pre-stressed concrete structures, such as containment vessels of nuclear power plants. These delayed strains include:

- *Autogeneous shrinkage*, as deformation related to the water consumption during the hydration reaction in early-age concrete. This is negligible for normal concrete.
- *Drying shrinkage*, as deformation related to the moisture diffusion from the inner core to the outside of the concrete member.
- *Basic creep strains*, as time-dependent deformation of a loaded specimen, without drying.
- *Drying creep strains*, as additional deformation, which occurs in drying in a loaded specimen (Pickett effect)

Probably the most uncertain and most difficult aspect of the design of reinforced and prestressed concrete structures is the prediction of time-dependent behavior. However, realistic prediction of concrete creep and shrinkage is of crucial importance for durability and long-time serviceability of concrete structures. For some structures the long-term performance from the safety view point, prediction of time dependent deformations are critical. Creep and shrinkage cause increases in deflection and curvature, cracking of concrete, loss of prestress, redistribution of stresses and leakages. The rate and degree of hydration of concrete plays a paramount role in the extent of creep and shrinkage.

Factors influencing shrinkage creep and fire damage

One of the most important factors effecting time dependent deformations, both shrinkage and creep, is the *relative humidity* of the medium surrounding the concrete.

- For a given concrete, creep is higher when the relative humidity is lower.
- Concrete exhibiting high shrinkage also generally shows a high creep.

This doesn't mean that the two phenomena are due to the same cause, but they may both be linked to the same aspect of the structure of the hydrated cement paste. Concrete cured and loaded in a constant relative humidity condition exhibits creep and that creep produces no loss of water from the concrete to the surrounding medium, nor is there any gain in weight during creep recovery.

- Drying shrinkage and creep is also influenced by the *modulus of elasticity of the aggregate and the aggregate content*.
- Drying shrinkage and creep are also influenced by the *cement content*. For constant cement content an incremental increase in W/C ratio increases both drying shrinkage and creep. For a constant W/C ratio an incremental increase in cement content reduces the creep but increase the drying shrinkage. This is the only instance in which an opposite effect exists.

Humidity, geometry of the concrete element and the temperature has an important impact on the creep and shrinkage. An incremental increase of relative humidity of air increases both the drying shrinkage and creep. Given the geometry of the concrete element having a thickness expressed as $h = 2A/P$; where $A =$ Section Area, $P =$

Perimeter, an incremental increase in the thickness h reduces the drying shrinkage and creep. Given the same curing history for two specimens, the one that is kept in a higher temperature will have more creep and drying shrinkage than the other one. There is a direct proportionality between the *magnitude of sustained stress* (loading at given age) and creep of concrete. Because of the effect of strength on creep at a given stress level, lower creep values were obtained for the longer period of curing before the application of the load. Shrinkage is not affected by this factor.

Rate and degree of hydration is the one single factor aspect that overshadows all other aspects of time dependent deformation and a proper representation of these aspects at different length and time scales accounting uncertainties within these parameters adds to the complexity of the problem.

Cement based materials such as concrete have a very complex structure over many length scales. According to Whittman (1983), concrete may be modeled at three different length scales, namely, macro, meso and micro. At the macro level, comprising of full-scale structures, the material may be considered as an isotropic continuum (meter scale). The meso-scale operates at the millimeter level and one can consider aggregates, pores, cracks, and interfaces. The micro scale presents the structure of the hardened cement. While one can conceptualize three different length scales in classifying the study of concrete it is hardly possible to delineate these scales in the process of looking for causes for concrete cracking.

At early ages the main part of the development of material properties takes place due to chemical reactions of cementatious materials. Curing conditions, consisting of temperature and moisture conditions as well as curing time, effects the degree of reaction. It has been shown that besides temperature, moisture conditions play an important role in the chemical reactions of cements (Powers 1947, Parrott 1986).

One of the mechanisms for weakening of concrete is the differential drying of concrete in the early stages of the concrete hydration when moisture gradients develop long before any load is applied. In the initial fresh concrete, hydration of cement reduces the available free water leading to shrinkage termed as ‘autogenous’ shrinkage. The hydration process in hardened concrete results in drying resulting in ‘self-dessication’. Further, due to evaporation there is a gradual reduction of water leading to additional shrinkage termed as ‘drying shrinkage’. Non-uniform drying causes drying shrinkage that induces tensile stresses that could be much higher than the low tensile strength leading to cracking of concrete (Bisschop and Van Mier, 2001). Drying shrinkage may be observed in macro scale in large block specimen, say of a cubic meter in size, or in nano-meter scale due to capillary condensation, which occurs in the gel phase in cement pastes (Benz et al. 1995, Carmeliet et al, 2001). Carmeliet et al (2001) have shown through experiments that nonlinear quasi static and dynamic material behavior primarily changes in the range of low saturation, where high fluid solid interactions are present. At the micro level un-hydrated cement particles, gel, crystalline hydration and porosity are observed. Studies into the microstructure of concrete at the micro scale have only recently been attempted (Xi and Jennings, 1992). For a precise definition of material properties in hardening concrete, chemical reactions and development of the microstructure have to be modeled by means of considering the degree of hydration. This may be in turn obtained from the moisture and temperature conditions. The process of

differential drying is extreme in highly porous material such as the porous interface transition zone around the aggregate. The interface transition zone is the weakest part of concrete and its microstructure is different from the rest of the cement paste (Mindess, 1989). Cracks tend to originate in this weak albeit small interface, transition-zone.

Related to the durability and serviceability of concrete structures, the removal of moisture due to self-desiccation (removal of water during hydration of hardened concrete) and the autogenous shrinkage (loss of water in hydration of hardening concrete) are important factors in estimating the moisture content. Moisture plays a significant role for concrete not only in the hydration process but also in the physical and chemical processes in various deterioration phenomena such as frost damage, early shrinkage, shrinkage cracking as well as movement of ions and gases (Bazant 1993, Oh and Cha, 1994). Bazant (1993) has pointed out that for concrete structures exposed to environment, to obtain realistic stresses for prediction of cracks, the associated moisture and heat transport problem has to be solved. Studies have been made to examine the phenomena of crack initiation and moisture transport (Setzer, 1976, Sadouki and Van Mier, 1997, Jankovic, Kuntz and Van Mier, 2001). Oh and Cha (1994) have developed a 3D finite element study on thermal and shrinkage stress analysis in concrete in terms of moisture content and degree of hydration. Jankovic et al (2001) have considered the moisture transport and fracture process in concrete through a lattice based gas automata and fracture model. A lattice model approach for drying of a two-phase composite has also been employed in an earlier study by Sadouski and Van Mier (1997).

Pore pressure rise and humidity loss in concrete due to heating is of great interest in prestressed concrete vessels of nuclear reactors under operating conditions, accidental overstress and fire. The presence of a thermal stress accelerates the moisture flux from inner to outer zones of mass concrete. A number of studies have examined the influence of temperature on fire resistance, shrinkage and stress states due to drying caused by fire (Bazant, 1976 & 1978, Becker and Bresler, 1977, Schneider, 1988, Majorana et al, 1998).

Studies have shown that fluids significantly influence the nonlinear response in porous materials due to the activation of internal molecular forces (Zinszner et al 1997, Van den abeale et al. 2001). The increased fluid solid interaction upon wetting causes the material to soften and swell. Simultaneously the strength of the material reduces and nonlinear hysteretic effects increase significantly. These studies have shown that nonlinear quasi-static and dynamic material behavior changes in the low range of saturation, which implies that presence of moisture plays a role in the nonlinear mechanism.

Creep in concrete is a function of both the state of the concrete composition and the magnitude of the imposed loads acting on the system (Bazant and Panula, 1979). A gradual removal of pore water with time under the action of loads results in ‘drying’ creep. Drying creep strains cannot be separated from other components of the delayed strains (Benboudjema et al 2001a). A drying test, a basic creep test and a total creep test need to be performed in order to get the drying creep strains. An elasto-plastic damage model approach together with the drying law has been employed to simulate the drying shrinkage and creep phenomena in both unloaded and loaded concrete specimen. Kovler (1997) has examined the phenomenon of drying creep in terms of an age adjusted effective modulus method.

Experimental data from creep tests under tension are used to calculate the aging coefficient of concrete for basic creep.

As indicated earlier, drying shrinkage is not a homogenous process and leads to skin cracking. Bazant (1994) and Granger (1997) explain the process of drying creep accompanying the drying shrinkage process. Persson (1997a, 1997b, 1999) has reported the results of a series of tests conducted on cylinder specimen over extended periods of time to assess the effect of moisture, curing conditions, and maturity of concrete on self-dessication and autogenous shrinkage and creep. One set of specimen in each series of these tests has also examined the effect of temperature on the creep response. Benjoudema et al (2001a) have developed an elasto-plastic damage model that reproduces the cracking process taking place in creep and shrinkage. Irreversible components of strain have been captured in this model are shown to be important components. Torrenti et al, (1999 & 2000) have shown that the use of a plastic damage model permits the capture of the residual strains present. The accurate description of the drying process permits the model to capture the effects of the mechanical loads that are concomitant to the drying process effectively. Bissonette et al (1999) have shown that drying shrinkage takes place in three stages, namely, a) water content gradients created by the drying process generate a stress gradient coupled with a high tension in the skin layer leading to cracking without any shrinkage; b) cracks stabilize and shrinkage takes place proportionally with the drying process; c) the stress gradients finally disappear but the cracks don't close leading to asymptotic shrinkage. Models for concrete creep have been developed in order to predict the longitudinal strains in concrete under uniaxial compressive loads. These models are extended to multi-axial states on the basis of creep Poisson's ratio (Bazant 1994, Granger et al 1997). Bazant (1995) reports a formulation of a model B3 for shrinkage and creep in concrete. The model accounts for a number of parameters such as the curing conditions, ambient temperature, age at loading, etc. Granger et al (1997) show the interrelationship of skin micro-cracking and non-uniformity of water content in the specimen and conclude that this is responsible for the drying creep process. However tests have shown that the Poisson's ratio in basic creep is not a constant with time. Its initial value is less than elastic values (Gopalakrishnan et al 1969, Li, 1994). It has been shown to be dependent on the multi-axial nature of the stress state. Benjoudema et al (2001b) have developed a basic creep model that is driven by both the spherical (volumetric) and the deviatoric component of the stress tensor as the corresponding creep strains are proportional to the corresponding stress components. Each part of the creep deformation is associated with a physical phenomenon. One physical process is the migration of the adsorbed water in the macro-porosity, while the other process corresponds to the sliding of the C-S-H gel sheets. Benjoudema et al (2001b) have linked the creep model to an isotropic damage model with plasticity. Papa et al (1998) have reviewed the state of models available to capture creep effects under multi-axial states of stress. They have reviewed models based on elasto-viscoplasticity proposed by Mazars (1986), and cam-clay models of Nova (1979, 1982) and Chan et al (1992, 1994) employed in the consolidation studies of rock salt. Papa et al (1998) in their study conclude that none of the existing models can capture all aspects of creep deformation taking place under tri-axial stress states.

Creep in concrete is particularly important as it can lead to failure after a very long time. Liu (1989) has performed creep fracture tests to observe time dependent relations for displacement and failure and other effects. In that study pre-cracked notched beams were studied under three point bending in sustained loading. The tests were augmented

by a time-dependent finite element analysis to study crack growth and fracture based on a framework of visco-elasticity and fracture mechanics. The applied load on the specimen ranged from 65% to 95% of static load in failure. The study found that creep related failure occurred when the sustained load exceeded 78% of the static failure load. Hansen (1991) performed creep studies on notched cantilever beam specimen. The study concluded that the fracture energy was influenced by a short period of sustained load implying that it is time-dependent. The effect was found to decrease with an increase in test age. Hansen found that for beams tested at 28 days, the width of the fracture process zone increased during the period of sustained loading. However, the effect was not observed in the beams tested after 90 days. Zhou (1992) conducted extensive tests to investigate the creep behavior of concrete. This included tension, compression and bending specimen consisting of cylindrical, cubical and prismatic geometry with notch inserts to ensure a pre determined fracture zone. The rate of load application was also a parameter in the study. In contrast to Hansen's study, Zhou's tests indicated a reduction in the fracture energy under sustained loading. Bazant and Gettu (1992) used a size effect model to investigate the effect of rate of loading on specimen having different sizes and accounted for the time dependency effects on the modulus of elasticity in their study. Both Zhou (1992) and Bazant and Gettu (1992) concluded that there was a decrease in the fracture energy with time. Carpinteri et al (1997) have conducted tensile and flexural creep tests on partially damaged specimen to obtain insights into creep crack growth and failure of strain softening materials. Sustained loads ranging from 75% to 95% of the carying capacity of the members were applied as sustained loads in that study. The study found that three distinct stages exist in the creep process, namely a primary, secondary and a tertiary stage. These stages have a decreasing, constant and increasing creep rate. Their study found that while the secondary stage dominates the whole failure lifetime, both secondary and tertiary stages are important in terms of creep deformation.

Both shrinkage and creep in concrete are a function of the curing conditions imposed at the initial stages and the composition of the mixture. Recently, the use of shrinkage reducing agents and the introduction of fibers in to the matrix, the magnitude of shrinkage have been controlled. Exposure of the concrete to high temperatures, such as 0 to 400 degrees Celsius leads to release of the pore water which transforms in to water vapour. The vapour imposes a pressure on the void channels so created in the system. This dehydration process results in inducing brittleness in the concrete also resulting in eventual failure. Studies by Gawin et al (1996, 2001), Nechnech et al (2001) and Majorana et al (1998) have considered the complex phenomena of moisture transport under thermal loading conditions using a combined numerical model for the mechanical, fluid and thermal effects. Majorana et al (1998) have proposed a finite element model for creep coupled with damage and related cross effects due to hygrothermal behavior. Gawin et al (2001) consider the concrete to be treated as a partially saturated porous material permitting the consideration of a hydration-dehydration, evaporation-condensation, adsorption-desorption phenomena and nonlinearities due to temperature and pressure. A two damage variable model consisting of a mechanical and thermal damage have been incorporated into a thermo-work-hardening plastic damage model for plain concrete in the study reported by Nechnech et al (2001).

Studies on Hydration kinetics and Treatment of Parameter Uncertainties

Studies on durability in concrete when exposed to various conditions, for example, such as sulphate and chloride ingress, carbonation, etc, need to account for variableness in parameters in the process (porosity of concrete, humidity within the concrete and in the exterior, degree and rate of hydration, vapour pressure, etc).

Baert et al (2011) have employed a traditional reaction equations (based on the theory of Powers) to study the hydration reactions of Portland cement and the pozzolanic reaction of fly ash separately. Portland clinker is considered as a mixture of four minerals, each with its own sensitivity to the presence of fly ash. The kinetics of the reactions of each clinker mineral have been analyzed by fitting generally known models such as the Avrami and Jander equations to isothermal heat measurements on pastes of cement, fly ash, and water. The proposed model therefore consists of different stages, in which nucleation, phase-boundary, and diffusion reactions become rate controlling. The kinetics of the pozzolanic reactions have been described with similar equations, implementing parameter values based on measured selective dissolution data. They conclude that Fly ash may accelerate the reaction of a clinker mineral, while at the same time it can decelerate another mineral. Depending on the relative proportions of the clinker minerals, the method can explain the apparent contradiction found in literature related to the acceleration or deceleration effect of fly ash on the cement hydration. Bentz (2006) has studied the role of water to cement ratio on the hydration kinetics and the model explores the influence of fillers replacing a portion of the cement on the hydration process.

Gardoni etal (2007) have used a Bayesian statistical framework to construct probabilistic model for the elastic modulus of concrete. The commonly used Pauw's formula to predict elastic modulus of concrete is very general and does not address the complexity of modern concretes, such as high-strength concrete, use of different types of aggregates and admixtures, etc. Gardoni et al (2007) evaluates the influence of different aggregate types, based on a large number of experimental data. The proposed framework to construct probabilistic models expands upon Pauw's formula and properly accounts for both aleatory and epistemic uncertainties. Bayesian updating is used to assess the unknown model parameters based on experimental data. A Bayesian stepwise deletion process is used to identify important explanatory functions and construct parsimonious models. As an application, the approach is used to develop a probabilistic model for concretes made using crushed limestone and crushed quartz schist coarse aggregates.

Jennings and Bullard (2011) have proposed a bottom up approach to engineer concrete. The study indicates that an approach rooted in fundamental, mechanistic models of concrete materials offers the only viable path for handling the enormous number of variables that are being introduced as new materials are added to the design space, and as new properties are mandated for a sustainable infrastructure. The study recommends that models must begin at the smallest length scales relevant for concrete properties; in some cases this is the scale of electron interactions among atoms and ions. But concrete has complex chemical and structural properties that are manifested at greater length and time scales, so atomic scale models must ultimately be integrated with new models that capture behavior at mesoscopic and macroscopic scales.

The role of C-S-H has been the focus of many recent studies (Thomas et al 2008; Smilauer et al 2010). Ulm et al 2004 have examined concrete as a multi-scale material and have examined its poro-elastic properties. Smilauer et al (2010) have proposed a powerful and robust numerical homogenization method based on fast Fourier transform (FFT) to identify the viscoelastic behavior of calcium silicate hydrates (C-S-H) in hardened cement paste from its heterogeneous composition. The identification is contingent upon the linearity of the creep law. Model B3 for concrete creep is adapted by Smilauer et al 2010 to characterize the creep of C-S-H in cement paste. It is found that the adaptation requires increasing the exponent of power law asymptote of creep compliance. This modification means that the rate of attenuation of creep with time is lower in C-S-H than in cement paste, and is explained by differences in stress redistribution. In cement paste, the stress is gradually transferred from the creeping C-S-H to the non creeping components. The visco-elastic properties of C-S-H at the resolution of 1 μm were identified from creep experiments on cement pastes 2 and 30 years old, having the water–cement ratio of 0.5. The irreversible part of C-S-H creep, obtained from these old specimens at almost saturated state, is found to be negligible unless the specimens undergo drying and re-saturation prior to the creep test. Allen et al (2007) in their studt have measured the composition and solid density of the principal binding reaction product of cement hydration, calcium– silicate–hydrate (C–S–H) gel, one of the most complex of all gels. The study quantifies a nanoscale calcium hydroxide phase that co-exists with C–S–H gel. Ulm et al (2004) advocate the use of micromechanics theory and using homogenization techniques at micro-poromechanics provide estimates of poroelastic properties such as the drained and undrained stiffness, Biot coefficient, Skempton coefficient and the Biot modulus. The study indicates that the Biot coefficient decreases with increase in scale while the Skempton coefficient remains unchanged over a larger length scasle.

Thomas et al (2008) have studied the effects of drying to various relative humidity (RH) levels on the internal structure of hydrated cement paste using small-angle neutron scattering (SANS). Specimens of young and mature portland cement paste were analyzed in the initial saturated state, in the dried state, and then again after re--saturation, allowing reversible and irreversible effects to be separated. The study found that while the observed changes on drying are mainly physical in nature, the ability of the microstructure to resist permanent structural rearrangement increased over time as the hydration and aging reactions progressed.

Kertal et al (2010) have made an attempt to evaluate the uncertainties and sensitivities of creep prediction models of standard concrete.. The four major models considered in their study are: model GL2000 by Gardner and Lockman, model MC90 according to CEB-FIP Model Code 1990, model ACI209 according to the American Concrete Institute and model B3 by Bažant and Bajewa. They first perform a sensitivity study in order to determine the parameters which mostly contribute to the uncertainties of the model prediction. They do this for uncorrelated and correlated input parameters and the differences are pointed out. Due to high parameter correlation, they infer that most standard sensitivity methods are not applicable and, so use a new method developed by Xu and Gertner is applied. They then compare the uncertainties of the creep prediction for all models and find that this reveals significant differences.

Peter et al (2008) have undertaken an evaluation of carbonation and the role of parametric uncertainties associated with the carbonation process. Carbonation caused by atmospheric carbon dioxide is one of the major physicochemical processes which can compromise the service life of reinforced concrete structures. While the bulk of the carbonation reaction is that of calcium hydroxide, other constituents of the porous matrix can also carbonate and compete with calcium hydroxide for carbon dioxide. Most studies neglect the carbonation of calcium–silicate hydrates and un-hydrated constituents in carbonation prediction models. Peter et al (2008) have proposed a mathematical model of carbonation and extended it to include additional carbonation and hydration reactions. The competition of the several reactions and their effect on the carbonation depth is investigated by dimensional analysis and numerical simulations. A parameter study emphasizes that multiple internal reaction layers are present. Their position and speed essentially depend on the strength of the different reactions. It is also observed that, for a wide range of parameters, the effect of some of the additional reactions on the carbonation depth is small.

Atteaga et al (2011) have studied the effects of uncertainties associated with chloride induced Corrosion. They question the use of a simplified chloride ingress into concrete as a diffusion problem where the chloride concentration throughout concrete is estimated analytically. They indicate that this simplified approach has several limitations. For instance, it does not consider chloride ingress by convection which is essential to model chloride penetration in unsaturated conditions as spray and tidal areas. This paper presents a model of chloride penetration where the governing equations are solved by coupling finite element and finite difference methods. The uncertainties related to the problem are also considered by using random variables to represent the model's parameters and the materials' properties, and stochastic processes to model environmental actions. Furthermore, this approach accounts for: (1) chloride binding capacity; (2) time-variant nature of temperature, humidity and surface chloride concentration; (3) concrete aging; and (4) chloride flow in unsaturated conditions. The proposed approach is illustrated by a numerical example where the factors controlling chloride ingress and the effect of weather conditions were studied. The results stress the importance of including the influence of the random nature of environmental actions, chloride binding, convection and two-dimensional chloride ingress for a comprehensive lifetime assessment.

Work Plan

1) Development of a hydration based model for concrete that accounts for the material properties of the mix ingredients, and effects of ambient conditions of humidity and temperature.
2) Data on creep and shrinkage obtained in earlier studies on normal and heavy density concrete from an earlier project and other results from the literature would be used to validate the model for short term results.
3) Procedures to incorporate uncertainties in the various physical process parameters would be developed and integrated into the hydration based model. This would then be used to make predictions for long term effects of creep and shrinkage.
4) Model validation through simulation of creep and shrinkage deformations in structural elements would be undertaken.

Justification for the proposed methodology:

A hygro-thermo-mechanical finite element formulation developed will be used to assess the level of creep and shrinkage taking place in concrete and the resulting loss in prestress. The experimental results from the previous and present study and others reported in the literature will be used to validate/refine the model. It is expected that the above series of tests will help establish robust analytical procedures for estimation of creep and shrinkage taking place under combinations of mechanical loads and variable hygro-thermal conditions.

Importance of Project Study to DAE:

The performance of the primary and secondary containment structure that are prestressed and reinforced concrete structural systems respectively, in a nuclear power plant is critical in preventing radio-active leakages from occurring. However, the effectiveness of the prestressing system in offering adequate pre-compression in the concrete structure with time has not been established satisfactorily to date. As many of the operating power plants reach their expected design operational life, and many new power plants are constructed to meet the energy needs of our country, the long-term performance of the primary containment system needs to be assessed. The establishment of good robust predictive methods for the estimation of the loss of prestress and the available prestress force will lead to reliable predictions of the existing operational (residual) life of the containment system and the power plant. A reliable estimation of the residual life of a containment system and the nuclear power-plant is an essential requirement prior to extending the plant service life. In order to undertake such exercises, there is a need for reliable and robust model based on hydration kinematics developed with the use of existing database of test data for creep and shrinkage in concrete grades and mixes under conditions similar to that prevailing in an operating nuclear power plants. Finally, analytical studies planned will help develop reliable estimates of creep and shrinkage under the influence of environmental parameters such as temperature and humidity and will be useful tool for the DAE.

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PART II - **PROJECT OBJECTIVES, RESEARCH PLAN and DELIVERABLES**

200. List of Objectives (Please see Instruction - Sr. No. 13):

- Develop a cement hydration based computational model for concrete that accounts for variations in material properties of the concrete mix constituents, relative humidity and temperature effects.
- Include effects of uncertainties associated/ inherent in the model and its parameters on hydration and consequently on the mechanical properties of concrete.
- Assess the influence of material properties of mix ingredients, humidity and temperature on mechanical properties of concrete.
- Model validation through simulation of structural concrete responses.

210. Describe the yearly Research Plan and identify the Deliverables (Please see Instruction - Sr. No. 14):

A. At PI/ CI's Institution

Ist Year:

- Hiring of project assistant (SRF, JRF) and technical assistant
- Literature collection and review on experimental and analytical studies undertaken to assess shrinkage and creep in plain, reinforced and prestressed concrete members, high temperature effects on concrete.
- Procurement of equipment.
- Commencement of the analytical work based on a thermo-hygro-mechanical constitutive model for concrete including aggregate petrographic aspects and its implementation into a finite element platform

IInd Year:

- Continue analytical modeling by including effects of uncertainty in parameters in the model development.

IIIrd Year:

- Model validation through simulation of structural member deformations due to creep and shrinkage.
- Submit final report.

B. At PC's Institution.

Ist Year:

IInd Year:

IIIrd Year:

211. Infrastructure facilities related to the project activity available at the PI/CI's Institute:

Sr. No.	Name of the Equipment	Model & Make	Year of Purchase
1	3 Walk in humidity and temperature controlled chambers		2004
2	Servo Hydraulic closed loop testing system	1200kN loading system closed loop.	2003

212. Facilities available at the PC's institution that would be useful to this project:

PART III - BUDGET ESTIMATES

…

300. Details of budget requirements (Please see Instruction - Sr. No. 15 to 21)

Particulars ⇩ Amount in Rs. ⇨	I Year	II Year	III Year	Total
310. Equipment	4,00,000/-			4,00,000/-
320. Staff Salary SRF: 1 Rs 18000/-+ 30%HRA	2,16,000/- + 64,800 (HRA)	2,16,000/- +64,800 (HRA)	2,40,000/- + 72,000 (HRA)	6,72,000/- +2,01,600 (HRA)
330. Technical Assistant 1	72,000/-	72,000/-	72,000/-	2,16,000/-
340. Consumables	4,50,000/-	3,50,000/-	3,00,000/-	11,00,000/-
350. Travel PI:	1,00,000/-	1,00,000/-	1,00,000/-	3,00,000/-
PC/DC:	-	-	-	-
360. Contingencies	1,50,000/-	1,50,000/-	50,000/-	3,50,000/-
370. Overheads	1,95,420/-	1,20,420/-	1,17,600/-	4,33,440/-
380. Grand Total	**16,48,220**	**10,73,220/-**	**9,51,600/-**	**36,73,040/-**

BUDGET DETAILS

310. Details of the budget for equipment to be procured by the PI:

Sl.No.	Item	Ist year	IInd year	IIIrd year	Total
Local:	• Computer • Abaqus software	50,000/- 3,50,000/-	-	-	4,00,000/-
Imported: Mention currency conversion rate used for estimation					
Total					4,00,000/-

340. Details of budget for consumables to be procured by the PI (Amount in Rupees):

Sl. No.	Item	Ist year	IInd year	IIIrd year	Total
	Cement, sand, aggregate, super-plasticizers, stationeries, CDs, strain gauges, demec gauge and pins, moisture sensors, thermocouples and other consumables	4,50,000/-	3,50,000/-	3,00,000/-	11,00,000/-
	Total	4,50,000/-	3,50,000/-	3,00,000/-	11,00,000/-

350. Details of travel:

Amount in Rupees ⇨	Ist year	IInd year	IIIrd year	Total
351. Proposed number of visits of **PC/DC** to **PI's** Institute	1	1	1	3
351A. Duration of stay (no. of days) during each visit	1-2	1-2	1-2	6
351B. Total funds required	-	-	-	-
352. Proposed number of visits of **PI to PC/DC's** institute	1	1	1	3
352A. Duration of stay (No. of days) during each visit	1-2	1-2	1-2	6
352B. Total funds required	50,000/-	50,000/-	50,000/-	1,50,000/-
353. Funds required by **PI** for travel to attend conferences within India.	50,000	50,000	50,000	1,50,000
Total	1,00,000/-	1,00,000/-	1,00,000/-	3,00,000/-

BUDGET JUSTIFICATIONS

310. Equipment: The temperature controlled chamber when integrated with the existing servo hydraulic closed loop universal testing machine (MTS) / Dartec system will facilitate the possibility of having the effect of load and temperature being applied simultaneously. This type of combined arrangement of thermo-mechanical loading is not available at present and would be a one of a kind feature even at small scale in India. All the equipment requested is essential for the project and will complement the facilities already existing in the PI/CIs Departments The Abaqus software charged is for one license in the project (Part of the CRP in Uncertainty at the Institute) and would help in calibrating various aspects of the model development work.

320. Staff: Funds to support: An SRF is requested for experimental work in the laboratory and carry out modeling.

330. Technical assistance: Technical assistance in the form of skilled helpers in the lab is needed to support the planned experimental program.

340. Consumables: The requested amount is essential for the various experimental studies planned

350. Travel: Field visits form an important component of the project and the amount requested is a bare minimum. Travel is for the PI to participate in meetings with BRNS/ BARC and for participation in national conference is planned.

360. Contingencies: These expenses would be for unforeseen expenses in the laboratory and will help in procuring books, reprints and other contingent expenses during the project.

PART IV - OTHER PROJECTS

410. List all previous projects that are **supported by BRNS or any other funding agency** in which PI is actively participating (either as PI or as CI):

Sl. No.	Title of the project	Total cost	Agency	Present status
1	Thermal Distortion and Vibration Control of Laminate Composite Structural Members Using Piezoelectric Laminates (AS PI) (April 2000-March 2002, 2 years)	Rs.3,69,150	IISc.-ISRO Space Technology Cell, IISc, Bangalore	Completed
2	Experimental and Analytical Study on the Behavior of Fiber Reinforced Plastic (FRP)	Rs. 14,94,525	DST, New Delhi	Completed

	Composite Reinforcements in Plain and Latex Modified Concrete Beam Elements. (AS PI) (December 2000 – December 2003, 3 years)			
3	Nonlinear Earthquake Response Analysis and Structural Optimization of Secondary Piping (As CI) (June 2002 – June 2005, 3 years)	Rs. 9,19,200	DST, New Delhi	Completed
4	Optimal Design of Axially Symmetrical Stiffened thin Shell Structures Under Buckling Criteria (April 2004- March 2006)	Rs 4,28,060	IISc.-ISRO Space Technology Cell, IISc. Bangalore	Completed
5	Experimental and Analytical study on the Behavior of Reinforced Concrete Beam Column Joints with and without fibers under cyclic loading (February 2004- March 2007)	Rs17, 65,595/-	IGCAR Kalpakaam	Completed
6	Characterization of Time dependent deformations in Concrete grades used in Indian Nuclear Power Plants (February 2004 - March 2008)	Rs. 34, 65,050/-	BRNS	Completed
7	Repair Techniques in Reinforced and Prestressed Concrete Structural Components and Assemblages (April 2004 – March 2007)	Rs8,46,000/-	CSIR	Completed
8	Condition Monitoring of Railway Bridges (September 2006 – 2009)	Rs74,500/-	SWR, Railways	Completed
9	Fire resistance and repair of earthquake damaged Structures (March 2008 – August 2011)	£146000	UKIERI	On-going
10	Damage Assessment, Repair and Retrofit of Reinforced Concrete Girders and Columns Using Fiber Reinforced Polymer Composite and Cementitious Materials (January 2010-March 2012)	Rs.4,88,000/-	CiSTUP, IISc	Ongoing

411. List all projects submitted **during the current financial year by PI to BRNS or any other agency for funding.** Give details on the present status of the application:

Sl. No.	Title of the project	Total cost	Agency	Present status
1	Making performance based structural engineering for fire resistance attainable	£40000.00	UKIERI	Proposed
2.	Development of a Model for Evaluating Prestress Losses Considering Creep & Shrinkage Losses in Concrete & Relaxation Losses In Steel Over 100 Years"	Rs 41, 18, 140/-	BRNS	Proposed

412. Brief description of the **project(s) submitted/sanctioned by/to PI by other agencies**. (Please see Instruction - Sr. No.22):

1) Develop a Finite Element Program to study the behavior of Laminate Composite Elements under thermal and mechanical vibration loads. Develop a Piezoelectric element and study its ability to control thermal distortion and vibration when used along with laminate composites. Develop Optimizing strategies for locating

piezoelectric elements for effective control of thermal distortion and vibration. This project has been completed and received a good rating under a review process by the IISc-STC cell.

2) Studies on the load deformation response of FRP rebar reinforced concrete beams under monotonic loading. Effect of latex additives and short randomly oriented fibers into the concrete matrix in these beam tests. Effects of corrosive environmental factors, through exposure of these beams to corrosive agents, on the structural behavior of these members. Finite Element model development to analyze the behavior of the beam specimen including non-linear effects in concrete. Develop design procedures for FRP rebar reinforced concrete elements**.** This project is completed. Prof.Ananth Ramaswamy is the PI and Dr.K.S.Nanjunda Rao is the CI.

3) Studies on the seismic performance of secondary piping networks. Optimal location of snubbers and dampers for desired structural performance of piping networks under seismic forces. This project is completed. Prof. C.S. Manohar is the PI and I, Prof. Ananth Ramaswamy, am the CI.

4) Studies were carried out on reinforced and prestressed concrete beams, columns and assemblages that are partially damaged and then repaired using diverse methods, such as external prestressing, tension flange/web strengthening with FRP and ultra high performance concrete strips/wraps, etc., and thereafter tested to failure to assess the repair potential of different schemes. Analytical formulations to understand the contribution of different sub-systems in repair technology were also be evolved. Prof.Ananth Ramaswamy is the PI in this project.

5) Behavior of beam column joints that are heavily reinforced were altered by substituting a portion of the joint reinforcement with fibers with a view to decongest the junction and thus enable effective concreting while not compromising on the ductility. The beam column joints so designed with fiber substitutes were assessed for its structural toughness and ductility under monotonic and cyclic loading. Prof.Ananth Ramaswamy is the PI in this project.

6) Time dependent deformations in the form of creep and shrinkage in normal and heavy density concrete were measured for different concrete mixes cured at different relative humidity and temperature conditions and tested at different ages of curing and at different load levels. Existing statistical models were calibrated using the test data and employed for long term prediction of these properties.

7) Repair of structural concrete beams and joints were carried out using FRP layers made from glass and carbon fabric. Repair was also attempted using self compacting concrete having fibers as a comparison. The repair schemes were also modeled on a finite element frame work and the responses matched.

8) Field studies were carried out on old existing railway bridges under service at their present operational loads and to explore the saftetylevels available with increased axle load levels.

9) The safety of structures against fire following an earthquake was the focus of this collaborative international project with the University of Edinburgh, IIT Roorkee and IISc.. The project comprised of modeling fire dynamics (University of Edinburgh), reliability and safety assessment and repair (IISc) and karge scale testing (IITR).

10) Thee study focuses on the ability of FRP based repair systems for rehabilitating fire / high temperature damaged applications. The use of FRP based repair with geopolymer layer of insulation also being studied for its efficacy.

413A. List all previous projects **that are supported by BRNS or any other funding agency in which CI** is actively participating (either as PI or as CI):

Sl. No.	Title of the project	Total cost	Agency	Present status
1	Mapping of shear/suture zones in southern India with remote sensing and geological applications. ***PI***: **Sajeev Krishnan**	Rs. 9.2 Lakhs	STC-ISRO	(2009-2012)
2	Research, education, and manpower development in the discipline of earth processes (PI)	Rs. 11.708 Crore	MoES	(2009-2014)

PIs: Kusala Rajendran, Prosenjit Ghosh, **Sajeev Krishnan**, D. Nagesh Kumar

3 Mineralogical and leaching studies for the recovery of uranium, niobium and REE values from Rasimalai alkali syenite pluton, Tamil Nadu, India — Rs. 29.128 Lakhs — BRNS — (2011-2014)
PI: S. Subramanian, ***CIs:*** **Sajeev Krishnan**, M.J. Deshpande, PC: S. Thangavel

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414A. List all projects submitted **during the current financial year by CI to BRNS or any other agency for funding**. Give details on the present status of the application:

Sl. No.	Title of the project	Total cost	Agency	Present status
NiL				

415A. Brief description of the project(s) submitted/sanctioned by/to CI by other agencies. (Please see Instruction - Sr.No.22):

Dr.Sajeev Krishnan

1 The project objective is to map the regional structures, and geology of the Palghat-Cauvery suture zone and adjacent area in southern India in order to come up with a detail and realistic map which could explain the tectonic setting as well as the palaeoseismologic scenario.

2. The project is a manpower development project. To strengthen the infrastructural facilities for earth science research and training at the newly created Centre for Earth Sciences at Indian Institute of Science, Bangalore. The project proposed to develop basic laboratories and infrastructure to strengthen our academic activities and to complement the advanced research facilities that are being developed through other sources of funding.

413 B List all previous projects that are **supported by BRNS or any other funding agency** in which CI is actively participating (either as PI or as CI): **Prof. C.S.Manohar**

No	Title of the project	Total cost	Agency	Present status
1	Vibration based condition assessment and reliability analysis of existing engineering structures	Rs 28.4 lakhs	BRNS	Ongoing 2010-2013 Duration: 3 years
2	Fire resistance and repair of earthquake damaged structures	£146000=00	United Kingdom-India Education and Research Initiative.	Ongoing 2007-2011 Duration: 4 years
3	Aseismic structural reliability analysis of nuclear core support structure	Rs 3.0 lakhs	IGCAR	Ongoing Duration: 1 year

The CI has completed several other funded research projects and a list of these projects is provided in section 510.

414B. List all projects submitted **during the current financial year by CI to BRNS or any other agency for funding.** Give details on the present status of the application:

Asif Usmani and C S Manohar (PI-s), Making performance based structural engineering for fire resistance attainable, A collaborative proposal submitted to the UKIERI Innovative partnerships 2011 with participation from IISc and University of Edinburgh and also four industrial partners from India and the UK (total funds requested: £40000.00).

415B. Brief description of the **project(s) submitted/sanctioned by/to PI by other agencies**.

The project proposal mentioned in item 414B has the following objectives:

- To develop a simple and clearly defined performance based structural engineering (PBSE) framework for structures subjected to fire including easy to use software tools that will encourage its wider adoption.
- To incorporate a more explicit treatment of uncertainty in the above framework.

The funding available here mainly supports expenses towards international travel and exchange of research students and does not provide funds for equipment/project staff.

PART IV - FACILITIES

416. List of **facilities** that will be extended to the investigators by the implementing institution for the project

A. **Infrastructure facilities**

Sr. No.	Item Name	Yes/No/ NR*	Sr. No.	Item Name	Yes/No/ NR*
1.	Workshop	No	7.	Telecommunication	Yes
2.	Water & Electricity	Yes	8.	Transportation	Yes
3.	Standby power supply	Mo	9.	Administrative l support	Yes
4.	Laboratory space & furniture	Yes	10.	Library facilities	Yes
5.	AC room for equipment	NR	11.	Computational facilities	Yes
6.	Refrigerator	NR	12.	Animal/Glass house	NR
	NR*: Not Required				

B. **Equipment and accessories** available within the Investigator's group/Dept. which can be utilized for the project.

Sr. No.	Name of the Equipment	Model & Make	Year of Purchase
1	3 Walk in humidity and temperature controlled chambers		2004
2	Servo Hydraulic closed loop testing system	1200kN Universal Testing Machine closed loop (MTS systems).	2003
	Diamond-Cutter for Rock cutting Semi-automatic Rotopol rock grinder Petrological microscope with digital imaging facility Stereo microscope Precision rock section machine-Discoplan-TS Field equipments Compass and Geological Hammers Field GPS Isodynamic magnetic separator for mineral separation Petrological microscope with digital imaging facility and heating freezing stage for fluid inclusions Petrological microscope 2 High-end Stereo microscope with fluorescent lighting Stereo microscope 2 Jaw-crusher for rock crushing Ball mill for rock powdering Sieves and Sieve Vibratory shaker	All imported equipments	2009-2010

SECTION-B

(Please see Instruction - Sr. No.23 & 24)

500. Curriculum vitae (CV) of **Principal Investigator** (PI),

Name & Designation: **ANANTH RAMASWAMY,** Professor,
Date & Place of Birth: 11th January 1963, Mumbai.
Nationality: Indian
Present post: Professor
Institution with address: Department of Civil Engineering, Indian Institute of Science, Bangalore 560012 India
Telephone No. (with STD code):+91-80-22932817/23608850 Fax No.: +91-80-23600404
E-mail ananth@civil.iisc.ernet.in

Qualifications
Ph.D. (1992, Louisiana State University, USA)
M.S. (1986, University of California, Davis, USA)
B.Tech., (1985, IIT, Madras)

Experience:
Professor, since July, 2009 at IISc.
Associate Professor, May 2001- July 2009 at IISc.
Assistant Professor, May 1995- May 2001 at IISc.
Visiting Lecturer, January 1994-May 1995, IIT Kharagpur
Research Assistant, 1987 –1991, LSU
Research Assistant, 1986, Univ. of California, Davis

Awards, Fellowships, Recognitions:

- Jaiprasad, R., Srinivasamurthy, B.R., Ramaswamy, A., Jaigopal, S. (2006) "Rehabilitation on 140 Years Old Brick Masonry Arch Bridge Across Vrishabhavathi Valley in Bangalore, Karnataka-Case Study" printed in Indian Roads Congress (IRC) Journal Volume 67 Part 1, 121-126 (C.P.W.D., Medal of Indian Roads Congress for best paper on maintenance.
- Associate Editor ASCE Journal of Bridge engineering. Since May 2010
- Associate Editor ASCE Journal of Structural Engineeirng, Since January 2012
- Expert Member, Department of Science and Technology, Project Assessment Committee August 2011, February 2012

Signature with date

Attach a list of publications during the last 10 years which is relevant to the project
(Reprints may please be mail only on demand)

1. Kishen J. M. Chandra, Ananth Ramaswamy, Manohar C S (in press) "Safety Assessment of Masonry Arch Bridge: Field Testing and Simulations", Journal of Bridge Engineering, ASCE.
2. Narayanamurthy, V., Chen, J.F., Cairns, J. and Ramaswamy, A. (2011) "Effect of shear deformation on interfacial stresses in plated beams subjected to arbitrary loading", International Journal of Adhesion & Adhesives, Vol. 31(8), pp. 862-874 doi:10.1016/j.ijadhadh.2011.08.007.
3. Thomas, Job, and Ramaswamy, A. (2009) "Nonlinear FE analysis of prestressed SFRC beams in flexure", Journal of Bridge Engineering, Proc. of ICE, UK, 162(BE3), 119-126.
4. Ali, Sk. Faruque and Ramaswamy, A. (2009) "Hybrid Structural Control using Magneto-rheological Dampers for Base Isolated Structures", IOP Smart Materials and Structures, doi 10.1088/0964-1726/18/5/055011.
5. Ali, Sk. Faruque and Ramaswamy, A. (2009) "Optimal Dynamic Inversion based Semi active Control of Benchmark Bridge using MR Dampers", Journal of Structural Control and Health Monitoring, DOI: 10.1002/stc.325, 16, 564-585.
6. Ali, Sk. Faruque and Ramaswamy, A. (2009) "Testing and Modeling of MR Damper and its Application to SDOF Systems using Integral Back-stepping Technique", Journal of Dynamic Systems, Measurement and Control, ASME, March, Vol. 131 / 021009-1to11.

7. Ali, Sk. Faruque and Ramaswamy, A. (2009) “Optimal Fuzzy Logic Control for MDOF Structural Systems Using Evolutionary Algorithm”, Engineering Applications of Artificial Intelligence, Elsevier, 22, 407-419.
8. Ali, Sk. Faruque and Ramaswamy, A. (2008) “GA optimized FLC driven semi-active control for Phase II smart nonlinear base isolated benchmark building”, Journal of Structural Control and Health Monitoring, 15, 797-820.
9. Ramaswamy, A, and Muttasim Adam Ahmedi (2008) “New materials in structural concrete repair”, Journal of Structural Engineering, SERC, Chennai, India, v.35 (4), pp. 26-36, April-June.
10. Thomas, J. and Ramaswamy, A. (2007) "Shear of Prestressed Concrete Beams having Steel Fibers ", ICE Structures & Buildings Journal, 160 (SB5), 287-293.
11. Thomas, J. and Ramaswamy, A. (2007) “Mechanical Properties of Steel Fiber Reinforced Concrete”, Journal of Materials in Civil Engineering, ASCE, 19(5), 385-392.
12. Saikia, B., Kumar, P., Thomas, J., Rao, K.S.N., and Ramaswamy A. (2007) “Serviceability Performance in Flexure of Beams with GFRP Rebars”, Construction and Building materials, 21, 1709-1719.
13. Jaiprasad, R., Srinivasamurthy, B.R., Ramaswamy, A., Jaigopal, S. (2006) “Rehabilitation on 140 Years Old Brick Masonry Arch Bridge Across Vrishabhavathi Valley in Bangalore, Karnataka-Case Study" printed in Indian Roads Congress (IRC) Journal Volume 67 Part 1, 121-126 *(C.P.W.D. Medal of Indian Roads Congress for best paper on maintenance)*.
14. Thomas, J., and Ramaswamy, A. (2006) “Width and Spacing of Flexural Cracks in Partially Prestressed T-Beams with Steel Fibers in Partial / Full Depth”, ACI Structural Journal, 103(4), 568-576.
15. Thomas, J., and Ramaswamy, A. (2006) “Load deflection performance of partially prestressed concrete T-beams with steel fibers in partial and full depth”, Structural Concrete Journal of FIB, 7(No. 2), 65-75.
16. Thomas, J., and Ramaswamy, A. (2006) “Shear Strength of Partially Prestressed Concrete T-Beams with Steel Fibers in Partial/Full Depth”, ACI Structural Journal, 103(3), 427-435.
17. Thomas, J. and Ramaswamy, A (2006) “Finite Element Analysis of Shear Critical Prestressed SFRC Beams”, Computers and Concrete, Techno-Press, 3(1), 65-77.
18. Thomas, J. and Ramaswamy, A. (2006) “Shear-flexure analysis of prestressed concrete T-beams containing steel fibers over partial or full depth” Structural Engineering International, Journal of the International Association of Bridge and Structural Engineers (IABSE), vol. 16(1), 66-73.
19. Saikia, B., Thomas, J., Ramaswamy A. and Rao, K.S.N. (2005)-“Performance of Hybrid Rebars as Longitudinal Reinforcement in Normal Strength Concrete”, Materials and Structures: A RILEM Journal, vol. 38 (No.284), pp. 857-864.
20. Ahlawat, A.S., and Ramaswamy, A., (2004) "Multi-Objective Optimal FLC Driven Active and Hybrid Control System for Seismically Excited Nonlinear Buildings", ASCE, Journal of Engineering Mechanics, v. 130(4), 416-423.
21. Ahlawat, A.S. and Ramaswamy, A., (2004) "Multi-objective Optimal FLC for Response Control of Wind-Excited Tall Buildings" ASCE, Journal of Engineering Mechanics, v130 (4), 524-530.
22. Padmarajaiah, S.K. and Ramaswamy, A. (2004) “Flexural Strength Predictions of Steel Fiber Reinforced High Strength Concrete in Fully / Partially Prestressed Beam Specimen”, Cement and Concrete Composites Journal, v26, 275-290.
23. Ahlawat, A.S. and Ramaswamy, A. (2003) “Multi-objective Optimal Absorber System for Torsionally Coupled Seismically Excited Structures”, Engineering Structures: Journal of Earthquake Engineering, Wind and Ocean Engineering, 25(7), 941-950.
24. Ahlawat, A.S. and Ramaswamy, A. (2002)“Multi-objective Optimal FLC Driven Hybrid Mass Damper for Torsionally Coupled Seismically Excited Structures”, Journal of Earthquake Engineering and Structural Dynamics, 31(12), 2121-2139.
25. Bansal, A. and Ramaswamy, A. (2002) “FE Analysis of Piezo-laminate Composites under thermal loads”, Journal of Intelligent Material Systems and Structures, v.13, No.5, 291-301.
26. Ahlawat, A.S. and Ramaswamy, A. (2002) “Multi-Objective Optimal Design of FLC Driven Hybrid Mass Damper for Seismically Excited Structures”, Earthquake Engineering and Structural Dynamics, 31(5), 1459-1479, May.
27. Padmarajaiah, S. K. and Ramaswamy, A. (2002)"Comparative Flexural Response of Full and Partial Depth Fibrous High Strength Concrete Prisms Containing Trough Shape Steel Fibers", Journal of Materials in Engineering, ASCE, v. 14(2), pp.130-136, March / April.
28. Padmarajaiah, S. K. and Ramaswamy, A.(2002) "A Finite Element Assessment of Flexural Strength of Prestressed Concrete Beams With Fiber Reinforcement", Journal of Cement and Concrete Composites, vol. 24(2), pp. 229-241, April.
29. Padmarajaiah, S. K. and Ramaswamy, A. (2001) "Crack Width Predictions for High Strength Concrete Fully / Partially Prestressed Beam Specimens Containing Steel Fibers", Structural Journal, ACI, v. 98(6), Nov.-Dec.,

pp.852-861.
30. Ahlawat, A.S. and Ramaswamy, A. (2001)"Multi-objective Optimal Structural Vibration Control Using Fuzzy Logic Control System", Journal of Structural Engineering, ASCE, 127(11), pp.1330-1337.
31. Padmarajaiah, S.K. and Ramaswamy, A. (2001)"Behavior of Fiber Reinforced High Strength Concrete Prestressed and Reinforced Beam Specimen Subjected to Shear", Structural Journal, ACI, v. 98(5), Sept.-Oct, pp. 752-761.
32. Padmarajaiah, S.K. and Ramaswamy, A. (2001) " A Beam and Arch Action Model for Computing the Shear Strength of Prestressed and Reinforced HSFRC Beams", Journal of Structural Engineering, SERC, Chennai, India, v.28 (1), pp. 7-15, April-June.

510. Curriculum vitae (CV) of **Co-Investigator** (CI), if applicable

Name & Designation: **Dr. Sajeev Krishnan,** Assistant Professor
Date & Place of Birth: 03rd March 1975, Vakathanam, Kerala, India
Nationality: Indian
Present post: Assistant Professor
Institution with address: Centre for Earth Sciences, Indian Institute of Science, Bangalore 560 012
Telephone No. (with STD code): 080-2293-3404 Fax No.: 080-2293-3405
E-mail: sajeev@ceas.iisc.ernet.in
Qualifications: PhD, Field: Petrology, Metamorphic Geology, Institute: Okayama University, Japan
Experience:

Name of institution	Location	Position	duration
Centre for Earth Science Studies	Trivandrum, India	Department of Science and Technology Research Fellow	(one year) - Until September 1999
Okayama University	Okayama, Japan	Research Student	(one year) Until September 2000
Okayama University	Okayama, Japan	Research Scholar	(Six months) Until March 2004
Chonbuk National University,	Chonju, Korea	Post doctoral Researcher	(One year) Until March 2005
Okayama University of Science	Okayama, Japan	JSPS Research Fellow	(One year nine months) Until January 8th 2007
Yonsei University	Seoul, South Korea	Research Professor	One year six months) Until July 20th 2008

Geological Instrument experience:
SHRIMP-II, LA-ICPMS, TIMS, Lesser RAMAN, ICPMS, EPMA (WDS & CL, SEM, BSEI imaging), XRF, along with normal petrographic instruments

Awards & Fellowships:
Academic awards and scholarships:
FIRST RANK IN MSc. Annamalai University in 1998
MONBUKAGAKUSHO SCHOLARSHIP of Japanese government for Ph.D. program from 1999 to 2003
Post-Doctoral researcher scholarship of Chonbuk National University, Korea
JSPS Research Fellow scholarship of Japanese Government
Title: *Temporal and spatial distribution of ultrahigh temperature metamorphism in East Gondwana*
Academic services:
Associate Editor: Gondwana Research (2008-2009 February)
Editor: Gondwana Research 2005-2007
Guest Editor: Lithos
Gondwana Research

Signature with date

List of publication attached

Sajeev Krishnan List of Publications

Papers (Articles):

A. International (ISI) Journals

Year 2012:

32. Dharma Rao, C.V., Santosh, M., Sajeev, K., Windley B.F. (2012) Chromite–silicate chemistry of the Neoarchean Sittampundi Complex, southern India: Implications for subduction-related arc magmatism *Precambrian Research (in press)*

Year 2011:

31.Thanh, N.X., **Sajeev, K.**, Itaya, T., Windley, B.F. (2011) Multiple garnet growth in garnet–kyanite–staurolite gneiss, Pangong metamorphic complex, Ladakh Himalaya: New constraints on tectonic setting. *Lithos, 127, 552-563.*

Year 2010:

30. **Sajeev, K.,** Williams, I.S., & Osanai, Y. (2010) Sensitive high-resolution ion microprobe U-Pb dating of prograde and retrograde ultrahigh-temperature metamorphism as exemplified by Sri Lankan granulites. *Geology* 11, 971-974.
29. **Sajeev, K.,** Kawai, T., Omori, S., Windley, B.F., & Maruyama S. (2010) *P-T* evolution of Glenelg eclogites, NW Scotland: Did they experience ultrahigh-pressure metamorphism? *Lithos* 114, 473-489.
28. **Sajeev**, **K.,** Jeong. J., Kwon, S., Kee, W-S., Kim. S.W., Komiya , T., Itaya, T., Jung, H-S., & Park, Y. (2010) High *P-T* granulite relicts from the Imjingang belt, South Korea: tectonic significance. *Gondwana Research* 17, 75-86.
27. Nakano, N., Osanai, Y., **Sajeev**, **K.,** Hayasaka, Y., Miyamoto, T., Minh, N. T., Owada, M. & Windley B.F. (2010) **Triassic eclogite from northern Vietnam: inferences and geological significance**. *Journal of Metamorphic Geology* 28, 59-76.

Year 2009:

26.**Sajeev**, **K.,** Windley, B.F., Connolly J.A.D., & Kon Y. (2009) Retrogressed eclogite (20 kbar, 1020ºC) from the Neoproterozoic Palghat-Cauvery suture zone, southern India. *Precambrian Research* v. 171, p. 23-36.
25. **Sajeev**, **K.** Osanai, Y. Kon, Y. & Itaya, T. (2009) Stability of pargasite during ultrahigh-temperature metamorphism: a consequence of titanium- and REE- partitioning? *American Mineralogist* v. 94, p. 535–545.
24. Santosh, M., **Sajeev, K.**, Li, J.H., Liu, S.J., & Itaya T. (2009) Counterclockwise exhumation of a hot orogen: The Paleoproterozoic ultrahigh-temperature granulites in the North China Craton. *Lithos* v. 110, p. 140–152.
23. Kwon, S., **Sajeev**, **K.,** Mitra, G., Park, Y., Kim, S.W., & Ryu, I-C. (2009) Evidence for Permo-Triassic collision in Far East Asia: The Korean collisional orogen. *Earth and Planetary Science Letters* v. 279, p. 340-349.
22. Thanh, N.X., Itaya T., **Sajeev, K.**, Ahmad, T., Kojuma, S., Ohtani, T., & Ehiro, M. (2009) K-Ar ages of biotite and muscovite from Pangong metamorphic complex, Shyok suture zone, India, Implications for the youngest post-collision metamorphic event in Ladakh Hymalaya. *Journal of Mineralogical and Petrological Sciences (JMPS)* v.104, p. 188-191.

Year 2007:

21. **Sajeev, K.**, Osanai, Y., Connolly, J.A.D., Suzuki, S. Ishioka, J., Kagami H. & Rino S. (2007) Extreme Crustal Metamorphism during a Neoproterozoic Event in Sri Lanka: A Study of Dry Mafic Granulites. *Journal of Geology* v. 115, p. 563–582.

20.Collins,A.S., Clark, C, **Sajeev, K**, Santosh, M., Kelsey D. E. & Hand M. (2007) Passage through India: The Mozambique Ocean suture, high pressure granulites and the Palghat-Cauvery Shear Zone System *Terra Nova* v. 19, p. 141-147.

Year 2006 :

19.**Sajeev, K**., Santosh, M. & Kim, H.S. (2006) Partial melting and P-T evolution of the Kodaikanal Metapelite Belt, southern India. *Lithos* v. 92, p. 465-483.

18.Santosh, M. & **Sajeev K.** (2006) Anticlockwise evolution of ultrahigh-temperature granulites within continental collision zone in southern India *Lithos* v. 92, p. 447-464.

17. **Sajeev, K.**, & Santosh, M. (2006) An unusual high-Mg Garnet-Spinel-Orthopyroxenite from southern India: evidence for ultrahigh-temperature metamorphism at high pressure conditions. *Geological Magazine*, v. 143, p. 923-932.

16.Santosh, M. **Sajeev K.** & J. Li (2006) Extreme crustal metamorphism during Columbia supercontinent assembly: Evidence from North China Craton. *Gondwana Re*search, v. 10, p. 256-266.

15.Osanai, Y., **Sajeev, K**., Owada, M., Kehelpannala, K.V.W., Prame, W.K.B. Nakano, N. & Jayatileke, S. (2006) Metamorphic evolution of ultrahigh-temperature and high-pressure granulites from Highland Complex, Sri Lanka. *Journal of Asian Earth Sciences,* v. 28, p. 20-37.

14. Kim, S W., Oh, C.W., Ryu, I. C., Williams, I. S., **Sajeev, K**., Santosh, M. & Rajesh V. J. (2006) Neoproterozoic bimodal volcanism in the Okcheon Belt, South Korea, and its comparison with the Nanhua Rift, South China: implications for rifting in Rodinia. *Journal of Geology* v. 114, p. 717-737.

13.Oh, C.W., **Sajeev, K.**, Kim, S.W. and Kwon, Y.W. (2006) Mangerite magmatism associated with a probable late-Permian to Triassic Hongseong-Odesan Collision Belt in South Korea. *Gondwana Research*. v. 9, p. 95–105

Year 2005

12.**Sajeev, K.** & Osanai, Y. (2005) Thermal gradients in the Sri Lankan granulite terrane:a garnet–biotite thermometric approach. *Journal of Metamorphic Geology*, v. 23,p. 383–397

11. Oh, C.W., Kim S.W., Choi, S.G., Zhai, M. Guo, J. & **Sajeev, K.** (2005) First finding of eclogite facies metamorphic event in South Korea and its correlation with the Dabie-Sulu collision belt in China. *Journal of Geology*, v. 113, p. 226-232.

Year 2004

10. **Sajeev, K.** & Osanai, Y. (2004) Ultrahigh-temperature Metamorphism (1150° C and 12 kbar) and Multi-stage Evolution of Mg-Al Granulites from Central Highland Complex, Sri Lanka, *Journal of Petrology,* v. 45, p. 1821-1844.

9. **Sajeev, K**., Osanai, Y. & Santosh, M. (2004) Ultrahigh-temperature metamorphism followed by two-stage decompression of garnet-orthopyroxene-sillimanite granulites from Ganguvarpatti, Madurai block, southern India. *Contributions to Mineralogy and Petrology,* v. 148, p. 29-46.

8. **Sajeev, K.** & Osanai, Y. (2004) 'Osumilite' and 'spinel+quartz' from Highland Complex, Sri Lanka: a case of cooling and decompression after ultrahigh-temperature metamorphism. *Journal of Mineralogical and Petrological Sciences (JMPS),* v.99, p. 320-327.

7. Tamashiro, I., Santosh, M., **Sajeev, K.**, Morimoto, T. & Tsunogae, T. (2004) Multistage orthopyroxene formation in ultrahigh-temperature granulites of Ganguvarpatti, southern India: implication for complex metamorphic evolution during Gondwana assembly. *Journal of Mineralogical and Petrological Sciences (JMPS),* v.99, p. 279-297.

Older:

6. **Sajeev, K**., Osanai, Y. & Santosh, M. (2001) Ultrahigh-temperature stability of sapphirine and kornerupine in Ganguvarpatti granulite, Madurai block, Southern India. *Gondwana Research*. v. 4, p.762-766.

5. Osanai, Y., Owada, M., Tsunogae, T., Toyoshima, T., Hokada, T., Long, T.V., **Sajeev, K**. & Nakano, N. (2001) Ultrahigh-temperature peletic granulite from Kontum massif, central Vietnam: Evidence for east Asian juxtaposition at ca 250 Ma. *Gondwana Research*. v. 4, p.720-723.

B. International (non-ISI) Journals:

4. **Sajeev, K**., Osanai, Y., Suzuki. S. & Kagami, H. (2003). Geochronological evidence for multistage-metamorphic events in ultrahigh-temperature granulites from central Highland Complex, Sri Lanka. *Polar Geoscience*s. v. 16, 138-149.

3.Shabeer, K. P., **Sajeev, K**., Okudaira, T. & Santosh, M. (2002) Two stage spinel generation in the high-grade metapelites of central Kerala Khondalite Belt: Implication for prograde P-T path. *Journal of Geosciences, Osaka city university*. v. 45 p. 29-43.

C. Local Journals:

2.**Sajeev, K.** & Osanai, Y. (2003) Geology of high- to ultrahigh-temperature granulites from central Madurai block, southern India; with emphasis on the evolution of Grt-Opx-Crd granulite. *Okayama University Science Reports*, v. 9, p. 1-8.

1. **Sajeev**, **K.** Itaya, T.& Santosh, M. (2006) Geology of southern Indian Granulite Terrane: A preliminary report of the 2005 field survey. *Okayama University of Science, Science Reports*, v. 31 p. 9-16.

Edited thematic Issue in International (ISI) Journal

Year 2008

1. Itaya, T., **Sajeev, K**. Clark, C. & Kusak, M. (2008) Micro-chronology and Evolution of the planet Earth. *Gondwana Research* v.**14, n 4, p. 567-700.**

Editorial: Micro-chronology and Evolution of the planet Earth p. 567-568.

Year 2006

2. **Sajeev**, **K.** & Santosh, M (2006) Extreme crustal metamorphism and related crust-mantle processes. *Lithos* v. 92 n 3-4, p.321-624.

Editorial: Extreme crustal metamorphism and crust–mantle processes: An introduction, p. v-ix, doi:10.1016/j.lithos.2006.03.048

3. Oh, C.W. **Sajeev**, **K.,** Kim, S.W. & Santosh, M. (2006) Tectonic Evolution of Korean Peninsula and Adjacent Crustal Fragments in Asia. *Gondwana Research* v. 9 n 1-2. p. 19-230.

Editorial: Tectonic evolution of Korean Peninsula and adjacent crustal fragments in Asia: Introduction p. 19-20.

International Symposiums / Abstract:

1. Williams, I.S., **Sajeev, K**, Trotter JA (2009) Advances in the SHRIMP II ion microprobe and its geological applications. 11th ISMAS-TRICON-2009. Hyderabad
2. B. Windley, **K. Sajeev** (2009) Archaean eclogites in the mainland Scourian, and Palaeoproterozoic garnet lherzolites and retrogressed eclogites at Rodel, Outer Hebrides, Scotland; implications for widespread subduction tectonics. Evolution of the Continental Crust. The Janet Watson Meeting, The Geological Society (Burlington House), London.
3. Thanh, N.X., **Sajeev, K.** Itaya, T. Tu M.T. (2009) Evolution of garnet-kyanite-staurolite gneiss in Pangong metamorphic complex, Ladakh Himalaya: new insights on tectonic setting. IAGR annual convention, Gondwana to Asia, Vietnam.
4. **Sajeev, K**., Kawai T, Omori S, Windley BF, Shibuya T, Sawaki Y Maruyama S (2007) Petrographic re-examinations of Glenelg eclogites: a step towards higher pressures? International Eclogite Field Symposium, Portree, July, P 97.
5. **Sajeev, K.** Santosh, M. & Itaya, T. (2006) High Pressure Granulites from the Palghat-Cauvery Shear Zone, Southern India, submitted to Granulites and Granulites 2006, **Brasília , Brazil, July, p 76.**
6. **Sajeev, K** & Suzuki, K. (2006) Monazite age-mapping and *PTt* evolution of Kodaikanal Metapelite Belt, southern India, submitted to IMA Kobe, July. P 320.
7. **Sajeev, K.** & Osanai, Y. (2003) First finding of Osumilite from Highland Complex, Sri Lanka: a case of melt-restite interaction resulted Isobaric cooling after UHT metamorphism. Vth Hutton symposium abstracts 127.
8. Osanai, Y**, Sajeev, K**, OWADA, M, Kehelpannala, K.V.W., Prame, W.K.B.N. and Nakano, N. (2003) Evolution of highest-grade metamorphic rocks from Central Highland Complex, Sri Lanka. Geological Survey and Mines Bureau, Sri Lanka, Centenary Publication, p. 25-31.
9. **Sajeev, K**. & Osanai, Y. (2002) Evidence for counter clockwise evolution of Spr-Qtz & Opx-Sil-Qtz bearing granulite from Highland Complex, Sri Lanka.16th Australian Geological Convention abstract volume. v. 67, P. 232.
10. Osanai, Y., Owada, M., Nakano, N., Tsunogae, T., Toyoshima, T., N., Nam, T. N., Binh, P. and **Sajeev, K**. (2002) Metamorphic Evolution of Kontum Massif, central Vietnam: reconnaissance of correlation with Gondwana breakup and Asia growth. 2002 PPO-ASIA, Sapporo (Japan).
11. **Sajeev, K**., Osanai, Y., Biju, S. & Santosh, M. (2000) Decompression processes of cordierite-sillimanite-biotite gneiss from central Madurai block, southern India. AGU, Western Pacific geophysics meeting, Tokyo. v. 81 P. 236.

CV of CI

C S Manohar
Professor and Chairman
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Indian Institute of Science
Bangalore 560 012 INDIA

Born : 11th May 1959, Hubli (Karnataka)
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Education

- BE (Civil Engg.), 1982, Karnatak University, India, First Class with Distinction.
- ME (Civil Engg.), 1984, Indian Institute of Science, First Class with Distinction.
- PhD (Faculty of Engineering), 1989, Indian Institute of Science, Bangalore.

Work Experience

Academic positions held at the Indian Institute of Science

- Professor, May 2005-present, Department of Civil Engineering.
- Associate Professor, May 1999-May 2005, Department of Civil Engineering.
- Assistant Professor, May 1993-May 1999, Department of Civil Engineering.

Other positions held at the Indian Institute of Science

- Chairman, December 2010- present, Department of Civil Engineering.
- Chairman, July 2007- December 2010, Centre for Earth Sciences.
- Associate Faculty Member, 2007-present, Centre for Earth Sciences.
- Member Secretary, IISc-IGCAR R & D Cell, 2011-present

Positions held outside the Indian Institute of Science

- Visiting Professor, October 2011, Carleton University, Ottawa, Canada.
- Visiting Scientist, May 2003, Dept. of Civil Engineering, University of Delaware, USA.
- Visiting Associate Professor, June-July, 2003, Dept. of Civil Engineering, The Johns Hopkins University, USA.
- Research Assistant, May 1991-May 1993, Dept. of Engineering Sciences, University of Oxford, UK.
- Scientist, Oct 1990-May 1991, Structural Engineering Research Centre, Chennai, India

Honors

- Member, Editorial Board, Probabilistic Engineering Mechanics (Elsevier)
- Member, Editorial Board, Structural Control and Health Monitoring (Wiley)
- Associate Editor (Structural Dynamics), ISET Journal of Earthquake Technology, (since 2007).
- Associate Editor, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation (Serial Publications).
- Member, Editorial Board, Earthquakes and Structures (from 2010) (Techno Press).
- Sir C V Raman award for young scientists for the year 1999, Instituted by Government of Karnataka, India.
- Member, Technical Committee of Dynamics, Engineering Mechanics Division, American Society of Civil Engineers, 2003-2007.
- Invitations to IUTAM symposia on Nonlinear Stochastic Mechanics, 1995, 2001, 2009.

Research interests

- Structural dynamics: modeling of nonlinearity and uncertainties; computational and experimental methods; inverse problems: structural system identification and damage detection using measured vibration data; statistical energy analysis.
- Stochastic structural mechanics: stochastic FEM; random vibrations; Bayesian filtering; Monte Carlo simulations & variance reduction schemes; structural reliability modeling.
- Earthquake engineering: seismic safety of large scale structures; science of earthquake simulations: hybrid test methods; real time substructuring; fire following earthquakes.

Papers in refereed journals (last ten years)

1. B Radhika and C S Manohar, 2011, Updating response sensitivity models of nonlinear vibrating structures using particle filters, Computers and Structures, 89(11-12), 901-911.
2. H A Nasrellah and C S Manohar, 2011, Finite element method based Monte Carlo filters for structural system identification, Probabilistic Engineering Mechanics, 26 (2011) 294–307.
3. H A Nasrellah and C S Manohar, 2011, Particle filters for structural system identification using multiple test and sensor data: a combined computational and experimental study, Structural Control and Health Monitoring, 18, 99–120.
4. B Radhika and C S Manohar, 2010, Reliability models for existing structures based on dynamic state estimation and data based asymptotic extreme value analysis, Probabilistic Engineering Mechanics, 25, 393-405.
5. H A Nasrellah and C S Manohar, 2010, A particle filtering approach for structural system identification in vehicle-structure interaction problems, Journal of Sound and Vibration. 329(9), 1289-1309.
6. R Sajeeb, C S Manohar and D Roy, 2010, A semi-analytical particle filter for identification of nonlinear oscillators, Probabilistic Engineering Mechanics, 25, 35-48
7. R Sivaprasad, S Venkatesha, and C S Manohar, 2009, Identification of dynamical systems with fractional derivative damping models using inverse sensitivity analysis, Computers, Materials and Continua, 9 (3), 179-207.
8. R Tipireddy, H A Nasrellah and C S Manohar, 2009, A Kalman filter based strategy for linear structural system identification based on multiple static and dynamic test data, Probabilistic Engineering Mechanics, 24, 60-74.
9. R Sajeeb, C S Manohar and D Roy, 2009, A Conditionally linearized Monte Carlo filter in nonlinear structural dynamics, International Journal of Nonlinear Mechanics, 44(7), 776-790
10. R Sajeeb, C S Manohar and D Roy, 2009, Rao-Blackwellization with substructuring for state and parameter estimations of a class of nonlinear dynamical systems, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation, 1(1-2) 2009.
11. S Venkatesha, R Rajender, and C S Manohar, 2008, Inverse sensitivity analysis of singular solutions of FRF matrix in structural system identification, CMES: Computer Modeling in Engineering and Science, 37(2), 113-152.
12. V Namdeo and C S Manohar, 2008, Force state maps using reproducing kernel particle method and kriging based functional representations, CMES: Computer Modeling in Engineering and Science, 32(3), 123-160.
13. S S Panda and C S Manohar, 2008, Applications of meta-models in finite element based reliability analysis, CMES: Computer Modeling in Engineering and Sciences, 28, N0. 3, 161-184.
14. B Radhika, S S Panda and C S Manohar, 2008, Time variant reliability analysis using data based extreme value analysis, CMES: Computer Modeling in Engineering and Sciences, 27(1-2),79-110.
15. S Ghosh, C S Manohar and D Roy, 2008, Sequential importance sampling filters with a new proposal distribution for parameter identification of structural systems, Proceedings of Royal Society of London, A, 464, 25-47.
16. V Namdeo and C S Manohar, 2007, Nonlinear structural dynamical system identification using adaptive particle filters, Journal of Sound and Vibration, 306, 524-563.
17. R Sajeeb, C S Manohar and D Roy, 2007, Control of Nonlinear Structural Dynamical Systems with Noise Using Particle Filters, Journal of Sound and Vibration, 306, 25, 111-135.
18. S Ghosh, D Roy and C S Manohar, 2007, New forms of extended Kalman filter via transversal linearization and applications to structural system identification, Computer Methods in Applied Mechanics and Engineering, 196, 5063-5083.
19. M Manjuprasad and C S Manohar, 2007, Adaptive random field mesh refinements in stochastic finite element reliability analysis of structures, CMES: Computer Modeling in Engineering and Sciences, 19(1), 23-54.
20. R Sajeeb, D Roy and C S Manohar, 2007, Numerical aspects of a real-time substructuring technique in structural dynamics, International Journal of Numerical Methods in Engineering, 72, 1261-1313.
21. A M Abbas and C S Manohar, 2007, Critical vector random earthquake loads for parametrically excited structures, Structural Safety, 29(1), 32-48.
22. Sayan Gupta and C S Manohar, 2006, Reliability analysis of randomly parametered linear vibrating systems subjected to stochastic excitations, Journal of Sound and Vibration, 297(3-5), 1000-1024.
23. C S Manohar and D Roy, 2006, Nonlinear structure system identification using Monte Carlo filters, Sadhana, Academy Proceedings in Engineering, Indian Academy of Science, 31(4), 399-427.
24. Sayan Gupta and C S Manohar, 2005, Extreme value distribution of von Mises stress in randomly vibrating structures, Journal of Vibration and Acoustics, Transaction of ASME, 127 (6), 547-555.

25. Sayan Gupta and C S Manohar, 2005, Development of multivariate extreme value distributions for random vibration applications, Journal of Engineering Mechanics, ASCE. 131(7), 712-720.
26. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part I: Linear structures, Journal of Sound and Vibration, 287, 865-882.
27. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part II: Nonlinear structures, Journal of Sound and Vibration, 287, 883-900.
28. C S Manohar and R Ghanem, 2005, Multivariate probability distribution of ordered peaks of vector Gaussian random processes, Probabilistic Engineering Mechanics, 20, pp 87-96.
29. Saikat Saha and C S Manohar, 2005, Inverse reliability design of structures subjected to partially specified earthquake loads, Probabilistic Engineering Mechanics, 20, 19-31.
30. Sayan Gupta and C S Manohar, 2004, Response surface method for time variant reliability analysis of nonlinear random structures under nonstationary excitations, 36, 267-280, Nonlinear Dynamics.
31. Sayan Gupta and C S Manohar, 2004, Improved response surface method for structural reliability analysis, 123-139, Structural safety.
32. S Ammanagai, S Venkatesha, and C S Manohar, 2004, Analytical and experimental investigations of structural damages in beams and built-up structures using vibration data, 31(1), 73-84, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
33. Luna Majumder and C S Manohar, 2003, A time domain approach for damage detection in bridge structures using vibration data with moving vehicle as an excitation source, 268, 699-716, Journal of sound and Vibration.
34. C S Manohar, S Venkatesha and S Sadasivan, 2003, Finite element analysis of vehicle-structure interactions during launching of remotely piloted air-vehicles, 30(1), 1-6, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
35. C S Manohar, R Ravi and Ch Srinivas, 2003, Nonlinear structures under random differential support motions and determination of critical input models, 2(3), 171-198, Advances in vibration engineering, Vibration Institute of India.
36. Luna Majumder and C S Manohar, 2002, Nonlinear reduced models for beam damage detection using data on moving oscillator-beam interactions, 82, 301-314, Computers and Structures.
37. Sayan Gupta and C S Manohar, 2002, Dynamic stiffness method for circular stochastic Timoshenko beams: response variability and reliability analyses, Journal of Sound and Vibrations, 253(5), 1051-085.
38. Abbas M and C S Manohar, 2002, Investigations into critical excitation models within deterministic and probabilistic frameworks: single point excitations, Earthquake Engineering and Structural Dynamics 31, 813-832.
39. A M Abbas and C S Manohar, 2002, Critical spatially varying earthquake load models, Journal of Structural Engineering, Structural Engineering Research Centre, Madras, 29, 39-52.

List of funded projects (last ten years)

1. C S Manohar and S Venkatesha, 2010-2013, Vibration based condition assessment and reliability analysis of existing structures', Funded by Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India.
2. C S Manohar, 2010, Development of a video based course on Stochastic Structural Dynamics, funded by National Programme on Technology Enhanced Learning, Government of India.
3. 2007-2010, Fire resistance and repair of earthquake damaged structures, United Kingdom-India Education and Research Initiative (UKIERI) Collaborative Research Awards 2007, Jointly developed with University of Edinburgh, IIT Roorkee and IISc, Bangalore; Team: Edinburgh: A S Usmani, J L Torero, P Pankaj, J F Chen, and M Gillie; IIT Roorkee: Pradeep Bhargava, Yogendra Singh, Umesh Kumar Sharma; IISc: C S Manohar and Ananth Ramaswamy.
4. C S Manohar and K Venkatraman, 2006-2008, Analytical prediction of squeak and rattle noise intensity in a seat belt retractor system, Funded by Delphi Automotive Systems, India.
5. C S Manohar, 2006-2008, Structural Reliability Under Seismic Loads, Funded by Cranes Software India Limited.
6. C S Manohar and V R Sonti, and A R Upadhya, 2005-2009, Modeling of nonlinearity in experimental structural dynamics, Aeronautical Research and Development Board, Government of India.
7. J M Chandra Kishen, Ananth Ramaswamy, C S Manohar, and D Roy, 2006-2009, Condition monitoring of railway bridges, Funded by Indian Railways (South Central Division).
8. C S Manohar and K Venkatraman, 2006, Acoustic vibration of sodium to air heat exchangers, Funded by IGCAR.

9. C S Manohar and K Venkatraman, 2008, Dynamic analysis of rotating parts of a turbine, Funded by Bharath Heavy Electricals Limited, Bhopal.
10. D Roy and C S Manohar, 2004-2007, Development of numerical methods for structural reliability analyses, Funded by Board of Research in Nuclear Studies, Department of Atomic Energy, Government of India.
11. C S Manohar and J M Chandra Kishen, 2002-2006, Seismic Probabilistic Safety Assessment (PSA) of nuclear power plants, Funded by Board of Research in Nuclear Studies, Department of Atomic Energy, Government of India.
12. C S Manohar and S Venkatesha, 2006, Testing and model validation for simple brackets and lectures on techniques and method used**,** Funded by John F Welch Technology Centre, General Electricals India, Bangalore.
13. C S Manohar, D Roy, and S Venkatesha, 2006, Environmental vibration survey at the National Centre for Biological Sciences at the proposed site for installing an electronic microscope, Bangalore.
14. C S Manohar and V R Sonti, 2003-2005, Bayesian updation of finite element sub-structure assemblies using qualification test data, Funded by Indian Space Research Organization-Indian Institute of Science Space Technology Cell.
15. C S Manohar, 2001-2004, Structural damage detection using vibration data and probabilistic health assessment, Funded by Council of Scientific and Industrial Research, Government of India.
16. C S Manohar and Kartik Venkatraman, 2002-2004, Vibration response prediction in a flight vehicle, Funded by Environmental Test Laboratory, Regional Research Centre, Hyderabad, Defence R & D Organization, Government of India.

520. Curriculum vitae (CV) of **Principal Collaborator** (PC):

The following format should be used to provide Curriculum vitae of the individuals mentioned above

Name & Designation:
Date & Place of Birth:
Nationality:
Present post:
Institution with address:
Telephone No. (with STD code): Fax No.:
E-mail:
Qualifications:
Experience:
Awards & Fellowships:

Signature with date

Attach a list of publications during the last 10 years which is relevant to the project
(Reprints may please be mail only on demand)

SECTION-C

CERTIFICATE-1 (Submit single hard copy only**)**
Certificate from the Head of the Institution of the Principal Investigator (PI) and Co-Investigator (CI) from Non-DAE Institution (Please see Instruction - Sr. No.4-6)

...

Project Title: **"Stochastic Modeling of Hydration Process in Concrete: Investigation into Creep and shrinkage"**

(1) Certified that this Institution agrees to the participation of
Principal Investigator:
Prof. Ananth Ramaswamy
Department of Civil Engineering
Indian Institute of Science,
Bangalore 560 012

Co- Investigators:
Dr. Sajeev Krishnan,
Centre for Earth Sciences
Indian Institute of Science,
Bangalore 560 012

Prof. C.S. Manohar
Department of Civil Engineering
Indian Institute of Science,
Bangalore 560 012

for the above project which is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS).

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) Certified that the management takes the responsibilities for the timely submission of audited (by external Chartered Accounted or Statutory Government Auditor) statement of account (SA), utilisation certificate (UC), details of staff recruited and equipment purchased for each year as well as the audited (by external Chartered Accounted or Statutory Government Auditor) consolidated SA and UC for the final year.

(4) **Particulars of University Bank A/c are as follows (Please see Instruction - Sr. No.7):**

- **a) Name of Account Holder:**
- **b) Account No.:**
- **c) Bank Name and Branch Address:**
- **d) Branch code:**
- **e) IFS Code: (16 digits)**

Date:

Place:

Name & signature of the
Head of the institution
or his authorised nominee

Seal:

Note: For Multi-Centre projects, similar certificate is needed from all the participating institutions.

CERTIFICATE-2 (Submit single hard copy only**)**

Certificate from the Head of the Institution of Principal Collaborator (PC) /Departmental Coordinator (DC) from DAE Institution

(Please see Instruction - Sr. No.7)

....

Project Title: **"Stochastic Modeling of Hydration Process in Concrete: Investigation into Creep and shrinkage"**

(1) Certified that this Institution agrees to the participation of Prof./Dr. _____ Department/Address _____ as Principal Collaborator (PC)/ Departmental Coordinator (DC) for the above project that is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS) by Prof./Dr. _____ Department/Address _____ as Principal Investigator (PI) .

The PC/ DC shall coordinate for timely submission of yearly progress reports and financial documents towards meaningful conclusion of the project as scheduled.

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) This institution assures to undertake the financial and other management responsibilities of the part of the project work that will be conducted in this institution.

(4) This Certificate is being issued with approval of the Group Board or the Group Board approval shall be taken, after the project is sanctioned by BRNS.

Date:

Place:

Name & signature of the
Head of the DAE institution/
Head of the Group

Seal:

CRP on Uncertainty Analysis of Engineering and Environmental Systems

Project-3

Petrographical, Chemical and Computational Studies on Concrete at High Temperature

A project proposal submitted to

BOARD OF RESEARCH IN NUCLEAR SCIENCES
Department of Atomic Energy
Government of India

By

Dr Sajeev Krishnan (PI)
Centre for Earth Sciences

Professor Ananth Ramaswamy (CI)
Professor C S Manohar (CI)
Department of Civil Engineering

Indian Institute of Science
Bangalore 560 012

February 2012

SECTION-A

PART I – PROJECT OVERVIEW (Please see Instruction - Sr. No. 8)

100. Advisory Committee Code Number (Please see Instruction - Sr. No. 9): **36**

101. Title: **Petrographical, Chemical and Computational Studies on Concrete at High Temperature**

102. Key Words & Name of 3 Referees (Please see Instruction - Sr. No. 10) Thermal effects in concrete, Petrography, melting of coarse aggregate, melt migration, strength of concrete, chemical diffusion, pressure temperature conditions; Mechanical Properties of Concrete, parametric uncertainties.

103. **Project Summary** (Please see Instruction - Sr. No. 11):

The proposed study aims to work on the effect of high temperature (e.g., fire) on concrete and its strength degradation which in turn influence the safety of these structures. Many such previous studies internationally concentrate on the dehydration and degradation of cement but less emphasis has been given to the aggregate and its behaviour under different temperature conditions. Here we propose a study with more emphasis on the type of course and fine aggregate (e.g., granite or other rocks formed at very high temperature pressure conditions) and its behaviour when exposed to different temperature conditions. Experimental studies to assess effects of high temperature will be undertaken as part of the proposed study and used to validate the model development. The coarse and fine aggregates for the concrete samples will be selected after calculating the formation (crystallization) temperature and pressure of the rock through mineral composition and iso-chemical phase diagrams. Petro-graphical studies on aggregate samples after being exposed to different temperature will be conducted and information obtained on melts and other thermodynamic aspects derived from these studies would serve as inputs to the hydration based model to account for aggregate effects on the development of concrete. The chemical diffusion during the high temperature may also have a roll in controlling the strength of concrete. This will be assessed in a micro scale from samples exposed at different temperature. The integrated hydration based model accounting for aggregate effects will be used to predict the degradation of concrete under high temperature conditions. Uncertainties inherent in the various physical process parameters will be accounted for in the simulation. Experimental studies on structural member responses to fire / high temperature will be used to assess the capabilities of the model.

Personal Details:

		Name	**Address**	**e-mail**	**Phone**	**Fax**
104.	PI	Dr. Sajeev Krishnan	Centre for Earth Sciences, IISc Bangalore 560012	sajeev@ceas.iisc.ernet.in	080-2293404	080-22933405
105.	CI	Prof. Ananth Ramaswamy Prof. C.S. Manohar	Department of Civil Engineering, IISc Bangalore 560012	ananth@civil.iisc.ernet.in manohar@civil.iisc.ernet.in	080-22932817/ 23608850 080-22933121	080-23600404 080-23600404
106.	PC Co-PC	Shri Akanshu Sharma Shri Tarvinder Singh	RSD, BARC	akanshu@barc.gov.in tarvindr@barc.gov.in; tarvindersinghs@gmail.com	022-25591530 022-25591554	

107. Total Budget Rs. 48,87,760/-/

108. Detailed Project Proposal Report Enclosed: Yes

Detailed Project Proposal

Background:

Consequences of long term exposure to high temperatures (e.g. fires) i.e., thermal induced damages can result substantial degradation of concrete, which is the backbone for all major structures used in both strategic (e.g., reactors) and common applications (buildings and outer urban structures). Micro-textural (petrographical) and chemical exchange/diffusion studies are not widely applied in concrete research. The major studies using the petrographic studies were done on old structures from which only limited samples are available. The major areas of research with petrographic application are on various aspects of cement alterations with time, for example, thaumasite sulphate attack (e.g., Eden, 2003).

The concrete research is highly concentrated on the quality development of the cement, however, very little research attention has been given to the material property of coarse and fine aggregates. Recently, Aslani and Bastami (2001) presented the constitutive relationships developed for normal-strength concrete and high-strength concrete subjected to fire to provide efficient modeling and specify the performance criteria for concrete structures exposed to fire. Khaliq and Kodur (2011) reported the strength and stiffness properties of concrete deteriorate with an increase in temperature as encountered during exposure to fire.

Similar studies warrant the importance of studying property behavior of concrete at different temperature-pressure conditions. However in our knowledge no attempts were made to observe the micro textural variation in concrete at various temperatures. In this proposal we will look into the behavior of coarse aggregate when exposed to fire at different temperature. The proposed research will be one of the first initiatives to use petrographic and electron microprobe studies for looking in to the behavior of coarse aggregate in concrete at different temperature and pressure conditions. Thermodynamic modeling can provide information of the formation conditions of the (temperature, pressure etc) rock fragments (coarse aggregates) and enable us to determine the melting temperature of the aggregate when exposed to fire or high-temperature conditions. The geochemical analysis of the rock fragments will give an idea about the possible chemical diffusion during melting. We will also look in to the effect of pressure normally affected in the form of load on concrete structures.

In the later part of the proposal we will use different rock-types which formed under different pressure-temperature conditions for making the concrete and check its resistance to fire/temperature. In order to propose this project we carried out a preliminary study to check the prospect of this research in terms of the impact of high temperature on concrete strength.

Cement based materials such as concrete have a very complex structure over many length scales. According to Whittman (1983), concrete may be modeled at three different length scales, namely, macro, meso and micro. At the macro level, comprising of full-scale structures, the material may be considered as an isotropic continuum (meter scale). The meso-scale operates at the millimeter level and one can consider aggregates, pores, cracks, and interfaces. The micro scale presents the structure of the hardened cement. While one can conceptualize three different length scales in classifying the study of concrete it is hardly possible to delineate these scales in the process of looking for causes for concrete cracking.

Related to the durability and serviceability of concrete structures, the removal of moisture due to self-desiccation (removal of water during hydration of hardened concrete) and the autogenous shrinkage (loss of water in hydration

of hardening concrete) are important factors in estimating the moisture content. Moisture plays a significant role for concrete not only in the hydration process but also in the physical and chemical processes in various deterioration phenomena such as frost damage, early shrinkage, shrinkage cracking as well as movement of ions and gases (Bazant, 1993, Oh and Cha, 1994). Bazant (1993) has pointed out that for concrete structures exposed to environment, to obtain realistic stresses for prediction of cracks, the associated moisture and heat transport problem has to be solved. Studies have been made to examine the phenomena of crack initiation and moisture transport (Setzer, 1976, Sadouki and Van Mier, 1997, Jankovic, et al., 2001). Oh and Cha (1994) have developed a 3D finite element study on thermal and shrinkage stress analysis in concrete in terms of moisture content and degree of hydration. Jankovic et al. (2001) have considered the moisture transport and fracture process in concrete through a lattice based gas automata and fracture model. A lattice model approach for drying of a two-phase composite has also been employed in an earlier study by Sadouski and Van Mier (1997).

Pore pressure rise and humidity loss in concrete due to heating is of great interest in prestressed concrete vessels of nuclear reactors under operating conditions, accidental overstress and fire. The presence of a thermal stress accelerates the moisture flux from inner to outer zones of mass concrete. A number of studies have examined the influence of temperature on fire resistance, shrinkage and stress states due to drying caused by fire (Bazant, 1976 & 1978, Becker and Bresler, 1977, Schneider, 1988, Majorana et al., 1998).

Studies have shown that fluids significantly influence the nonlinear response in porous materials due to the activation of internal molecular forces (Zinszner et al., 1997, Van Den Abeale et al., 2001). The increased fluid solid interaction upon wetting causes the material to soften and swell. Simultaneously the strength of the material reduces and nonlinear hysteretic effects increase significantly. These studies have shown that nonlinear quasi-static and dynamic material behavior changes in the low range of saturation, which implies that presence of moisture plays a role in the nonlinear mechanism.

Studies by Gawin and Schrefler (1996), Gawin et al. (2001), Nechnech et al. (2001) and Majorana et al. (1998) have considered the complex phenomena of moisture transport under thermal loading conditions using a combined numerical model for the mechanical, fluid and thermal effects. Majorana et al. (1998) have proposed a finite element model for creep coupled with damage and related cross effects due to hygrothermal behavior. Gawin et al. (2001) consider the concrete to be treated as a partially saturated porous material permitting the consideration of a hydration-dehydration, evaporation-condensation, adsorption-desorption phenomena and nonlinearities due to temperature and pressure. A two damage variable model consisting of a mechanical and thermal damage have been incorporated into a thermo-work-hardening plastic damage model for plain concrete in the study reported by Nechnech et al. (2001).

The degradation of concrete exposed to high temperature is driven by the process of removal of free water present in the system in the first instance. Under sustained high temperature, the bound water is then released leading to dehydration and breakages of the chemical hydrant compounds. This process results in a progressive growth of damage in mechanical strength. Under extreme temperatures the aggregate crosses its melting temperature and

disintegrates resulting in substantial strength degradation. The coefficients associated with these physical and chemical processes have considerable variations based on composition and pore structure. Thus these parameters introduce considerable uncertainty in the progress of the process and need to be addressed in that framework.

Preliminary study:

A preliminary round of studies have been carried out on 25MPa and 35MPa normal concrete (compressive strength) containing granitic coarse aggregate. The samples were molded in a standard cylinder of 150mm diameter and 300mm length and exposed to different levels of temperature and exposure time by placing the cylinders in an oven. The specimen were removed from the oven after such an exposure, cooled and tested to failure. The temperature levels considered were in a range from 450 degree Celsius to 715 degree Celsius and the corresponding exposure time ranged from 3 to 4 hours.

2 micron thick diamond polished thin sections of concrete samples (original sample, samples heated at 425°C for 4 hours, 550°C for 4 hours, 715°C for 2 hours and 715°C for 4 hours) were made for petrographic observation. The original samples shows well defined coarse aggregates, fine aggregate and cement. The coarse aggregate consist of quartz, K-feldspar and plagioclase (Fig.1a,b). The mineralogy indicate the rock used in this sample is granite or granitoid with major composition will be rich in Si-Al-Za-Ka-Ca. The crystallization temperature the course aggregate can assessed using thermodynamic modeling and geothermometry. For these calculations mineral chemical analysis is required. In the preliminary study we have not attempted the chemical analysis yet.

From the experimental studies it is well understood that the crystallization temperature of most of the granitic rocks are around 700-750°C, however considering the re-melting of granites pressure could also play an important role.

In the preliminary experiments we consider only atmospheric pressure while in the this proposal we propose experiments with controlled pressure and temperature conditions by considering the temperature of fire as well as the load of the building.

In the high-temperature results, no significant changes were observed on samples heated at 415°C and 550°C for 4 hours (Fig. 1c,d). The reduction in compressive strength was only in the order of 10 to 15% against the control cylinders.

When the sample is exposed to 715°C for 2 hours (Fig.2) minor melt formations are observed along the grain boundary of the minerals. This is a very significant observation and the melting could reduce the strength of the concrete considerably. The corresponding loss in strength was of the order of 50%.

When the sample is exposed at the same temperature (715 degree C) for 4 hours (Fig.3a,b,c) significant production of melt is observed along the grain boundary and the strength is reduced to 70% from the original control sample. It is important to do further studies like composition of the melt and melt migration along the grain boundary and fractures to assess the behavior of concrete.

By observing these phenomena we also propose to look in to the property of concrete especially the coarse aggregate of different composition with similar experiments. This is important because in a situation of very high temperature rocks with refractive minerals can withstand while normal low-temperature magma generated rocks (e.g., granite) will melt. We also propose to assess the ultraviolet property of concrete at various temperatures to assess the melt migration and behavioral changes in the cement

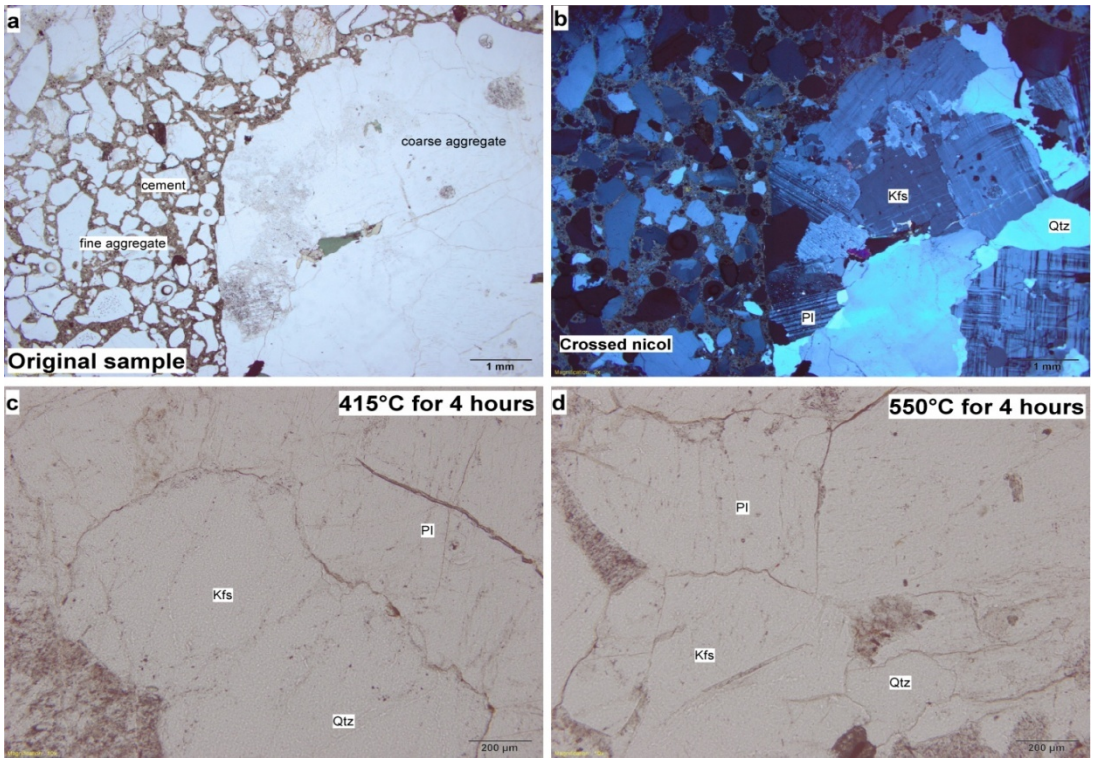

Fig. 1 thin section photomicrographs of concrete samples. a,b) original sample with granitic coarse aggregate. c) Sample exposed to 415°C for 4 hours and d) 550°C for 4 hours. Note no significant changes are observed.

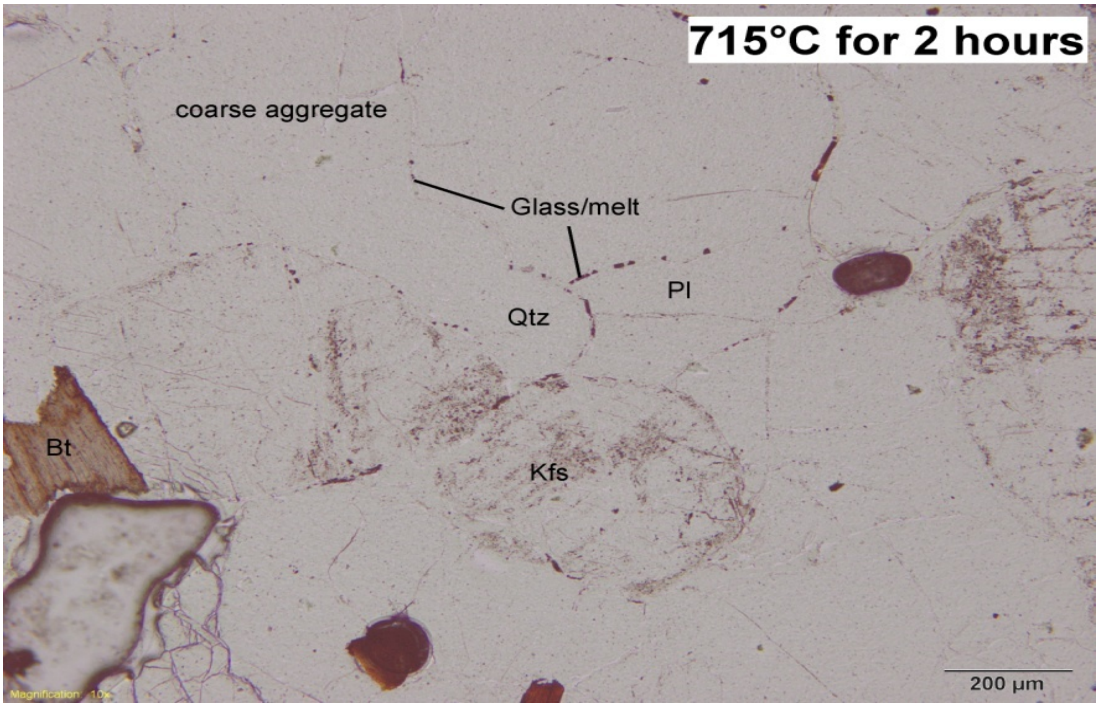

Fig. 2 Photomicrographs of concrete sample exposed to 715°C for 2 hours. Note the formation of minor melts along the grain boundary of minerals.

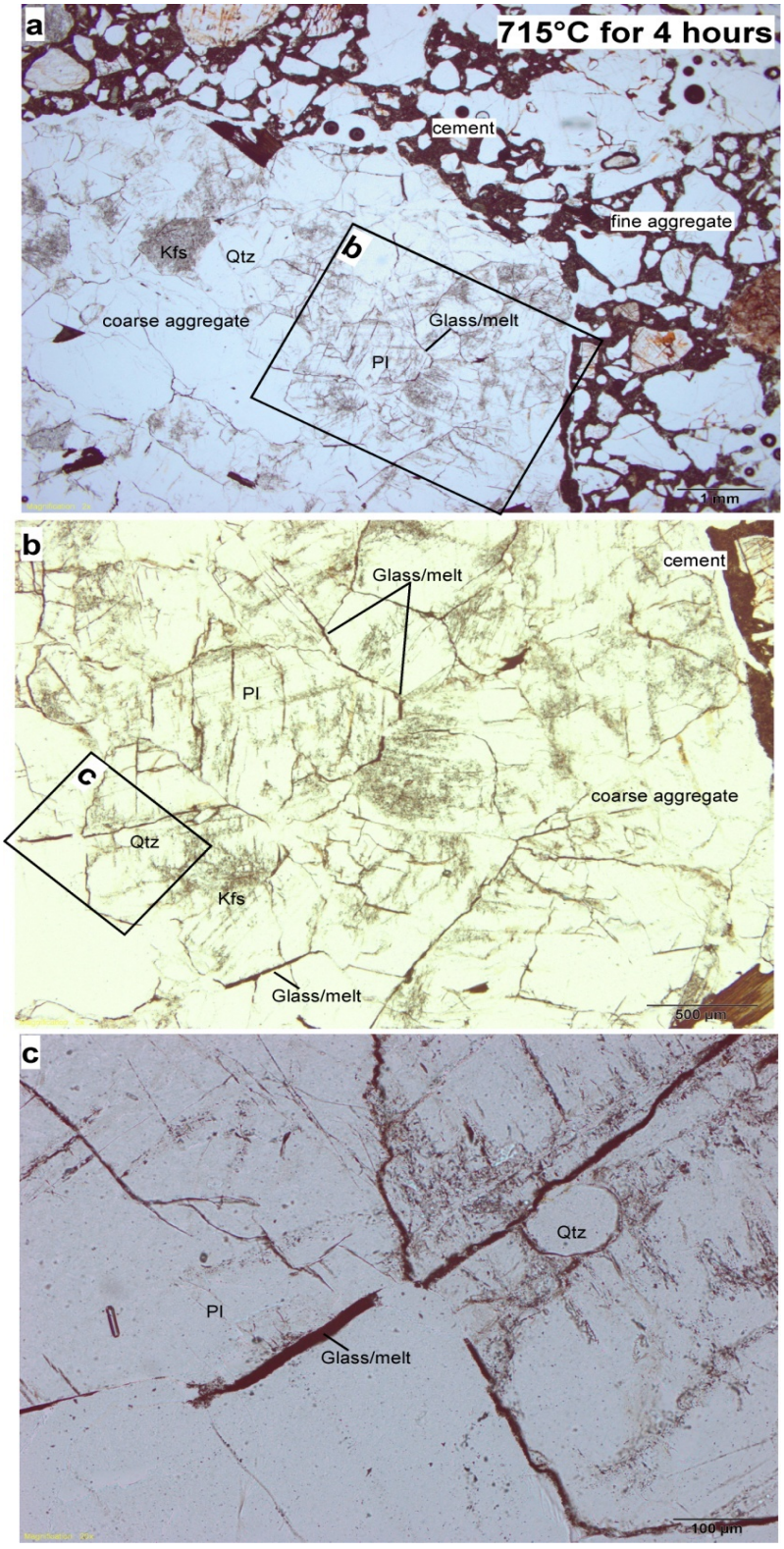

Fig. 3,a,b,c Photomicrographs of concrete sample exposed to 715°C for 4 hours. Note the significant formation of glass/melts along the grain boundary of minerals.

Work Plan

1) Construction of concrete samples with granite coarse aggregate.
2) Check the strength of the concrete before exposure to higher temperatures.
3) Expose the concrete samples at different temperature conditions and asses the strength loss under combined thermo-mechanical loading.
4) Use the samples for thin section making and detailed petrography to observe the micro-level variations with the coarse aggregates.
5) Mineralogical studies and detailed petro-graphic studies will be carried out on all samples.
6) Studies on melting behavior of coarse aggregate
7) Construction of concrete samples with coarse aggregate of different rock compositions and repeat the same experiments.
8) UV and compositional behavior of melt and coarse aggregate.
9) Modeling of the dehydration and melting process coupled with mechanical loads and temperature will be undertaken. Uncertainties present in the process parameters will be accounted in the model.
10) Results reported on structural components tested under fire/ high temperature will be used to assess the model capabilities.

Justification for the proposed methodology:

Experimental studies will first be undertaken on small cylindrical concrete specimen to measure both uniaxial deformations in concrete due to controlled simultaneous high temperature and mechanical loading to understand the degradation process under thermo-mechanical loads. To assess the state of concrete after such tests petro-graphical tests would be conducted on the samples. Information on aggregates will help in improving the ability of the model in predicting the progressive degradation process due to fire exposure. The microstructural and mineral chemical studies on coarse aggregate will give information on its physical and chemical behavior at different temperature. The same experiments will be repeated using various rock types as coarse aggregate so that the in the final result we will be able to propose aggregates that can withstand various temperature and pressure conditions.

Importance of Project Study to DAE:

The performance of the primary and secondary containment structure that are prestressed and reinforced concrete structural systems respectively, in a nuclear power plant is critical in preventing radio-active leakages from occurring. However, the effectiveness of the prestressing system in offering adequate pre-compression in the concrete structure with time has not been established satisfactorily to date. As many of the operating power plants reach their expected design operational life, and many new power plants are constructed to meet the energy needs of our country, the long-term performance of the primary containment system needs to be assessed. The establishment of good robust predictive methods for the estimation of the loss of prestress and the available prestress force will lead to reliable predictions of the existing operational (residual) life of the containment system and the power plant.

The thermo-mechanical degradation model will provide information on extent of damage present in the concrete and consequently the available prestress in the structure. A reliable estimation of the residual life of a containment system and the nuclear power-plant is an essential requirement prior to extending the plant service life.

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PART II - **PROJECT OBJECTIVES, RESEARCH PLAN and DELIVERABLES**

200. List of Objectives (Please see Instruction - Sr. No. 13):

- Behavior of coarse aggregate when exposed to different temperature
- Melting of coarse aggregate and melt migration effect
- Chemical diffusion and chemical reaction at high pressure temperature conditions
- Develop a data set on the behavior of concrete to fire (very High Temperature) with different coarse aggregate material (rocks)
- Concrete degradation model under thermo-mechanical loading will be developed and validated with available test results from the present study and others reported in the literature.
- Uncertainties that influence the material properties of mix ingredients, moisture and heat transfer processes and their effect on mechanical properties of concrete will be studied.
- Results from tests on structural members exposed to high temperature and loading will then be used to validate the model.

210. Describe the yearly Research Plan and identify the Deliverables (Please see Instruction - Sr. No. 14):

A. At PI/ CI's Institution

Ist Year:

- Hiring of project assistant (SRF, JRF) and technical assistant
- Literature collection and review on experimental and analytical studies undertaken on high temperature effects on concrete.
- Procurement of equipment(s) and initiation of the experimental program to study high temperature effects on concrete degradation
- Behavior of coarse aggregate (mainly granite) when exposed to different temperature
- Melting of granite coarse aggregate and melt migration effect
- Chemical diffusion and chemical reaction at high pressure temperature conditions for concrete with granite coarse aggregate
- Thermodynamic modeling for the crystallization pressure and temperature condition of granitic coarse aggregate
- Modeling of concrete degradation with combined temperature exposure and mechanical loads.
- Field work for collecting various rock type samples for using as coarse aggregate

IInd Year:

- Field work for collecting various rock type samples for using as coarse aggregate.
- Whole-rock and mineral chemistry of various rock samples to know the initial composition
- Thermodynamic Modeling to understand the formation condition to predict the melting condition
- Repetition of the same experiments proposed in the granitic samples with various coarse aggregates
- Continue analytical modeling by including effects of uncertainty in parameters in the model development

IIIrd Year:

- Melting of coarse aggregate and melt migration effect in various rock samples.
- Chemical diffusion and chemical reaction at high pressure temperature conditions for concrete with coarse aggregate of various rock types.
- Data assessment and proposing a scale of different coarse aggregate with resistance to temperature Complete Computational model for concrete integrating various aspects.
- Validation of the model through simulation of test results on structural concrete exposed to thermo-mechanical loads.
- Submit final report.

B. At PC's Institution.

Ist Year:

IInd Year:

IIIrd Year:

211. Infrastructure facilities related to the project activity available at the PI/CI's Institute:

Sr. No.	Name of the Equipment	Model & Make	Year of Purchase
1	3 Walk in humidity and temperature controlled chambers		2004
2	Servo Hydraulic closed loop testing system	1200kN loading system closed loop.	2003
3	• Diamond-Cutter for Rock cutting • Semi-automatic Rotopol rock grinder • Petrological microscope with digital imaging facility • Stereo microscope • Precision rock section machine-Discoplan-TS • Field equipments • Compass and Geological Hammers • Field GPS • Isodynamic magnetic separator for mineral separation • Petrological microscope with digital imaging facility and heating freezing stage for fluid inclusions • Petrological microscope 2	All imported equipments	2009-2010

	• High-end Stereo microscope • Stereo microscope 2 • Jaw-crusher for rock crushing • Ball mill for rock powdering • Sieves and Sieve Vibratory shaker • Microbiological Microscope • Laminar Hood • Rotary shaker • Atomic absorption spectrophotometer • SEM, TEM • X-ray diffractometer		

212. Facilities available at the PC's institution that would be useful to this project:

PART III - BUDGET ESTIMATES

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300. Details of budget requirements (Please see Instruction - Sr. No. 15 to 21)

Particulars ⇩ Amount in Rs. ⇨	I Year	II Year	III Year	Total
310. Equipment	17,50,000/-			17, 50,000/-
320. Staff Salary SRF: 2 Rs 18000/-+ 30%HRA per month	2,80,800/-	2,80,800/-	2,80,800/-	8,42,400/-
330. Technical Assistance	1,20,000/-	1,20,000/-	1,20,000/-	3,60,000/-
340. Consumables	2,00,000/-	2,00,000/-	1,50,000/-	5,50,000/-
350. Travel PI:	1,50,000/-	1,50,000/-	1,00,000/-	4,00,000/-
PC/DC:	-	-	-	-
360. Contingencies and working expenses	2,00,000/-	1,00,000/-	1,00,000/-	4,00,000/-
370. Overheads	3,75,120/-	1,12,620/-	97,620/-	5,85,360/-
380. Grand Total	**30,75,920**/-	**9,63,420**/-	**8,48,420**/-	**48,87,760**/-

BUDGET DETAILS

310. Details of the budget for equipment to be procured by the PI:

Sl.No.	Item	Ist year	IInd year	IIIrd year	Total
Local:	Thermal chamber attachment to UTM Computer	10,00,000/- 50,000/-	-	-	10,50,000/-
Imported: Mention currency conversion rate used for estimation	Fluorescent Illuminator, UV filters and accessories	7,00,000/-			7,00,000/-
Total					17,50,000/-

340. Details of budget for consumables to be procured by the PI (Amount in Rupees):

Sl. No.	Item	Ist year	IInd year	IIIrd year	Total
	Cement, sand, aggregate, super-plasticizers, stationeries, CDs, thermocouples Diamond blade for first and second	2,00,000/-	2,00,000/-	1,50,000/-	5,50,000/-

	cutter, Silicon carbide powder, Diamond paste, glass slide and other consumables				
	Total	2,00,000/-	2,00,000/-	1,50,000/-	5,50,000/-

350. Details of travel:

Amount in Rupees ⇨	Ist year	IInd year	IIIrd year	Total
351. Proposed number of visits of **PC/DC** to **PI's** Institute				
351A. Duration of stay (no. of days) during each visit				
351B. Total funds required				
352. Proposed number of visits of **PI to PC/DC's** institute	1	1	1	3
352A. Duration of stay (No. of days) during each visit	1-2	1-2	1-2	6
352B. Total funds required	50,000/-	50,000/-	50,000/-	1,50,000/-
353. Funds required by **PI** for travel to attend conferences within India.	50,000	50,000	25,000	1,25,000
354. Funds for Other visits Field visits for sample collection (please give details)	50,000	50,000	25,000	1,25,000
Total	1,50,000/-	1,50,000/-	1,00,000/-	4,00,000/-

BUDGET JUSTIFICATIONS

310. Equipment: The temperature controlled chamber when integrated with the existing servo hydraulic closed loop universal testing machine (MTS) / Dartec system will facilitate the possibility of having the effect of load and temperature being applied simultaneously. This type of combined arrangement of thermo-mechanical loading is not available at present and would be a one of a kind feature even at small scale in India. Fluorescent Illuminator, UV filters and accessories are important to look in to micro-structural behavior of the sample exposed to various temperature pressure conditions. Computer will be used for the digital imaging and processing of datasets. All the equipment requested is essential for the project and will complement the facilities already existing in the PI/CIs Departments

320. Staff: Funds to support: One SRF are requested for experimental/field work.

330. Technical assistance: One technical assistant staff in the form of skilled helper in the lab is desirable to support and conduct the planned experimental program and for the help in the field work

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340. Consumables: The requested amount is essential for the various experimental studies planned

350. Travel: Field visits form an important component of the project and the amount requested is a bare minimum. Travel is for the PI to participate in meetings with BRNS/ BARC and for participation in national conference is planned.

360. Contingencies and working expenses: These expenses would be for mineral and other chemical analysis and sample processing. This will also be used for other unforeseen expenses in the laboratory and will help in procuring books, reprints and other contingent expenses during the project.

PART IV - OTHER PROJECTS

410. List all previous projects that are **supported by BRNS or any other funding agency** in which PI is actively participating (either as PI or as CI):

Sl. No.	Title of the project	Total cost	Agency	Present status
1	Mapping of shear/suture zones in southern India with remote sensing and geological applications. ***PI***: **Sajeev Krishnan**	Rs. 9.2 Lakhs	STC-ISRO	(2009-2012)
2	Research, education, and manpower development in the discipline of earth processes (PI) ***PIs***: Kusala Rajendran, Prosenjit Ghosh, **Sajeev Krishnan**, D. Nagesh Kumar	Rs. 11.708 Crore	MoES	(2009-2014)
3	Mineralogical and leaching studies for the recovery of uranium, niobium and REE values from Rasimalai alkali syenite pluton, Tamil Nadu, India PI: S. Subramanian, ***CIs:*** **Sajeev Krishnan**, M.J. Deshpande, PC: S. Thangavel	Rs. 29.128 Lakhs	BRNS	(2011-2014)

411. List all projects submitted **during the current financial year by PI to BRNS or any other agency for funding.** Give details on the present status of the application:

412. Brief description of the **project(s) submitted/sanctioned by/to PI by other agencies**. (Please see Instruction - Sr. No.22):

1 The project objective is to map the regional structures, and geology of the Palghat-Cauvery suture zone and adjacent area in southern India in order to come up with a detail and realistic map which could explain the tectonic setting as well as the palaeoseismologic scenario.

2. The project is a manpower development project. To strengthen the infrastructural facilities for earth science research and training at the newly created Centre for Earth Sciences at Indian Institute of Science, Bangalore. The project proposed to develop basic laboratories and infrastructure to strengthen our academic activities and to complement the advanced research facilities that are being developed through other sources of funding.

413A. List all previous projects **that are supported by BRNS or any other funding agency in which CI** is actively participating (either as PI or as CI):

Sl. No.	Title of the project	Total cost	Agency	Present status
1	Thermal Distortion and Vibration Control of Laminate Composite Structural Members Using Piezoelectric Laminates (AS PI) (April 2000-March 2002, 2 years)	Rs.3,69,150	IISc.-ISRO Space Technology Cell, IISc, Bangalore	Completed
2	Experimental and Analytical Study on the Behavior of Fiber Reinforced Plastic (FRP) Composite Reinforcements in Plain and Latex Modified Concrete Beam Elements. (AS PI) (December 2000 – December 2003, 3 years)	Rs. 14,94,525	DST, New Delhi	Completed
3	Nonlinear Earthquake Response Analysis	Rs. 9,19,200	DST, New Delhi	Completed

	and Structural Optimization of Secondary Piping (As CI) (June 2002 – June 2005, 3 years)			
4	Optimal Design of Axially Symmetrical Stiffened thin Shell Structures Under Buckling Criteria (April 2004- March 2006)	Rs 4,28,060	IISc.-ISRO Space Technology Cell, IISc. Bangalore	Completed
5	Experimental and Analytical study on the Behavior of Reinforced Concrete Beam Column Joints with and without fibers under cyclic loading (February 2004- March 2007)	Rs17, 65,595/-	IGCAR Kalpakaam	Completed
6	Characterization of Time dependent deformations in Concrete grades used in Indian Nuclear Power Plants (February 2004 - March 2008)	Rs. 34, 65,050/-	BRNS	Completed
7	Repair Techniques in Reinforced and Prestressed Concrete Structural Components and Assemblages (April 2004 – March 2007)	Rs8,46,000/-	CSIR	Completed
8	Condition Monitoring of Railway Bridges (September 2006 – 2009)	Rs74,500/-	SWR, Railways	Completed
9	Fire resistance and repair of earthquake damaged Structures (March 2008 – August 2011)	£146000	UKIERI	On-going
10	Damage Assessment, Repair and Retrofit of Reinforced Concrete Girders and Columns Using Fiber Reinforced Polymer Composite and Cementitious Materials (January 2010-March 2012)	Rs.4,88,000/-	CiSTUP, IISc	Ongoing

414A. List all projects submitted **during the current financial year by CI to BRNS or any other agency for funding**. Give details on the present status of the application:

Sl. No.	Title of the project	Total cost	Agency	Present status
1	Making performance based structural engineering for fire resistance attainable	£40000.00	UKIERI	Proposed
2.	Development of a Model for Evaluating Prestress Losses Considering Creep & Shrinkage Losses in Concrete & Relaxation Losses In Steel Over 100 Years"	Rs 41, 18, 140/-	BRNS	Proposed

415A. Brief description of the project(s) submitted/sanctioned by/to CI by other agencies. (Please see Instruction - Sr.No.22):

1) Develop a Finite Element Program to study the behavior of Laminate Composite Elements under thermal and mechanical vibration loads. Develop a Piezoelectric element and study its ability to control thermal distortion and vibration when used along with laminate composites. Develop Optimizing strategies for locating

piezoelectric elements for effective control of thermal distortion and vibration. This project has been completed and received a good rating under a review process by the IISc-STC cell.

2) Studies on the load deformation response of FRP rebar reinforced concrete beams under monotonic loading. Effect of latex additives and short randomly oriented fibers into the concrete matrix in these beam tests. Effects of corrosive environmental factors, through exposure of these beams to corrosive agents, on the structural behavior of these members. Finite Element model development to analyze the behavior of the beam specimen including non-linear effects in concrete. Develop design procedures for FRP rebar reinforced concrete elements**.** This project is completed. Prof.Ananth Ramaswamy is the PI and Dr.K.S.Nanjunda Rao is the CI.

3) Studies on the seismic performance of secondary piping networks. Optimal location of snubbers and dampers for desired structural performance of piping networks under seismic forces. This project is completed. Prof. C.S. Manohar is the PI and I, Prof. Ananth Ramaswamy, am the CI.

4) Studies were carried out on reinforced and prestressed concrete beams, columns and assemblages that are partially damaged and then repaired using diverse methods, such as external prestressing, tension flange/web strengthening with FRP and ultra high performance concrete strips/wraps, etc., and thereafter tested to failure to assess the repair potential of different schemes. Analytical formulations to understand the contribution of different sub-systems in repair technology were also be evolved. Prof.Ananth Ramaswamy is the PI in this project.

5) Behavior of beam column joints that are heavily reinforced were altered by substituting a portion of the joint reinforcement with fibers with a view to decongest the junction and thus enable effective concreting while not compromising on the ductility. The beam column joints so designed with fiber substitutes were assessed for its structural toughness and ductility under monotonic and cyclic loading. Prof.Ananth Ramaswamy is the PI in this project.

6) Time dependent deformations in the form of creep and shrinkage in normal and heavy density concrete were measured for different concrete mixes cured at different relative humidity and temperature conditions and tested at different ages of curing and at different load levels. Existing statistical models were calibrated using the test data and employed for long term prediction of these properties.

7) Repair of structural concrete beams and joints were carried out using FRP layers made from glass and carbon fabric. Repair was also attempted using self compacting concrete having fibers as a comparison. The repair schemes were also modeled on a finite element frame work and the responses matched.

8) Field studies were carried out on old existing railway bridges under service at their present operational loads and to explore the saftetylevels available with increased axle load levels.

9) The safety of structures against fire following an earthquake was the focus of this collaborative international project with the University of Edinburgh, IIT Roorkee and IISc.. The project comprised of modeling fire dynamics (University of Edinburgh), reliability and safety assessment and repair (IISc) and karge scale testing (IITR).

11) Thee study focuses on the ability of FRP based repair systems for rehabilitating fire / high temperature damaged applications. The use of FRP based repair with geopolymer layer of insulation also being studied for its efficacy.

413 B List all previous projects that are **supported by BRNS or any other funding agency** in which CI is actively participating (either as PI or as CI): **Prof. C.S.Manohar**

No	Title of the project	Total cost	Agency	Present status
1	Vibration based condition assessment and reliability analysis of existing engineering structures	Rs 28.4 lakhs	BRNS	Ongoing 2010-2013 Duration: 3 years
2	Fire resistance and repair of earthquake damaged structures	£146000=00	United Kingdom-India Education and Research Initiative.	Ongoing 2007-2011 Duration: 4 years

3	Aseismic structural reliability analysis of nuclear core support structure	Rs 3.0 lakhs	IGCAR	Ongoing Duration: 1 year

The CI has completed several other funded research projects and a list of these projects is provided in section 510.

414B. List all projects submitted **during the current financial year by CI to BRNS or any other agency for funding.** Give details on the present status of the application:

Asif Usmani and C S Manohar (PI-s), Making performance based structural engineering for fire resistance attainable, A collaborative proposal submitted to the UKIERI Innovative partnerships 2011 with participation from IISc and University of Edinburgh and also four industrial partners from India and the UK (total funds requested: £40000.00).

415B. Brief description of the **project(s) submitted/sanctioned by/to CI by other agencies**.

The project proposal mentioned in item 414B has the following objectives:

- To develop a simple and clearly defined performance based structural engineering (PBSE) framework for structures subjected to fire including easy to use software tools that will encourage its wider adoption.
- To incorporate a more explicit treatment of uncertainty in the above framework.

The funding available here mainly supports expenses towards international travel and exchange of research students and does not provide funds for equipment/project staff.

PART IV - FACILITIES

416. List of **facilities** that will be extended to the investigators by the implementing institution for the project

A. **Infrastructure facilities**

Sr. No.	Item Name	Yes/No/ NR*	Sr. No.	Item Name	Yes/No/ NR*
1.	Workshop	No	7.	Telecommunication	Yes
2.	Water & Electricity	Yes	8.	Transportation	Yes
3.	Standby power supply	Mo	9.	Administrative l support	Yes
4.	Laboratory space & furniture	Yes	10.	Library facilities	Yes
5.	AC room for equipment	NR	11.	Computational facilities	Yes
6.	Refrigerator	NR	12.	Animal/Glass house	NR
	NR*: Not Required				

B. **Equipment and accessories** available within the Investigator's group/Dept. which can be utilized for the project.

Sr. No.	**Name of the Equipment**	**Model & Make**	**Year of Purchase**
1	3 Walk in humidity and temperature controlled chambers		2004
2	Servo Hydraulic closed loop testing system	1200kN Universal Testing Machine closed loop (MTS systems).	2003
	Diamond-Cutter for Rock cutting Semi-automatic Rotopol rock grinder Petrological microscope with digital imaging facility Stereo microscope Precision rock section machine-Discoplan-TS Field equipments Compass and Geological Hammers Field GPS Isodynamic magnetic separator for mineral separation Petrological microscope with digital imaging facility and heating freezing stage for fluid inclusions Petrological microscope 2 High-end Stereo microscope with fluorescent lighting Stereo microscope 2 Jaw-crusher for rock crushing Ball mill for rock powdering Sieves and Sieve Vibratory shaker	All imported equipments	2009-2010

SECTION-B

(Please see Instruction - Sr. No.23 & 24)

500. Curriculum vitae (CV) of **Principal Investigator** (PI),

Name & Designation: **Dr. Sajeev Krishnan,** Assistant Professor
Date & Place of Birth: 03rd March 1975, Vakathanam, Kerala, India
Nationality: Indian
Present post: Assistant Professor
Institution with address: Centre for Earth Sciences, Indian Institute of Science, Bangalore 560 012
Telephone No. (with STD code): 080-2293-3404 Fax No.: 080-2293-3405
E-mail: sajeev@ceas.iisc.ernet.in
Qualifications: PhD, Field: Petrology, Metamorphic Geology, Institute: Okayama University, Japan
Experience:

Name of institution	Location	Position	duration
Centre for Earth Science Studies	Trivandrum, India	Department of Science and Technology Research Fellow	(one year) - Until September 1999
Okayama University	Okayama, Japan	Research Student	(one year) Until September 2000
Okayama University	Okayama, Japan	Research Scholar	(Six months) Until March 2004
Chonbuk National University,	Chonju, Korea	Post doctoral Researcher	(One year) Until March 2005
Okayama University of Science	Okayama, Japan	JSPS Research Fellow	(One year nine months) Until January 8th 2007
Yonsei University	Seoul, South Korea	Research Professor	One year six months) Until July 20th 2008

Geological Instrument experience:
SHRIMP-II, LA-ICPMS, TIMS, Lesser RAMAN, ICPMS, EPMA (WDS & CL, SEM, BSEI imaging), XRF, along with normal petrographic instruments
Awards & Fellowships:
Academic awards and scholarships:

FIRST RANK IN MSc. Annamalai University in 1998
MONBUKAGAKUSHO SCHOLARSHIP of Japanese government for Ph.D. program from 1999 to 2003
Post-Doctoral researcher scholarship of Chonbuk National University, Korea
JSPS Research Fellow scholarship of Japanese Government
Title: *Temporal and spatial distribution of ultrahigh temperature metamorphism in East Gondwana*

Academic services:
Associate Editor: Gondwana Research (2008-2009 February)
Editor: Gondwana Research 2005-2007
Guest Editor: Lithos, Gondwana Research

Signature with date

List of publication attached

Sajeev Krishnan List of Publications

Papers (Articles):

A. International (ISI) Journals

Year 2012:

32. Dharma Rao, C.V., Santosh, M., Sajeev, K., Windley B.F. (2012) Chromite–silicate chemistry of the Neoarchean Sittampundi Complex, southern India: Implications for subduction-related arc magmatism *Precambrian Research (in press)*

Year 2011:

31.Thanh, N.X., **Sajeev, K.**, Itaya, T., Windley, B.F. (2011) Multiple garnet growth in garnet–kyanite–staurolite gneiss, Pangong metamorphic complex, Ladakh Himalaya: New constraints on tectonic setting. *Lithos*, *127, 552-563.*

Year 2010:

30. **Sajeev, K.,** Williams, I.S., & Osanai, Y. (2010) Sensitive high-resolution ion microprobe U-Pb dating of prograde and retrograde ultrahigh-temperature metamorphism as exemplified by Sri Lankan granulites. *Geology* 11, 971-974.
29. **Sajeev, K.,** Kawai, T., Omori, S., Windley, B.F., & Maruyama S. (2010) *P-T* evolution of Glenelg eclogites, NW Scotland: Did they experience ultrahigh-pressure metamorphism? *Lithos* 114, 473-489.
28. **Sajeev**, **K.,** Jeong. J., Kwon, S., Kee, W-S., Kim. S.W., Komiya , T., Itaya, T., Jung, H-S., & Park, Y. (2010) High *P-T* granulite relicts from the Imjingang belt, South Korea: tectonic significance. *Gondwana Research* 17, 75-86.
27. Nakano, N., Osanai, Y., **Sajeev**, **K.,** Hayasaka, Y., Miyamoto, T., Minh, N. T., Owada, M. & Windley B.F. (2010) Triassic eclogite from northern Vietnam: inferences and geological significance. *Journal of Metamorphic Geology* 28, 59-76.

Year 2009:

26.**Sajeev**, **K.,** Windley, B.F., Connolly J.A.D., & Kon Y. (2009) Retrogressed eclogite (20 kbar, 1020ºC) from the Neoproterozoic Palghat-Cauvery suture zone, southern India. *Precambrian Research* v. 171, p. 23-36.
25. **Sajeev**, **K.** Osanai, Y. Kon, Y. & Itaya, T. (2009) Stability of pargasite during ultrahigh-temperature metamorphism: a consequence of titanium- and REE- partitioning? *American Mineralogist* v. 94, p. 535–545.
24. Santosh, M., **Sajeev, K.**, Li, J.H., Liu, S.J., & Itaya T. (2009) Counterclockwise exhumation of a hot orogen: The Paleoproterozoic ultrahigh-temperature granulites in the North China Craton. *Lithos* v. 110, p. 140–152.
23. Kwon, S., **Sajeev**, **K.,** Mitra, G., Park, Y., Kim, S.W., & Ryu, I-C. (2009) Evidence for Permo-Triassic collision in Far East Asia: The Korean collisional orogen. *Earth and Planetary Science Letters* v. 279, p. 340-349.
22. Thanh, N.X., Itaya T., **Sajeev, K.**, Ahmad, T., Kojuma, S., Ohtani, T., & Ehiro, M. (2009) K-Ar ages of biotite and muscovite from Pangong metamorphic complex, Shyok suture zone, India, Implications for the youngest post-collision metamorphic event in Ladakh Hymalaya. *Journal of Mineralogical and Petrological Sciences (JMPS)* v.104, p. 188-191.

Year 2007:

21. **Sajeev, K.**, Osanai, Y., Connolly, J.A.D., Suzuki, S. Ishioka, J., Kagami H. & Rino S. (2007) Extreme Crustal Metamorphism during a Neoproterozoic Event in Sri Lanka: A Study of Dry Mafic Granulites. *Journal of Geology* v. 115, p. 563–582.

20.Collins,A.S., Clark, C, **Sajeev, K**, Santosh, M., Kelsey D. E. & Hand M. (2007) Passage through India: The Mozambique Ocean suture, high pressure granulites and the Palghat-Cauvery Shear Zone System *Terra Nova* v. 19, p. 141-147.

Year 2006 :

19.**Sajeev, K**., Santosh, M. & Kim, H.S. (2006) Partial melting and P-T evolution of the Kodaikanal Metapelite Belt, southern India. *Lithos* v. 92, p. 465-483.
18.Santosh, M. & **Sajeev K.** (2006) Anticlockwise evolution of ultrahigh-temperature granulites within continental collision zone in southern India *Lithos* v. 92, p. 447-464.

17. **Sajeev, K.**, & Santosh, M. (2006) An unusual high-Mg Garnet-Spinel-Orthopyroxenite from southern India: evidence for ultrahigh-temperature metamorphism at high pressure conditions. *Geological Magazine*, v. 143, p. 923-932.

16.Santosh, M. **Sajeev K.** & J. Li (2006) Extreme crustal metamorphism during Columbia supercontinent assembly: Evidence from North China Craton. *Gondwana Re*search, v. 10, p. 256-266.

15.Osanai, Y., **Sajeev, K**., Owada, M., Kehelpannala, K.V.W., Prame, W.K.B. Nakano, N. & Jayatileke, S. (2006) Metamorphic evolution of ultrahigh-temperature and high-pressure granulites from Highland Complex, Sri Lanka. *Journal of Asian Earth Sciences,* v. 28, p. 20-37.

14. Kim, S W., Oh, C.W., Ryu, I. C., Williams, I. S., **Sajeev, K**., Santosh, M. & Rajesh V. J. (2006) Neoproterozoic bimodal volcanism in the Okcheon Belt, South Korea, and its comparison with the Nanhua Rift, South China: implications for rifting in Rodinia. *Journal of Geology* v. 114, p. 717-737.

13.Oh, C.W., **Sajeev, K.**, Kim, S.W. and Kwon, Y.W. (2006) Mangerite magmatism associated with a probable late-Permian to Triassic Hongseong-Odesan Collision Belt in South Korea. *Gondwana Research*. v. 9, p. 95–105

Year 2005

12.**Sajeev, K.** & Osanai, Y. (2005) Thermal gradients in the Sri Lankan granulite terrane:a garnet–biotite thermometric approach. *Journal of Metamorphic Geology*, v. 23,p. 383–397

11. Oh, C.W., Kim S.W., Choi, S.G., Zhai, M. Guo, J. & **Sajeev, K.** (2005) First finding of eclogite facies metamorphic event in South Korea and its correlation with the Dabie-Sulu collision belt in China. *Journal of Geology*, v. 113, p. 226-232.

Year 2004

10. **Sajeev, K.** & Osanai, Y. (2004) Ultrahigh-temperature Metamorphism (1150° C and 12 kbar) and Multi-stage Evolution of Mg-Al Granulites from Central Highland Complex, Sri Lanka, *Journal of Petrology,* v. 45, p. 1821-1844.

9. **Sajeev, K**., Osanai, Y. & Santosh, M. (2004) Ultrahigh-temperature metamorphism followed by two-stage decompression of garnet-orthopyroxene-sillimanite granulites from Ganguvarpatti, Madurai block, southern India. *Contributions to Mineralogy and Petrology,* v. 148, p. 29-46.

8. **Sajeev, K.** & Osanai, Y. (2004) 'Osumilite' and 'spinel+quartz' from Highland Complex, Sri Lanka: a case of cooling and decompression after ultrahigh-temperature metamorphism. *Journal of Mineralogical and Petrological Sciences (JMPS),* v.99, p. 320-327.

7. Tamashiro, I., Santosh, M., **Sajeev, K.**, Morimoto, T. & Tsunogae, T. (2004) Multistage orthopyroxene formation in ultrahigh-temperature granulites of Ganguvarpatti, southern India: implication for complex metamorphic evolution during Gondwana assembly. *Journal of Mineralogical and Petrological Sciences (JMPS),* v.99, p. 279-297.

Older:

6. **Sajeev, K**., Osanai, Y. & Santosh, M. (2001) Ultrahigh-temperature stability of sapphirine and kornerupine in Ganguvarpatti granulite, Madurai block, Southern India. *Gondwana Research*. v. 4, p.762-766.

5. Osanai, Y., Owada, M., Tsunogae, T., Toyoshima, T., Hokada, T., Long, T.V., **Sajeev, K**. & Nakano, N. (2001) Ultrahigh-temperature peletic granulite from Kontum massif, central Vietnam: Evidence for east Asian juxtaposition at ca 250 Ma. *Gondwana Research*. v. 4, p.720-723.

B. International (non-ISI) Journals:

4. **Sajeev, K**., Osanai, Y., Suzuki. S. & Kagami, H. (2003). Geochronological evidence for multistage-metamorphic events in ultrahigh-temperature granulites from central Highland Complex, Sri Lanka. *Polar Geosciences*. v. 16, 138-149.

3.Shabeer, K. P., **Sajeev, K**., Okudaira, T. & Santosh, M. (2002) Two stage spinel generation in the high-grade metapelites of central Kerala Khondalite Belt: Implication for prograde P-T path. *Journal of Geosciences, Osaka city university*. v. 45 p. 29-43.

C. Local Journals:

2.**Sajeev, K.** & Osanai, Y. (2003) Geology of high- to ultrahigh-temperature granulites from central Madurai block, southern India; with emphasis on the evolution of Grt-Opx-Crd granulite. *Okayama University Science Reports*, v. 9, p. 1-8.

1. **Sajeev**, **K.** Itaya, T.& Santosh, M. (2006) Geology of southern Indian Granulite Terrane: A preliminary report of the 2005 field survey. *Okayama University of Science, Science Reports*, v. 31 p. 9-16.

Edited thematic Issue in International (ISI) Journal

Year 2008

1. Itaya, T., **Sajeev, K**. Clark, C. & Kusak, M. (2008) Micro-chronology and Evolution of the planet Earth. *Gondwana Research* v.**14, n 4, p. 567-700.**

Editorial: Micro-chronology and Evolution of the planet Earth p. 567-568.

Year 2006

2. **Sajeev**, **K.** & Santosh, M (2006) Extreme crustal metamorphism and related crust-mantle processes. *Lithos* v. 92 n 3-4, p.321-624.

Editorial: Extreme crustal metamorphism and crust–mantle processes: An introduction, p. v-ix, doi:10.1016/j.lithos.2006.03.048

3. Oh, C.W. **Sajeev**, **K.,** Kim, S.W. & Santosh, M. (2006) Tectonic Evolution of Korean Peninsula and Adjacent Crustal Fragments in Asia. *Gondwana Research* v. 9 n 1-2. p. 19-230.

Editorial: Tectonic evolution of Korean Peninsula and adjacent crustal fragments in Asia: Introduction p. 19-20.

International Symposiums / Abstract:

1. Williams, I.S., **Sajeev, K**, Trotter JA (2009) Advances in the SHRIMP II ion microprobe and its geological applications. 11th ISMAS-TRICON-2009. Hyderabad
2. B. Windley, **K. Sajeev** (2009) Archaean eclogites in the mainland Scourian, and Palaeoproterozoic garnet lherzolites and retrogressed eclogites at Rodel, Outer Hebrides, Scotland; implications for widespread subduction tectonics. Evolution of the Continental Crust. The Janet Watson Meeting, The Geological Society (Burlington House), London.
3. Thanh, N.X., **Sajeev, K.** Itaya, T. Tu M.T. (2009) Evolution of garnet-kyanite-staurolite gneiss in Pangong metamorphic complex, Ladakh Himalaya: new insights on tectonic setting. IAGR annual convention, Gondwana to Asia, Vietnam.
4. **Sajeev, K**., Kawai T, Omori S, Windley BF, Shibuya T, Sawaki Y Maruyama S (2007) Petrographic re-examinations of Glenelg eclogites: a step towards higher pressures? International Eclogite Field Symposium, Portree, July, P 97.
5. **Sajeev, K.** Santosh, M. & Itaya, T. (2006) High Pressure Granulites from the Palghat-Cauvery Shear Zone, Southern India, submitted to Granulites and Granulites 2006, **Brasília , Brazil, July, p 76.**
6. **Sajeev, K** & Suzuki, K. (2006) Monazite age-mapping and *PTt* evolution of Kodaikanal Metapelite Belt, southern India, submitted to IMA Kobe, July. P 320.
7. **Sajeev, K.** & Osanai, Y. (2003) First finding of Osumilite from Highland Complex, Sri Lanka: a case of melt-restite interaction resulted Isobaric cooling after UHT metamorphism. Vth Hutton symposium abstracts 127.
8. Osanai, Y**, Sajeev, K**, OWADA, M, Kehelpannala, K.V.W., Prame, W.K.B.N. and Nakano, N. (2003) Evolution of highest-grade metamorphic rocks from Central Highland Complex, Sri Lanka. Geological Survey and Mines Bureau, Sri Lanka, Centenary Publication, p. 25-31.
9. **Sajeev, K**. & Osanai, Y. (2002) Evidence for counter clockwise evolution of Spr-Qtz & Opx-Sil-Qtz bearing granulite from Highland Complex, Sri Lanka.16th Australian Geological Convention abstract volume. v. 67, P. 232.
10. Osanai, Y., Owada, M., Nakano, N., Tsunogae, T., Toyoshima, T., N., Nam, T. N., Binh, P. and **Sajeev, K**. (2002) Metamorphic Evolution of Kontum Massif, central Vietnam: reconnaissance of correlation with Gondwana breakup and Asia growth. 2002 PPO-ASIA, Sapporo (Japan).
11. **Sajeev, K**., Osanai, Y., Biju, S. & Santosh, M. (2000) Decompression processes of cordierite-sillimanite-biotite gneiss from central Madurai block, southern India. AGU, Western Pacific geophysics meeting, Tokyo. v. 81 P. 236.

510. Curriculum vitae (CV) of **Co-Investigator** (CI), if applicable

Name & Designation: **ANANTH RAMASWAMY,** Professor,
Date & Place of Birth: 11th January 1963, Mumbai.
Nationality: Indian
Present post: Professor
Institution with address: Department of Civil Engineering, Indian Institute of Science, Bangalore 560012 India
Telephone No. (with STD code):+91-80-22932817/23608850 Fax No.: +91-80-23600404
E-mail ananth@civil.iisc.ernet.in

Qualifications
Ph.D. (1992, Louisiana State University, USA)
M.S. (1986, University of California, Davis, USA)
B.Tech., (1985, IIT, Madras)

Experience:
Professor, since July, 2009 at IISc.
Associate Professor, May 2001- July 2009 at IISc.
Assistant Professor, May 1995- May 2001 at IISc.
Visiting Lecturer, January 1994-May 1995, IIT Kharagpur
Research Assistant, 1987 –1991, LSU
Research Assistant, 1986, Univ. of California, Davis

Awards, Fellowships, Recognitions:

- Jaiprasad, R., Srinivasamurthy, B.R., Ramaswamy, A., Jaigopal, S. (2006) "Rehabilitation on 140 Years Old Brick Masonry Arch Bridge Across Vrishabhavathi Valley in Bangalore, Karnataka-Case Study" printed in Indian Roads Congress (IRC) Journal Volume 67 Part 1, 121-126 (C.P.W.D. Medal of Indian Roads Congress for best paper on maintenance.
- Associate Editor ASCE Journal of Bridge engineering. Since May 2010
- Expert Member, Department of Science and Technology, Project Assessment Committee August 2011

Signature with date

Attach a list of publications during the last 10 years which is relevant to the project
(Reprints may please be mail only on demand)

1. Thomas, Job, and Ramaswamy, A. (2009) "Nonlinear FE analysis of prestressed SFRC beams in flexure", Journal of Bridge Engineering, Proc. of ICE, UK, 162(BE3), 119-126.
2. Ramaswamy, A, and Muttasim Adam Ahmedi (2008) "New materials in structural concrete repair", Journal of Structural Engineering, SERC, Chennai, India, v.35 (4), pp. 26-36, April-June.
3. Thomas, J. and Ramaswamy, A. (2007) "Shear of Prestressed Concrete Beams having Steel Fibers ", ICE Structures & Buildings Journal, 160 (SB5), 287-293.
4. Thomas, J. and Ramaswamy, A. (2007) "Mechanical Properties of Steel Fiber Reinforced Concrete", Journal of Materials in Civil Engineering, ASCE, 19(5), 385-392.
5. Saikia, B., Kumar, P., Thomas, J., Rao, K.S.N., and Ramaswamy A. (2007) "Serviceability Performance in Flexure of Beams with GFRP Rebars", Construction and Building materials, 21, 1709-1719.
6. Jaiprasad, R., Srinivasamurthy, B.R., Ramaswamy, A., Jaigopal, S. (2006) "Rehabilitation on 140 Years Old Brick Masonry Arch Bridge Across Vrishabhavathi Valley in Bangalore, Karnataka-Case Study" printed in Indian Roads Congress (IRC) Journal Volume 67 Part 1, 121-126 *(C.P.W.D. Medal of Indian Roads Congress for best paper on maintenance)*.
7. Thomas, J., and Ramaswamy, A. (2006) "Width and Spacing of Flexural Cracks in Partially Prestressed T-Beams with Steel Fibers in Partial / Full Depth", ACI Structural Journal, 103(4), 568-576.
8. Thomas, J., and Ramaswamy, A. (2006) "Load deflection performance of partially prestressed concrete T-beams with steel fibers in partial and full depth", Structural Concrete Journal of FIB, 7(No. 2), 65-75.
9. Thomas, J., and Ramaswamy, A. (2006) "Shear Strength of Partially Prestressed Concrete T-Beams with Steel Fibers in Partial/Full Depth", ACI Structural Journal, 103(3), 427-435.
10. Thomas, J. and Ramaswamy, A (2006) "Finite Element Analysis of Shear Critical Prestressed SFRC Beams", Computers and Concrete, Techno-Press, 3(1), 65-77.
11. Thomas, J. and Ramaswamy, A. (2006) "Shear-flexure analysis of prestressed concrete T-beams containing steel fibers over partial or full depth" Structural Engineering International, Journal of the International

Association of Bridge and Structural Engineers (IABSE), vol. 16(1), 66-73.
12. Saikia, B., Thomas, J., Ramaswamy A. and Rao, K.S.N. (2005)-"Performance of Hybrid Rebars as Longitudinal Reinforcement in Normal Strength Concrete", Materials and Structures: A RILEM Journal, vol. 38 (No.284), pp. 857-864.
13. Padmarajaiah, S.K. and Ramaswamy, A. (2004) "Flexural Strength Predictions of Steel Fiber Reinforced High Strength Concrete in Fully / Partially Prestressed Beam Specimen", Cement and Concrete Composites Journal, v26, 275-290
14. Padmarajaiah, S. K. and Ramaswamy, A. (2002)"Comparative Flexural Response of Full and Partial Depth Fibrous High Strength Concrete Prisms Containing Trough Shape Steel Fibers", Journal of Materials in Engineering, ASCE, v. 14(2), pp.130-136, March / April.
15. Padmarajaiah, S. K. and Ramaswamy, A.(2002) "A Finite Element Assessment of Flexural Strength of Prestressed Concrete Beams With Fiber Reinforcement", Journal of Cement and Concrete Composites, vol. 24(2), pp. 229-241, April.
16. Padmarajaiah, S. K. and Ramaswamy, A. (2001) "Crack Width Predictions for High Strength Concrete Fully / Partially Prestressed Beam Specimens Containing Steel Fibers", Structural Journal, ACI, v. 98(6), Nov.-Dec., pp.852-861.
17. Padmarajaiah, S.K. and Ramaswamy, A. (2001)"Behavior of Fiber Reinforced High Strength Concrete Prestressed and Reinforced Beam Specimen Subjected to Shear", Structural Journal, ACI, v. 98(5), Sept.-Oct, pp. 752-761.
18. Padmarajaiah, S.K. and Ramaswamy, A. (2001) " A Beam and Arch Action Model for Computing the Shear Strength of Prestressed and Reinforced HSFRC Beams", Journal of Structural Engineering, SERC, Chennai, India, v.28 (1), pp. 7-15, April-June.

CV of CI

C S Manohar
Professor and Chairman
Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012 INDIA

Born : 11th May 1959, Hubli (Karnataka)
Indian National
Phone: +91 80 2293 3121 Fax: +91 80-23600 404
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Education

- BE (Civil Engg.), 1982, Karnatak University, India, First Class with Distinction.
- ME (Civil Engg.), 1984, Indian Institute of Science, First Class with Distinction.
- PhD (Faculty of Engineering), 1989, Indian Institute of Science, Bangalore.

Work Experience

Academic positions held at the Indian Institute of Science

- Professor, May 2005-present, Department of Civil Engineering.
- Associate Professor, May 1999-May 2005, Department of Civil Engineering.
- Assistant Professor, May 1993-May 1999, Department of Civil Engineering.

Other positions held at the Indian Institute of Science

- Chairman, December 2010- present, Department of Civil Engineering.
- Chairman, July 2007- December 2010, Centre for Earth Sciences.
- Associate Faculty Member, 2007-present, Centre for Earth Sciences.
- Member Secretary, IISc-IGCAR R & D Cell, 2011-present

Positions held outside the Indian Institute of Science

- Visiting Professor, October 2011, Carleton University, Ottawa, Canada.
- Visiting Scientist, May 2003, Dept. of Civil Engineering, University of Delaware, USA.
- Visiting Associate Professor, June-July, 2003, Dept. of Civil Engineering, The Johns Hopkins University, USA.
- Research Assistant, May 1991-May 1993, Dept. of Engineering Sciences, University of Oxford, UK.
- Scientist, Oct 1990-May 1991, Structural Engineering Research Centre, Chennai, India

Honors

- Member, Editorial Board, Probabilistic Engineering Mechanics (Elsevier)
- Member, Editorial Board, Structural Control and Health Monitoring (Wiley)
- Associate Editor (Structural Dynamics), ISET Journal of Earthquake Technology, (since 2007).
- Associate Editor, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation (Serial Publications).
- Member, Editorial Board, Earthquakes and Structures (from 2010) (Techno Press).
- Sir C V Raman award for young scientists for the year 1999, Instituted by Government of Karnataka, India.
- Member, Technical Committee of Dynamics, Engineering Mechanics Division, American Society of Civil Engineers, 2003-2007.
- Invitations to IUTAM symposia on Nonlinear Stochastic Mechanics, 1995, 2001, 2009.

Research interests

- Structural dynamics: modeling of nonlinearity and uncertainties; computational and experimental methods; inverse problems: structural system identification and damage detection using measured vibration data; statistical energy analysis.
- Stochastic structural mechanics: stochastic FEM; random vibrations; Bayesian filtering; Monte Carlo simulations & variance reduction schemes; structural reliability modeling.
- Earthquake engineering: seismic safety of large scale structures; science of earthquake simulations: hybrid test methods; real time substructuring; fire following earthquakes.

Papers in refereed journals (last ten years)

1. B Radhika and C S Manohar, 2011, Updating response sensitivity models of nonlinear vibrating structures using particle filters, Computers and Structures, 89(11-12), 901-911.
2. H A Nasrellah and C S Manohar, 2011, Finite element method based Monte Carlo filters for structural system identification, Probabilistic Engineering Mechanics, 26 (2011) 294–307.
3. H A Nasrellah and C S Manohar, 2011, Particle filters for structural system identification using multiple test and sensor data: a combined computational and experimental study, Structural Control and Health Monitoring, 18, 99–120.
4. B Radhika and C S Manohar, 2010, Reliability models for existing structures based on dynamic state estimation and data based asymptotic extreme value analysis, Probabilistic Engineering Mechanics, 25, 393-405.
5. H A Nasrellah and C S Manohar, 2010, A particle filtering approach for structural system identification in vehicle-structure interaction problems, Journal of Sound and Vibration. 329(9), 1289-1309.
6. R Sajeeb, C S Manohar and D Roy, 2010, A semi-analytical particle filter for identification of nonlinear oscillators, Probabilistic Engineering Mechanics, 25, 35-48
7. R Sivaprasad, S Venkatesha, and C S Manohar, 2009, Identification of dynamical systems with fractional derivative damping models using inverse sensitivity analysis, Computers, Materials and Continua, 9 (3), 179-207.
8. R Tipireddy, H A Nasrellah and C S Manohar, 2009, A Kalman filter based strategy for linear structural system identification based on multiple static and dynamic test data, Probabilistic Engineering Mechanics, 24, 60-74.
9. R Sajeeb, C S Manohar and D Roy, 2009, A Conditionally linearized Monte Carlo filter in nonlinear structural dynamics, International Journal of Nonlinear Mechanics, 44(7), 776-790
10. R Sajeeb, C S Manohar and D Roy, 2009, Rao-Blackwellization with substructuring for state and parameter estimations of a class of nonlinear dynamical systems, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation, 1(1-2) 2009.
11. S Venkatesha, R Rajender, and C S Manohar, 2008, Inverse sensitivity analysis of singular solutions of FRF matrix in structural system identification, CMES: Computer Modeling in Engineering and Science, 37(2), 113-152.
12. V Namdeo and C S Manohar, 2008, Force state maps using reproducing kernel particle method and kriging based functional representations, CMES: Computer Modeling in Engineering and Science, 32(3), 123-160.
13. S S Panda and C S Manohar, 2008, Applications of meta-models in finite element based reliability analysis, CMES: Computer Modeling in Engineering and Sciences, 28, N0. 3, 161-184.
14. B Radhika, S S Panda and C S Manohar, 2008, Time variant reliability analysis using data based extreme value analysis, CMES: Computer Modeling in Engineering and Sciences, 27(1-2),79-110.
15. S Ghosh, C S Manohar and D Roy, 2008, Sequential importance sampling filters with a new proposal distribution for parameter identification of structural systems, Proceedings of Royal Society of London, A, 464, 25-47.
16. V Namdeo and C S Manohar, 2007, Nonlinear structural dynamical system identification using adaptive particle filters, Journal of Sound and Vibration, 306, 524-563.
17. R Sajeeb, C S Manohar and D Roy, 2007, Control of Nonlinear Structural Dynamical Systems with Noise Using Particle Filters, Journal of Sound and Vibration, 306, 25, 111-135.
18. S Ghosh, D Roy and C S Manohar, 2007, New forms of extended Kalman filter via transversal linearization and applications to structural system identification, Computer Methods in Applied Mechanics and Engineering, 196, 5063-5083.
19. M Manjuprasad and C S Manohar, 2007, Adaptive random field mesh refinements in stochastic finite element reliability analysis of structures, CMES: Computer Modeling in Engineering and Sciences, 19(1), 23-54.
20. R Sajeeb, D Roy and C S Manohar, 2007, Numerical aspects of a real-time substructuring technique in structural dynamics, International Journal of Numerical Methods in Engineering, 72, 1261-1313.
21. A M Abbas and C S Manohar, 2007, Critical vector random earthquake loads for parametrically excited structures, Structural Safety, 29(1), 32-48.
22. Sayan Gupta and C S Manohar, 2006, Reliability analysis of randomly parametered linear vibrating systems subjected to stochastic excitations, Journal of Sound and Vibration, 297(3-5), 1000-1024.
23. C S Manohar and D Roy, 2006, Nonlinear structure system identification using Monte Carlo filters, Sadhana, Academy Proceedings in Engineering, Indian Academy of Science, 31(4), 399-427.
24. Sayan Gupta and C S Manohar, 2005, Extreme value distribution of von Mises stress in randomly vibrating structures, Journal of Vibration and Acoustics, Transaction of ASME, 127 (6), 547-555.

25. Sayan Gupta and C S Manohar, 2005, Development of multivariate extreme value distributions for random vibration applications, Journal of Engineering Mechanics, ASCE. 131(7), 712-720.
26. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part I: Linear structures, Journal of Sound and Vibration, 287, 865-882.
27. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part II: Nonlinear structures, Journal of Sound and Vibration, 287, 883-900.
28. C S Manohar and R Ghanem, 2005, Multivariate probability distribution of ordered peaks of vector Gaussian random processes, Probabilistic Engineering Mechanics, 20, pp 87-96.
29. Saikat Saha and C S Manohar, 2005, Inverse reliability design of structures subjected to partially specified earthquake loads, Probabilistic Engineering Mechanics, 20, 19-31.
30. Sayan Gupta and C S Manohar, 2004, Response surface method for time variant reliability analysis of nonlinear random structures under nonstationary excitations, 36, 267-280, Nonlinear Dynamics.
31. Sayan Gupta and C S Manohar, 2004, Improved response surface method for structural reliability analysis, 123-139, Structural safety.
32. S Ammanagai, S Venkatesha, and C S Manohar, 2004, Analytical and experimental investigations of structural damages in beams and built-up structures using vibration data, 31(1), 73-84, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
33. Luna Majumder and C S Manohar, 2003, A time domain approach for damage detection in bridge structures using vibration data with moving vehicle as an excitation source, 268, 699-716, Journal of sound and Vibration.
34. C S Manohar, S Venkatesha and S Sadasivan, 2003, Finite element analysis of vehicle-structure interactions during launching of remotely piloted air-vehicles, 30(1), 1-6, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
35. C S Manohar, R Ravi and Ch Srinivas, 2003, Nonlinear structures under random differential support motions and determination of critical input models, 2(3), 171-198, Advances in vibration engineering, Vibration Institute of India.
36. Luna Majumder and C S Manohar, 2002, Nonlinear reduced models for beam damage detection using data on moving oscillator-beam interactions, 82, 301-314, Computers and Structures.
37. Sayan Gupta and C S Manohar, 2002, Dynamic stiffness method for circular stochastic Timoshenko beams: response variability and reliability analyses, Journal of Sound and Vibrations, 253(5), 1051-085.
38. Abbas M and C S Manohar, 2002, Investigations into critical excitation models within deterministic and probabilistic frameworks: single point excitations, Earthquake Engineering and Structural Dynamics 31, 813-832.
39. A M Abbas and C S Manohar, 2002, Critical spatially varying earthquake load models, Journal of Structural Engineering, Structural Engineering Research Centre, Madras, 29, 39-52.

List of funded projects (last ten years)

1. C S Manohar and S Venkatesha, 2010-2013, Vibration based condition assessment and reliability analysis of existing structures', Funded by Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India.
2. C S Manohar, 2010, Development of a video based course on Stochastic Structural Dynamics, funded by National Programme on Technology Enhanced Learning, Government of India.
3. 2007-2010, Fire resistance and repair of earthquake damaged structures, United Kingdom-India Education and Research Initiative (UKIERI) Collaborative Research Awards 2007, Jointly developed with University of Edinburgh, IIT Roorkee and IISc, Bangalore; Team: Edinburgh: A S Usmani, J L Torero, P Pankaj, J F Chen, and M Gillie; IIT Roorkee: Pradeep Bhargava, Yogendra Singh, Umesh Kumar Sharma; IISc: C S Manohar and Ananth Ramaswamy.
4. C S Manohar and K Venkatraman, 2006-2008, Analytical prediction of squeak and rattle noise intensity in a seat belt retractor system, Funded by Delphi Automotive Systems, India.
5. C S Manohar, 2006-2008, Structural Reliability Under Seismic Loads, Funded by Cranes Software India Limited.
6. C S Manohar and V R Sonti, and A R Upadhya, 2005-2009, Modeling of nonlinearity in experimental structural dynamics, Aeronautical Research and Development Board, Government of India.
7. J M Chandra Kishen, Ananth Ramaswamy, C S Manohar, and D Roy, 2006-2009, Condition monitoring of railway bridges, Funded by Indian Railways (South Central Division).
8. C S Manohar and K Venkatraman, 2006, Acoustic vibration of sodium to air heat exchangers, Funded by IGCAR.

9. C S Manohar and K Venkatraman, 2008, Dynamic analysis of rotating parts of a turbine, Funded by Bharath Heavy Electricals Limited, Bhopal.
10. D Roy and C S Manohar, 2004-2007, Development of numerical methods for structural reliability analyses, Funded by Board of Research in Nuclear Studies, Department of Atomic Energy, Government of India.
11. C S Manohar and J M Chandra Kishen, 2002-2006, Seismic Probabilistic Safety Assessment (PSA) of nuclear power plants, Funded by Board of Research in Nuclear Studies, Department of Atomic Energy, Government of India.
12. C S Manohar and S Venkatesha, 2006, Testing and model validation for simple brackets and lectures on techniques and method used**,** Funded by John F Welch Technology Centre, General Electricals India, Bangalore.
13. C S Manohar, D Roy, and S Venkatesha, 2006, Environmental vibration survey at the National Centre for Biological Sciences at the proposed site for installing an electronic microscope, Bangalore.
14. C S Manohar and V R Sonti, 2003-2005, Bayesian updation of finite element sub-structure assemblies using qualification test data, Funded by Indian Space Research Organization-Indian Institute of Science Space Technology Cell.
15. C S Manohar, 2001-2004, Structural damage detection using vibration data and probabilistic health assessment, Funded by Council of Scientific and Industrial Research, Government of India.
16. C S Manohar and Kartik Venkatraman, 2002-2004, Vibration response prediction in a flight vehicle, Funded by Environmental Test Laboratory, Regional Research Centre, Hyderabad, Defence R & D Organization, Government of India.

520. Curriculum vitae (CV) of **Principal Collaborator** (PC):

The following format should be used to provide Curriculum vitae of the individuals mentioned above

Name & Designation:
Date & Place of Birth:
Nationality:
Present post:
Institution with address:
Telephone No. (with STD code): Fax No.:
E-mail:
Qualifications:
Experience:
Awards & Fellowships:

Signature with date

Attach a list of publications during the last 10 years which is relevant to the project
(Reprints may please be mail only on demand)

SECTION-C

CERTIFICATE-1 (Submit single hard copy only**)**
Certificate from the Head of the Institution of the Principal Investigator (PI) and Co-Investigator (CI) from Non-DAE Institution (Please see Instruction - Sr. No.4-6)

...

Project Title: **Petrographical, Chemical and Computational Studies on Concrete at High Temperature**

(1) Certified that this Institution agrees to the participation of
Principal Investigator:
Dr. Sajeev Krishnan,
Centre for Earth Sciences
Indian Institute of Science,
Bangalore 560 012

Co- Investigators:
Prof. Ananth Ramaswamy
Department of Civil Engineering
Indian Institute of Science,
Bangalore 560 012

Prof. C.S. Manohar
Department of Civil Engineering
Indian Institute of Science,
Bangalore 560 012

for the above project which is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS).

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) Certified that the management takes the responsibilities for the timely submission of audited (by external Chartered Accounted or Statutory Government Auditor) statement of account (SA), utilisation certificate (UC), details of staff recruited and equipment purchased for each year as well as the audited (by external Chartered Accounted or Statutory Government Auditor) consolidated SA and UC for the final year.

(4) **Particulars of University Bank A/c are as follows (Please see Instruction - Sr. No.7):**

a) **Name of Account Holder:**
b) **Account No.:**
c) **Bank Name and Branch Address:**
d) **Branch code:**
e) **IFS Code: (16 digits)**

Date:

Place:

Name & signature of the
Head of the institution
or his authorised nominee

Seal:

Note: For Multi-Centre projects, similar certificate is needed from all the participating institutions.

CERTIFICATE-2 (Submit single hard copy only**)**

Certificate from the Head of the Institution of Principal Collaborator (PC) /Departmental Coordinator (DC) from DAE Institution

(Please see Instruction - Sr. No.7)

....

Project Title:

(1) Certified that this Institution agrees to the participation of Prof./Dr. _____ Department/Address _____ as Principal Collaborator (PC)/ Departmental Coordinator (DC) for the above project that is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS) by Prof./Dr. _____ Department/Address _____ as Principal Investigator (PI) .

The PC/ DC shall coordinate for timely submission of yearly progress reports and financial documents towards meaningful conclusion of the project as scheduled.

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) This institution assures to undertake the financial and other management responsibilities of the part of the project work that will be conducted in this institution.

(4) This Certificate is being issued with approval of the Group Board or the Group Board approval shall be taken, after the project is sanctioned by BRNS.

Date:

Place:

Name & signature of the
Head of the DAE institution/
Head of the Group

Seal:

CRP on Uncertainty Analysis of Engineering and Environmental Systems

Project-4

Studies on Fatigue Crack Growth in Graphite

A project proposal submitted to

BOARD OF RESEARCH IN NUCLEAR SCIENCES
Department of Atomic Energy
Government of India

By

Professor J M Chandra Kishen (PI)
Professor C S Manohar (CI)

Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

August 2011

SECTION-A

PART I – PROJECT OVERVIEW (Please see Instruction - Sr. No. 8)

100. Advisory Committee Code Number (Please see Instruction - Sr. No. 9): **34** / **35** / **36** / **37**

101. Title: **Studies on Fatigue Crack Growth in Graphite**

102. Key Words & Name of 3 Referees (Please see Instruction - Sr. No. 10):

Fracture, Fatigue, Crack growth, Dimensional analysis, Probabilistic, Graphite

103. Project Summary (Please see Instruction - Sr. No. 11):

Components of nuclear power plants make use of graphite as one of their primary materials. These components are subjected to varying amplitude of loads. Hence, it is proposed to carry out experimental and analytical studies on graphite under static and fatigue loading. A fatigue crack growth curve would be developed using the experimental data for graphite. A crack propagation law would be proposed from first principles using the theory of fracture mechanics and concepts of dimensional analysis. A probabilistic study would be conducted in order to determine the most sensitive parameters involved in fatigue failure of graphite.

Personal Details:

		Name	Address	e-mail	Phone	Fax
104.	PI	Prof. J. M. Chandra Kishen	Dept. Of Civil Engineering, Indian Institute of Science, Bangalore 560 012	**chandrak@civil.iisc.ernet.in**	22933117	23600404
105.	CI	Prof. C. S. Manohar	---do---	**manohar@civil.iisc.ernet.in**	22933121	23600404
106.	PC	Shri Rohit Rastogi	RSD, BARC Mumbai 400085	rrastogi@barc.gov.in	25591522	
	CPC	Dr. M. K. Samal	RSD, BARC Mumbai 400085	mksamal@barc.gov.in	25591523	

107. Total Budget Rs. 58, 20, 740/=

108. Detailed Project Proposal Report Enclosed: Yes

PART II - PROJECT OBJECTIVES, RESEARCH PLAN and DELIVERABLES

200. Objectives

The proposed study deals with the fatigue crack propagation in graphite. The fatigue crack growth curve for graphite would be developed using the principles of fracture mechanics. This would require extensive experimental data. The data from experiments would help in identifying the threshold stress intensity factor for graphite below which there would be no crack propagation and also to classify the different regimes of crack growth. Furthermore, an analytical crack propagation law would be proposed from first principles using the concepts of dimensional analysis. Various parameters related to loading (frequency, amplitude, load ratio), geometry (size, crack length) and material (tensile strength, fracture toughness) would be considered in the analytical model to describe the rate of crack propagation. Since, most of these parameters are random in nature, a probabilistic analysis would be carried out to determine the sensitivity of each parameter to crack growth. The steps involved in this study would include:

1. determination of important elastic and fracture properties of graphite, namely Mode I and Mode II fracture toughness (K_{Ic} and K_{IIc}), specific fracture energy (G_F), length of fracture process zone, the brittleness number, stress-crack opening relationship, R-curve, tensile strength and width of fracture process zone.
2. determination of fatigue crack growth curve through fatigue tests on small compact tension graphite specimens.
3. development of an analytical crack propagation law from first principles to describe the rate of fatigue crack growth.
4. determination of sensitivity of various parameters involved in the crack growth law through probabilistic studies.

210. Describe the yearly Research Plan and identify the Deliverables (Please see Instruction - Sr. No. 14):

A. At PI/ CI's Institution

I Year:

- Hiring of project personal
- Purchase of equipment
- Literature review
- Identification of parameters to be used in the experimental program
- Testing of pilot specimens and freezing of parameters
- Preliminary tests to obtain the elastic and fracture properties of graphite
- **Deliverables: Elastic and fracture properties of graphite; Parameters to be adopted in the experimental program**

II Year:

- Testing of actual specimens to establish the fatigue crack growth curve
- Development of analytical crack propagation models
- Validation of the models using experimental results
- **Deliverables: Fatigue crack growth curve for graphite; Analytical fatigue crack propagation law.**

III Year::

- Parametric studies
- Probabilistic modeling
- **Deliverables: Final report**

B. At PC's Institution.

Ist Year:

IInd Year:

IIIrd Year:

211. Infrastructure facilities related to the project activity available at the PI/CI's Institute:

Power supply to run computers, office space for the two project staff, library facilities and administrative and secretarial support

212. Facilities available at the PC's institution that would be useful to this project:

PART III - BUDGET ESTIMATES

…

300. Details of budget requirements (Please see Instruction - Sr. No. 15 to 21)

Particulars ⇩ Amount in Rs. ⇨	I Year	II Year	III Year	Total
310. Equipment	24,50,000/=	---	---	24,50,000/=
320. Staff Salary JRF:				
SRF:	2,80,800/=	2,80,800/=	3,12,000/=	8,73,600/=
RA:				
330. Technical Assistance	1,08,000/=	1,08,000/=	1,08,000/=	3,24,000/=
340. Consumables	3,00,000/=	5,00,000/=	2,00,000/=	10,00,000/=
350. Travel PI:	55,000/=	55,000/=	55,000/=	1,65,000/=
PC/DC:	25,000/=	25,000/=	25,000/=	75,000/=
360. Contingencies	50,000/=	1,00,000/=	50,000/=	2,00,000/=
370. Overheads	4,82,820/=	1,45,320/=	1,05,000/=	6,50,640/=
380. Grand Total	**37,51,620/=**	**12,14,120/=**	**8,55,000/=**	**58,20,740/=**

BUDGET DETAILS

310. Details of the budget for equipment to be procured by the PI:

Sl.No.	Item	Ist year	IInd year	IIIrd year	Total
Local:	25 kN Servo-hydraulic testing machine Personal computer	24,00,000/- 50,000/=	---	---	24,00,000/= 50,000/=
Imported: Mention currency conversion rate used for estimation					
Total		24,50,000/=			24,50,000/=

340. Details of budget for consumables to be procured by the PI (Amount in Rupees):

Sl. No.	Item	Ist year	IInd year	IIIrd year	Total
1.	Graphite specimens in their final form (Five blocks of 1ftX1ftX3ft at Rs. 80,000 per block plus machining)	2,50,000/=	3,50,000/=	1,00,000	7,00,000/=
2.	Oil change, filter for UTM	---	50,000/=	50,000/=	1,00,000/=
3.	Strain gages, Aluminum plates for fixing LVDT, epoxies etc.	50,000	1,00,000/=	50,000/=	2,00,000/=
	Total	3,00,000/=	5,00,000/=	2,00,000/=	10,00,000/=

350. Details of travel:

Amount in Rupees ⇨	Ist year	IInd year	IIIrd year	Total
351. Proposed number of visits of **PC/DC** to **PI's** Institute	1	1	1	3
351A. Duration of stay (no. of days) during each visit	3	3	3	9
351B. Total funds required	25,000/=	25,000/=	25,000/=	75,000/=
352. Proposed number of visits of **PI to PC/DC's** institute	1	1	1	3
352A. Duration of stay (No. of days) during each visit	3	3	3	9
352B. Total funds required	25,000/=	25,000/=	25,000/=	75,000/=
353. Funds required by **PI** for travel to attend conferences within India.	30,000/=	30,000/=	30,000/=	90,000/=
354. Funds for Other visits (please give details)				

BUDGET JUSTIFICATIONS

310. Equipment:

A 25 kN servo-hydraulic testing machine is required for conducting static and fatigue tests on graphite specimens. A lot of experimental data s required for obtaining the fatigue crack growth curve.

A personal computer for Ph.D. student is required for data keeping and computational work.

320. Staff:

One Ph.D student (SRF) would be employed for carrying out experiments and doing the analytical studies. The

student would be paid Rs. 18, 000/= per month plus 30% HRA for the first two years and rs. 20,000/= per month plus 30% HRA for the third year.

330. Technical assistance:

One technical assistance (Res. 9000/= per month) is required for helping the Ph.D. student in carrying out the experiments and in the day to day maintenance of the equipment.

340. Consumables:

The consumables are required for procuring materials for preparing the specimens. Strain gages, strain gaging kit, solders etc., are required in the experimental work. Aluminum plates are required for preparing targets which help in fixing of COD gage. Oil and filters are required for smooth running of the machine.

350. Travel:

The funds are required for holding project reviews by the project team and to attend one conference in related areas of work.

360. Contingencies:

- It is proposed to acquire recent literature on fatigue and fracture, reliability engineering and other related material.
- Expenses towards advertisement and selection of staff
- Paying tuition fee for the project staff if they are registered students at IISc.
- Other unforeseen expenses which are bound to occur during experimental work.

PART IV - OTHER PROJECTS

410. List all previous projects that are **supported by BRNS or any other funding agency** in which PI is actively participating (either as PI or as CI):

Sl. No.	Title of the project	Total cost	Agency	Present status
1.	Seismic Probabilistic Safety Assessment of Nuclear Power Plants (As CI, PI: Prof. C. S. Manohar)	Rs. 13,04005/=	DAE	Completed
2.	Characterization of Time Dependent Deformations in Concrete Grades Used in Nuclear Power Plants (As CI; PI Prof. A. Ramaswamy)	Rs. 34,51,000/=	DAE	Completed

411. List all projects submitted **during the current financial year by PI to BRNS or any other agency for funding.** Give details on the present status of the application: **None.**

412. Brief description of the **project(s) submitted/sanctioned by/to PI by other agencies**.

Project Title: Quantification of damage for residual life assessment of damaged infrastructures.

Funded by: Centre for infrastructure, sustainable transportation and urban planning, IISc., Bangalore

Project period: January 2010 to December 2011

Brief Description: This project proposal aims to quantify damage in reinforced concrete structures and to propose suitable damage indicators that would help in the assessment of the residual strength of concrete structure.

This involves quantification of the degradation of flexural stiffness in terms of a global damage index defined for the entire beam or column. The primary objective is to obtain an analytical correlation between local damage parameter and the global damage index.. A failure criterion based on fracture mechanics and damage mechanics principles in conjunction with the finite element method is proposed in order to estimate the residual strength of damaged structures.

413. List all previous projects **that are supported by BRNS or any other funding agency in which CI** is actively participating (either as PI or as CI):

No	Title of the project	Total cost	Agency	Present status
1	Vibration based condition assessment and reliability analysis of existing engineering structures	Rs 28.4 lakhs	BRNS	Ongoing 2010-2013 Duration: 3 years
2	Fire resistance and repair of earthquake damaged structures	£146000=00	United Kingdom-India Education and Research Initiative.	Ongoing 2007-2011 Duration: 4 years
3	Aseismic structural reliability analysis of nuclear core support structure	Rs 3.0 lakhs	IGCAR	Ongoing Duration: 1 year

The CI has completed several other funded research projects and a list of these projects is provided in section 510.

414. List all projects submitted **during the current financial year by CI to BRNS or any other agency for funding.** Give details on the present status of the application:

Asif Usmani and C S Manohar (PI-s), Making performance based structural engineering for fire resistance attainable, A collaborative proposal submitted to the UKIERI Innovative partnerships 2011 with participation from IISc and University of Edinburgh and also four industrial partners from India and the UK (total funds requested: £40000.00).

415. Brief description of the **project(s) submitted/sanctioned by/to PI by other agencies**.

The project proposal mentioned in item 414 has the following objectives:

- To develop a simple and clearly defined performance based structural engineering (PBSE) framework for structures subjected to fire including easy to use software tools that will encourage its wider adoption.
- To incorporate a more explicit treatment of uncertainty in the above framework.

The funding available here mainly supports expenses towards international travel and exchange of research students and does not provide funds for equipment/project staff.

PART IV - FACILITIES

416. List of **facilities** that will be extended to the investigators by the implementing institution for the project

A. **Infrastructure facilities**

Sr. No.	Item Name	Yes/No/ NR*	Sr. No.	Item Name	Yes/No/ NR*
1.	Workshop	NR	7.	Telecommunication	Yes
2.	Water & Electricity	Yes	8.	Transportation	NR
3.	Standby power supply	Yes	9.	Administrative l support	Yes
4.	Laboratory space & furniture	Yes	10.	Library facilities	Yes
5.	AC room for equipment	NR	11.	Computational facilities	Yes
6.	Refrigerator	NR	12.	Animal/Glass house	NR
	NR*: Not Required				

B. **Equipment and accessories** available within the Investigator's group/Dept. which can be utilized for the project.

Sr. No.	Name of the Equipment	Model & Make	Year of Purchase

SECTION-B

500. Curriculum vitae (CV) of **Principal Investigator** (PI),

Name: J M Chandra Kishen
Designation: Professor
Date of birth: 4th September 1964
Place of birth: Bangalore
Nationality: Indian
Present post: Professor
Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012
Institution with address: Department of Civil Engineering
Indian Institute of science, Bangalore 560 012.
Telephone no. 080-309 2527
Fax no. 080-3600 404
email: chandrak@civil.iisc.ernet.in

Qualifications

Degree	Year	Institution/University	Subjects
BE	1988	Bangalore University	Civil Engineering
ME	1992	Indian Institute of Science, Bangalore	Civil Engineering (Structural Engg.)
PhD	1996	University of Colorado, Boulder, U.S.A.	Civil Engineering (Structural Engg.)

Experience

Positions held

Designation	Organization	Period
Site Engineer	Ranka Construction Company, Bangalore	1988-1989
Lead Graduate Teacher	University of Colorado at Boulder	1995-1996
Lecturer	IISc, Bangalore	1996-1999
Assistant Professor	IISc, Bangalore	1999-2005
Associate Professor	IISc., Bangalore	2005 – 2011 (Sept.)
Professor	IISc, Bangalore	2011 (Oct) - present

Areas of expertise

- Computational and experimental fracture mechanics
- Fracture Mechanics based crack propagation analysis of bi-material interface systems.
- Finite element modeling and analysis
- Structural rehabilitation

Publications of PI during the last ten years relevant to the project

1. Santosh G. Shah and J. M. Chandra Kishen, 2011, "Fracture Properties of Concrete-Concrete Interfaces Using Digital Image Correlation", International Journal of Experimental Mechanics (Springer), Vol. 55, No. 3, pp. 303-313.

2. Santosh G. Shah, Bhasya V. and J. M. Chandra Kishen, "Tension Softening Parameters for Concrete-Concrete Interfaces", Accepted for publication in ACI Structural Journal..

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23. J. M. Chandra Kishen and Trisha Sain, 2004, "Damage Detection Using Static Test Data", Journal of Structural Engineering, India, Vol. 31, No. 1, pp. 15-21.

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510. Curriculum vitae (CV) of **Co-Investigator** (CI)

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Education

- BE (Civil Engg.), 1982, Karnatak University, India, First Class with Distinction.
- ME (Civil Engg.), 1984, Indian Institute of Science, First Class with Distinction.
- PhD (Faculty of Engineering), 1989, Indian Institute of Science, Bangalore.

Work Experience

Academic positions held at the Indian Institute of Science

- Professor, May 2005-present, Department of Civil Engineering.
- Associate Professor, May 1999-May 2005, Department of Civil Engineering.
- Assistant Professor, May 1993-May 1999, Department of Civil Engineering.

Other positions held at the Indian Institute of Science

- Chairman, December 2010- present, Department of Civil Engineering.
- Chairman, July 2007- December 2010, Centre for Earth Sciences.
- Associate Faculty Member, 2007-present, Centre for Earth Sciences.
- Member Secretary, IISc-IGCAR R & D Cell, 2011-present

Positions held outside the Indian Institute of Science

- Visiting Professor, October 2011, Carleton University, Ottawa, Canada.
- Visiting Scientist, May 2003, Dept. of Civil Engineering, University of Delaware, USA.
- Visiting Associate Professor, June-July, 2003, Dept. of Civil Engineering, The Johns Hopkins University, USA.
- Research Assistant, May 1991-May 1993, Dept. of Engineering Sciences, University of Oxford, UK.
- Scientist, Oct 1990-May 1991, Structural Engineering Research Centre, Chennai, India

Honors

- Member, Editorial Board, Probabilistic Engineering Mechanics (Elsevier)
- Member, Editorial Board, Structural Control and Health Monitoring (Wiley)
- Associate Editor (Structural Dynamics), ISET Journal of Earthquake Technology, (since 2007).
- Associate Editor, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation (Serial Publications).
- Member, Editorial Board, Earthquakes and Structures (from 2010) (Techno Press).
- Sir C V Raman award for young scientists for the year 1999, Instituted by Government of Karnataka, India.
- Member, Technical Committee of Dynamics, Engineering Mechanics Division, American Society of Civil Engineers, 2003-2007.
- Invitations to IUTAM symposia on Nonlinear Stochastic Mechanics, 1995, 2001, 2009.

Research interests

- Structural dynamics: modeling of nonlinearity and uncertainties; computational and experimental methods; inverse problems: structural system identification and damage detection using measured vibration data; statistical energy analysis.
- Stochastic structural mechanics: stochastic FEM; random vibrations; Bayesian filtering; Monte Carlo simulations & variance reduction schemes; structural reliability modeling.
- Earthquake engineering: seismic safety of large scale structures; science of earthquake simulations: hybrid test methods; real time substructuring; fire following earthquakes.

Papers in refereed journals (last ten years)

1. B Radhika and C S Manohar, 2011, Updating response sensitivity models of nonlinear vibrating structures using particle filters, Computers and Structures, 89(11-12), 901-911.
2. H A Nasrellah and C S Manohar, 2011, Finite element method based Monte Carlo filters for structural system identification, Probabilistic Engineering Mechanics, 26 (2011) 294–307.
3. H A Nasrellah and C S Manohar, 2011, Particle filters for structural system identification using multiple test and sensor data: a combined computational and experimental study, Structural Control and Health Monitoring, 18, 99–120.
4. B Radhika and C S Manohar, 2010, Reliability models for existing structures based on dynamic state estimation and data based asymptotic extreme value analysis, Probabilistic Engineering Mechanics, 25, 393-405.
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6. R Sajeeb, C S Manohar and D Roy, 2010, A semi-analytical particle filter for identification of nonlinear oscillators, Probabilistic Engineering Mechanics, 25, 35-48
7. R Sivaprasad, S Venkatesha, and C S Manohar, 2009, Identification of dynamical systems with fractional derivative damping models using inverse sensitivity analysis, Computers, Materials and Continua, 9 (3), 179-207.
8. R Tipireddy, H A Nasrellah and C S Manohar, 2009, A Kalman filter based strategy for linear structural system identification based on multiple static and dynamic test data, Probabilistic Engineering Mechanics, 24, 60-74.
9. R Sajeeb, C S Manohar and D Roy, 2009, A Conditionally linearized Monte Carlo filter in nonlinear structural dynamics, International Journal of Nonlinear Mechanics, 44(7), 776-790
10. R Sajeeb, C S Manohar and D Roy, 2009, Rao-Blackwellization with substructuring for state and parameter estimations of a class of nonlinear dynamical systems, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation, 1(1-2) 2009.
11. S Venkatesha, R Rajender, and C S Manohar, 2008, Inverse sensitivity analysis of singular solutions of FRF matrix in structural system identification, CMES: Computer Modeling in Engineering and Science, 37(2), 113-152.
12. V Namdeo and C S Manohar, 2008, Force state maps using reproducing kernel particle method and kriging based functional representations, CMES: Computer Modeling in Engineering and Science, 32(3), 123-160.
13. S S Panda and C S Manohar, 2008, Applications of meta-models in finite element based reliability analysis, CMES: Computer Modeling in Engineering and Sciences, 28, N0. 3, 161-184.
14. B Radhika, S S Panda and C S Manohar, 2008, Time variant reliability analysis using data based extreme value analysis, CMES: Computer Modeling in Engineering and Sciences, 27(1-2),79-110.
15. S Ghosh, C S Manohar and D Roy, 2008, Sequential importance sampling filters with a new proposal distribution for parameter identification of structural systems, Proceedings of Royal Society of London, A, 464, 25-47.
16. V Namdeo and C S Manohar, 2007, Nonlinear structural dynamical system identification using adaptive particle filters, Journal of Sound and Vibration, 306, 524-563.
17. R Sajeeb, C S Manohar and D Roy, 2007, Control of Nonlinear Structural Dynamical Systems with Noise Using Particle Filters, Journal of Sound and Vibration, 306, 25, 111-135.
18. S Ghosh, D Roy and C S Manohar, 2007, New forms of extended Kalman filter via transversal linearization and applications to structural system identification, Computer Methods in Applied Mechanics and Engineering, 196, 5063-5083.
19. M Manjuprasad and C S Manohar, 2007, Adaptive random field mesh refinements in stochastic finite element reliability analysis of structures, CMES: Computer Modeling in Engineering and Sciences, 19(1), 23-54.
20. R Sajeeb, D Roy and C S Manohar, 2007, Numerical aspects of a real-time substructuring technique in structural dynamics, International Journal of Numerical Methods in Engineering, 72, 1261-1313.
21. A M Abbas and C S Manohar, 2007, Critical vector random earthquake loads for parametrically excited structures, Structural Safety, 29(1), 32-48.
22. Sayan Gupta and C S Manohar, 2006, Reliability analysis of randomly parametered linear vibrating systems subjected to stochastic excitations, Journal of Sound and Vibration, 297(3-5), 1000-1024.
23. C S Manohar and D Roy, 2006, Nonlinear structure system identification using Monte Carlo filters, Sadhana, Academy Proceedings in Engineering, Indian Academy of Science, 31(4), 399-427.
24. Sayan Gupta and C S Manohar, 2005, Extreme value distribution of von Mises stress in randomly vibrating structures, Journal of Vibration and Acoustics, Transaction of ASME, 127 (6), 547-555.

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26. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part I: Linear structures, Journal of Sound and Vibration, 287, 865-882.
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28. C S Manohar and R Ghanem, 2005, Multivariate probability distribution of ordered peaks of vector Gaussian random processes, Probabilistic Engineering Mechanics, 20, pp 87-96.
29. Saikat Saha and C S Manohar, 2005, Inverse reliability design of structures subjected to partially specified earthquake loads, Probabilistic Engineering Mechanics, 20, 19-31.
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32. S Ammanagai, S Venkatesha, and C S Manohar, 2004, Analytical and experimental investigations of structural damages in beams and built-up structures using vibration data, 31(1), 73-84, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
33. Luna Majumder and C S Manohar, 2003, A time domain approach for damage detection in bridge structures using vibration data with moving vehicle as an excitation source, 268, 699-716, Journal of sound and Vibration.
34. C S Manohar, S Venkatesha and S Sadasivan, 2003, Finite element analysis of vehicle-structure interactions during launching of remotely piloted air-vehicles, 30(1), 1-6, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
35. C S Manohar, R Ravi and Ch Srinivas, 2003, Nonlinear structures under random differential support motions and determination of critical input models, 2(3), 171-198, Advances in vibration engineering, Vibration Institute of India.
36. Luna Majumder and C S Manohar, 2002, Nonlinear reduced models for beam damage detection using data on moving oscillator-beam interactions, 82, 301-314, Computers and Structures.
37. Sayan Gupta and C S Manohar, 2002, Dynamic stiffness method for circular stochastic Timoshenko beams: response variability and reliability analyses, Journal of Sound and Vibrations, 253(5), 1051-085.
38. Abbas M and C S Manohar, 2002, Investigations into critical excitation models within deterministic and probabilistic frameworks: single point excitations, Earthquake Engineering and Structural Dynamics 31, 813-832.
39. A M Abbas and C S Manohar, 2002, Critical spatially varying earthquake load models, Journal of Structural Engineering, Structural Engineering Research Centre, Madras, 29, 39-52.

List of funded projects (last ten years)

1. C S Manohar and S Venkatesha, 2010-2013, Vibration based condition assessment and reliability analysis of existing structures', Funded by Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India.
2. C S Manohar, 2010, Development of a video based course on Stochastic Structural Dynamics, funded by National Programme on Technology Enhanced Learning, Government of India.
3. 2007-2010, Fire resistance and repair of earthquake damaged structures, United Kingdom-India Education and Research Initiative (UKIERI) Collaborative Research Awards 2007, Jointly developed with University of Edinburgh, IIT Roorkee and IISc, Bangalore; Team: Edinburgh: A S Usmani, J L Torero, P Pankaj, J F Chen, and M Gillie; IIT Roorkee: Pradeep Bhargava, Yogendra Singh, Umesh Kumar Sharma; IISc: C S Manohar and Ananth Ramaswamy.
4. C S Manohar and K Venkatraman, 2006-2008, Analytical prediction of squeak and rattle noise intensity in a seat belt retractor system, Funded by Delphi Automotive Systems, India.
5. C S Manohar, 2006-2008, Structural Reliability Under Seismic Loads, Funded by Cranes Software India Limited.
6. C S Manohar and V R Sonti, and A R Upadhya, 2005-2009, Modeling of nonlinearity in experimental structural dynamics, Aeronautical Research and Development Board, Government of India.
7. J M Chandra Kishen, Ananth Ramaswamy, C S Manohar, and D Roy, 2006-2009, Condition monitoring of railway bridges, Funded by Indian Railways (South Central Division).
8. C S Manohar and K Venkatraman, 2006, Acoustic vibration of sodium to air heat exchangers, Funded by IGCAR.

9. C S Manohar and K Venkatraman, 2008, Dynamic analysis of rotating parts of a turbine, Funded by Bharath Heavy Electricals Limited, Bhopal.
10. D Roy and C S Manohar, 2004-2007, Development of numerical methods for structural reliability analyses, Funded by Board of Research in Nuclear Studies, Department of Atomic Energy, Government of India.
11. C S Manohar and J M Chandra Kishen, 2002-2006, Seismic Probabilistic Safety Assessment (PSA) of nuclear power plants, Funded by Board of Research in Nuclear Studies, Department of Atomic Energy, Government of India.
12. C S Manohar and S Venkatesha, 2006, Testing and model validation for simple brackets and lectures on techniques and method used**,** Funded by John F Welch Technology Centre, General Electricals India, Bangalore.
13. C S Manohar, D Roy, and S Venkatesha, 2006, Environmental vibration survey at the National Centre for Biological Sciences at the proposed site for installing an electronic microscope, Bangalore.
14. C S Manohar and V R Sonti, 2003-2005, Bayesian updation of finite element sub-structure assemblies using qualification test data, Funded by Indian Space Research Organization-Indian Institute of Science Space Technology Cell.
15. C S Manohar, 2001-2004, Structural damage detection using vibration data and probabilistic health assessment, Funded by Council of Scientific and Industrial Research, Government of India.
16. C S Manohar and Kartik Venkatraman, 2002-2004, Vibration response prediction in a flight vehicle, Funded by Environmental Test Laboratory, Regional Research Centre, Hyderabad, Defence R & D Organization, Government of India.

520. Curriculum vitae (CV) of **Principal Collaborator** (PC)

SECTION-C

CERTIFICATE-1 (Submit single hard copy only**)**
Certificate from the Head of the Institution of the Principal Investigator (PI) and Co-Investigator (CI) from Non-DAE Institution (Please see Instruction - Sr. No.4-6)

...

Project Title: **Studies on Fatigue Crack Growth in Graphite**

(1) Certified that this Institution agrees to the participation of

Prof. J. M. Chandra Kishen (PI) **Prof. C. S. Manohar (CI)**

Dept. of Civil Engineering
Indian Institute of Science
Bangalore 560 012

for the above project which is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS).

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) Certified that the management takes the responsibilities for the timely submission of audited (by external Chartered Accounted or Statutory Government Auditor) statement of account (SA), utilisation certificate (UC), details of staff recruited and equipment purchased for each year as well as the audited (by external Chartered Accounted or Statutory Government Auditor) consolidated SA and UC for the final year.

(4) **Particulars of University Bank A/c are as follows (Please see Instruction - Sr. No.7):**

a) Name of Account Holder:

b) Account No.:

c) Bank Name and Branch Address:

d) Branch code:

e) IFS Code: (16 digits)

Date:

Place:

Name & signature of the
Head of the institution
or his authorised nominee

Seal:

Note: For Multi-Centre projects, similar certificate is needed from all the participating institutions.

CERTIFICATE-2 (Submit single hard copy only**)**

Certificate from the Head of the Institution of Principal Collaborator (PC) /Departmental Coordinator (DC) from DAE Institution

(Please see Instruction - Sr. No.7)

....

Project Title:

(1) Certified that this Institution agrees to the participation of Prof./Dr. _____ Department/Address _____ as Principal Collaborator (PC)/ Departmental Coordinator (DC) for the above project that is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS) by Prof./Dr. _____ Department/Address _____ as Principal Investigator (PI) .

The PC/ DC shall coordinate for timely submission of yearly progress reports and financial documents towards meaningful conclusion of the project as scheduled.

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) This institution assures to undertake the financial and other management responsibilities of the part of the project work that will be conducted in this institution.

(4) This Certificate is being issued with approval of the Group Board or the Group Board approval shall be taken, after the project is sanctioned by BRNS.

Date:

Place:

Name & signature of the
Head of the DAE institution/
Head of the Group

Seal:

Annexure to item 200: Details of the project

Studies on Fatigue Crack Growth in Graphite

Summary

It is well known to engineers that fatigue accounts for majority of material failures. Fatigue failure is characterized by slow but steady crack propagation in the weaker section of structural components due to the action of cyclic loads. Although, the nominal stress may be well below the yield limit of the material, the stresses may be high enough locally or near an existing crack tip causing further propagation of crack, eventually leading to failure. In the case of metals and ceramics, fatigue fracture has been studied extensively but for graphitee, however, the knowledge of fatigue fracture is limited. The available literature, on the studies related to fatigue behavior of graphite using principles and concepts of fracture mechanics is rather limited and have been mainly phenomenological. Further, due to difference in mechanisms in fatigue crack propagation in graphite and metals, the existing models developed for metals can not predict the results for graphite accurately. Another important issue lies in the empirical nature of the mathematical models without any physical/mathematical basic thereby, limiting the universality. Often, the involved parameters in the empirical laws do not give any physical meaning in the context of crack growth mechanism. Moreover, without knowing the physical meaning of the quantity under consideration and their influence on the crack propagation, interpretations can not made for different scale. It is of prime importance to highlight such issues in the formulation of mathematical models. Further, very few attempts have been made to study fatigue crack propagation by using global energy concept. Non-homogeneity at small scales and the presence of a process zone in graphite necessitates the use of global energy approach instead of local stress concept.

The main objectives of the present work are

- To conduct experiments on graphite specimens under static and fatigue loading in order to evaluate its elastic and fracture properties. And to obtain the fatigue crack growth curve. Parameters such as the loading ratio, frequency of applied loading, the size of specimen would be studied experimentally.
- To propose a fatigue crack propagation law for graphite when subjected to constant and variable amplitude loading using the concepts of dimensional analysis. This law takes into consideration the effects of tensile strength, fracture toughness, loading ratio and most importantly the structural size. A relationship would be obtained between the above parameters using the principles of self-similarity. The model initially derived for constant amplitude cyclic loading cases, would be eventually modified to include the effects of intermittent overloads during loading cycle. The proposed law would be validated with experimental results of different investigators that are available in the literature.
- To study the sensitivity of different parameters using a probabilistic analysis.

Background

Fatigue phenomenon is a gradual, permanent, micro structural change that takes place in a material due to the application of repeated loading. In the case of brittle materials like graphite, due to inhomogeneous nature and

presence of pre-existing structural defects, the crack initiation phase is generally not considered in the estimation of fatigue life unlike comparatively more homogeneous materials like steel. Due to the complexities involved in the nature and behavior of the subject of graphite, fatigue is not a very well explored topic.

The conventional approach to handle fatigue problems is based on safe life approach (S-N curve) which essentially does not differentiate between crack initiation, propagation and final failure. Moreover, the equations evolved from S-N curve concept do not consider the fundamental material parameters in the design, as a result of which the information meant for one design case is not applicable to other design cases with changing applied loading and boundary conditions. With the advent of fracture mechanics approach, the design of structures encountering fluctuating stresses has changed the direction and mechanistic methods have been proposed to predict the crack propagation behavior along with the life prediction. Following this methodology, fatigue failure is prevented even without keeping higher safety margins by using damage tolerant mechanism. The theory behind the mechanism is to predict the fatigue crack propagation (FCP) as well as the number of load cycles required for an existing crack at a critical location to reach critical crack length leading to the failure of the structure.

The crack growth curve of a ductile structural component when subjected to fatigue loading depicts a sigmoidal pattern. This curve can be divided into three distinct regions namely sub-threshold crack propagation (short crack), stable crack propagation (long crack) and unstable crack propagation depending on the crack propagation rate. Most of the fatigue life is spent before the formation of long cracks. Hence, from damage tolerant point of view, crack initiation and early crack propagation (short crack stage) phase are the most important and correct concepts need to be developed for reliable fatigue life assessment. The commonly used procedures for fatigue life computation make use of the same growth models for both small as well as long cracks and various studies have proved this to be inappropriate. Short cracks exhibit a considerably higher growth rate than when computed on extrapolation of the conventional crack growth models developed for long cracks. Furthermore, rapid crack propagation occurs following an exponential law in third unstable crack propagation zone. Hence, each zone in the crack growth phenomenon needs to be modeled appropriately by considering all the influencing parameters.

The crack growth models derived using the cumulative fatigue damage (CFD) approach and fatigue crack propagation (FCP) approach are observed to be mostly empirical in nature thereby making the equations inhomogeneous. In case of brittle materials like graphite, which exhibit size effect, the crack propagation models developed using a particular experimental data set can not be applied for different loading and structural sizes without including the corresponding governing parameters in the formulation. Most often, the existing crack growth models do not involve the appropriate quantities which are important from design perspective rather, they are obtained through best fit with arbitrarily defined parameters without having physical meaning. Further, the existing analytical models to estimate fatigue life for graphite are based on linear elastic fracture mechanics criterion. Heterogeneity and presence of process zone in graphite necessitates the use of non-linear fracture parameters and global energy approach instead of local stress concept. The use of energy based criterion is more appropriate for analytical and computational modeling of graphite like brittle materials. Development of an unified crack growth model for graphite to define the entire crack growth curve is one of the challenging tasks.

It is aimed in the present proposal to address the difficulties by developing a fatigue crack propagation law that combines all the important parameters related to the loading as well as geometry using the theory of fracture mechanics and the concepts of dimensional analysis. A probabilistic study is proposed to be conducted in order to evaluate the most sensitive parameters for fatigue crack propagation in graphite.

A brief review of current state of the art

The first and most commonly used fatigue law for metals based on fracture mechanics concepts relating the crack length increment per load cycle (*da/dN*) to the applied stress intensity factor range (*ΔK*) was developed by Paris and Erdogan [1], and is given by

$$\frac{da}{dN} = C(\Delta K)^m$$

where *a* is the crack length; *N* is the number of load cycles and *C* and *m* are material constants. The fatigue crack growth curve is sigmoidal in nature with three distinct regions. Paris law holds in the intermediate range (zone II) of *ΔK* where there is little influence of material micro-structure and loading ratio and hence the parameters *C* and *m* are generally considered as material constants. Paris law is found to be applicable for most of the ductile materials like metals.

Application of the commonly used Paris law in metals to brittle materials like ceramics and concrete has been done by many researchers [2,3,4]. Since the fatigue crack propagation rate depends on applied stress ratio, the whole effect of stress range is incorporated through a single relation in the Foreman law [5] and Walker law [6] through stress intensity factor and maximum stress .

The fatigue mechanisms in brittle materials being different from the metallic observations, experimental/analytical studies on ductile materials can not be used to understand their behavior under cyclic loading conditions. With the application of cyclic loading, the physical changes taking place in concrete like brittle material macro-structure has been presented by Beres [7] though an experimental study. These changes can be described qualitatively by means of strains representing the volumetric changes in the specimen and variation of strength. An increase of strength is observed in the lower stress range up to a few load cycles followed by a reduction in strength with subsequent increase in load cycles.

Analytical investigations of a microstructure based brittle fracture model has been done by Ishihara et al. [8] for predicting the strength of graphite under varying stress gradient. The stress gradient was produced by changing different stress combination of tensile and bending stresses. Parameters such as grain size, pore size and pore distribution have been used after determining them using image analysis and microstructural observations. It was concluded that the Weibull theory and the fracture model yielded almost the same strength.

Hodgkins et al. [9] have used X-ray microtomography (XRT) and electronic speckle pattern interferometry (ESPI) to study the crack propagation behaviour of Gilsocarbon nuclear graphite. The XRT was used to observe three-

dimensional crack shape within the specimen while the ESPI has been used to study the strain distributions and their development around growing cracks. Permanent strains were observed near the crack tips along with crack bridging ligaments in the crack wake. R-curve behaviour was interpreted using these observations.

Open problems

Although fracture studies on graphite has been reported in the literature, very little information is available on the fatigue crack growth curves and fatigue crack propagation models. Especially, the threshold limits of stress intensity factor range and the behaviour of short cracks in graphite is not well explored. The crack propagation laws are rather empirical and need to be developed from first principles using rational theories of fracture mechanics and dimensional analysis. The uncertainty issues involving material and loading parameters are needed to be addressed.

Importance of the project to DAE

Components of nuclear power plants make use of graphite as one of their primary materials. These components are subjected to varying amplitude of loads. Hence, it is important that the basic fracture and fatigue properties are understood through experimental investigations and analytical studies.

References

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9. Hodgkins A., Marrow J., Mummery P., Marsden B., Fok A. and Babout L. (2004). “Fracture behavior of nuclear graphite.” Proceedings of the second international topical meeting on high temperature reactor technology, Beijing, China, September 22 – 24.

CRP on Uncertainty Analysis of Engineering and Environmental Systems

Project-5

Uncertainty quantification in multiscale analysis of nanocomposite materials

A project proposal submitted to

BOARD OF RESEARCH IN NUCLEAR SCIENCES
Department of Atomic Energy
Government of India

By

Dr Debraj Ghosh (PI)
Professor J M Chandra Kishen (Co-I)

Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

PC: Dr. M.K. Samal, RSD, BARC
Co-PC: Shri Rohit Rastogi, RSD, BARC

August 2011

SECTION-A

PART I – PROJECT OVERVIEW (Please see Instruction - Sr. No. 8)

100. Advisory Committee Code Number (Please see Instruction - Sr. No. 9): **36**

101. Title: Uncertainty quantification in multiscale analysis of nanocomposite materials

102. Key Words & Name of 3 Referees :

Key Words : Uncertainty quantification, computational mechanics, probabilistic mechanics, multiscale, molecular dynamics.

Name of 3 Referees

1. Prof. Baidurya Bhattacharya, Associate Professor , Department of Civil Engineering, Indian Institute of Technology, Kharagpur 721302, Phone: (03222) 28-3422, Fax: (03222) 28-2254, Email: baidurya@iitkgp.ac.in

2. Dr. Sayan Gupta, Assistant Professor , Department of Applied Mechanics, Room No. MSB- 229, Indian Institute of Technology Madras, Chennai 600036, Phone: (044) 2257 4055, Email: sayan@iitm.ac.in, gupta.sayan@gmail.com

3. Prof. A Meher Prasad, Professor, Department of Civl Engineering, Indian Institute of Technology Madras, Chennai, 600036, Phone ; (044) 2257 4260, Email: prasadam@iitm.ac.in

103. Project Summary:

This project is aimed at developing an uncertainty quantification tool for multiscale analysis in a nanocomposite material made up with carbon nanotubes (CNT) in an Alumina matrix, with a potential application being a quoting material. In the multiscale analysis, the nanotube will be analysed using molecular dynamics (MD), and the metal matrix will be modeled and analysed using the finite element (FE) method. Broadly the work will have two parts (1) studying the effect of uncertainties in the behavior (such as elastic response, buckling) of the CNTs, (2) studying the effects of these uncertainties in the nanocomposite through a multiscale analysis. A probabilistic framework will be used to model and analyse uncertainty. A homogenisation method will be used for multiscale analysis. For the molecular dynamics simulation, the freely available computer code LAMMPS will be used, whereas the FE codes will be written in-house, at least in the first phase. Later on an attempt will be made to couple ABAQUS with the atomistic code for multiscale analysis. Among the sources of uncertainty, defects, chirality, random orientation, distribution of CNTs, heterogeneity in the properties of the alumina matrix will be considered.

Personal Details:

		Name	Address	e-mail	Phone	Fax
104.	**PI**	Dr. Debraj Ghosh	Department of Civil Engineering Indian Institute of Science Bangalore 560012	dghosh@civil.iisc.ernet.in	080-2293-2818	080-2360-0404
105.	**CI**	Prof. J M Chandra Kishen	Department of Civil Engineering Indian Institute of Science, Bangalore 560012	chandrak@civil.iisc.ernet.in	080-2293-3117	080-2360-0404
106.	**PC**					

107. Total Budget Rs. 24,25,640

108. Detailed Project Proposal Report Enclosed: Yes

TECHNICAL INFORMATION OF THE PROJECT IN DETAIL

This project is aimed at uncertainty quantification in analysis of alumina (aluminum oxide) - carbon nanotube (CNT) nanocomposite. The reinforcement of CNT improves ductility, wear resistance, and fracture toughness, which makes this nanocomposite as a suitable candidate for various applications such as coating [1-3]. Due to the presence of two materials of very different length scales, studying the mechanical behavior of a nanocomposite naturally invokes a multiscale method [4]. Due to manufacturing variability, limited knowledge about the physics, there are uncertainties in both at the continuum matrix level (macro-scale) and the nanotube level (nano-scale) [5-8]. Moreover, once the nanotubes are mixed with the alumina (or any other ceramic/metal/polymer) matrix additional uncertainties arise in terms of orientation of the nanotubes, volume fraction, clustering, interface bonding, for example. Therefore, a multiscale analysis of nanocomposites must take into account these uncertainties for a reliable prediction of a behavior. However, in order to perform a successful multiscale analysis, it is important to understand the mechanics at both nano and macro scales considering uncertainties into account. The proposed work has two stages : (i) an uncertainty quantification will be carried out for the CNTs, and (ii) a class of multiscale analysis techniques called homogenisation will be explored for its ability to handle uncertainties in both the length-scales. For the CNTs both the linear and nonlinear behavior will be studied, whereas for the nanocomposite mainly the linear regime will be explored. For the nanocomposites the final quantities of interest will be probability distributions of the elastic properties. Suitability of the homogenisation technique for capturing nonlinear behavior of the nanocomposite will also be explored, which will serve as a prelude to a future deeper exploration to more complex mechanics such as fracture. The uncertainty will be handled in a probabilistic framework.

The mechanics of CNTs is best studied using a molecular dynamics (MD) simulation. In this method, the equation of motion is written at the molecular (or atomistic level), and the resulting coupled system of time-dependent ordinary differential equations (ODEs) are solved using a time-integration scheme [10, 12]. One popular choice of the time-integrator is the Velocity-Verlet method. An interatomic potential is needed for an MD simulation. Here for the CNTs the REBO and Tersoff/Tersoff-Brenner potentials will be used. Some major sources of uncertainties in the CNTs are vacancy defects, Stone-Wales defects, variability in chirality and dimensions among different tubes. Some of these uncertainties and their effect on the mechanical characteristics of the CNTs will be studied. One specific example of such study is to look at the effect of uncertainty on the buckling behavior through MD simulations (probabilistically). A few major computational challenges in this example are (i) automatic detection of the buckling strain from the time-history output of the MD simulations, (ii) total computational cost. The MD simulation itself is computationally very expensive, and the presence of uncertainty will invoke multiple MD simulations (for instance, in a Monte Carlo (MC) simulation over an ensemble of MD simulations), which will exacerbate the cost. Although there are a number of works on studying the buckling behavior of CNTs and effect of uncertainties [9], this kind of computational study on the probabilistic behavior of the buckling strain has not yet been addressed in the literature. In this regard, this will be a new contribution in this work. Similarly a few other such mechanical behavior of the CNTs will be studied in a probabilistic framework. In the

proposed work the MD computation will be done using the open-source program LAMMPS developed by the Sandia National Laboratories [10]. For the probabilistic analysis, an MC approach (acting as the outer loop of the LAMMPS MD simulations) will be adopted first. Then avenues for reducing the total computational cost will be explored; one possible way might be exploring variance-reduction techniques.

The multiscale methods can be broadly classified into two groups : hierarchical and concurrent. In the hierarchical methods, the mechanics at one scale (usually the finer scale) is modeled using an averaging technique, and this model is fed into the other scale (the coarser scale), where the further analysis is carried out. Examples of such methods are homogenisation methods [11]. In the concurrent methods, all the scales (fine and coarse) are resolved simultaneously, with a mechanism of information exchange among different scales in place. For example, the bridging scale method [12]. There have been a number of detailed survey and numerical comparisons among various multiscale methods [4, 13]. Although often there is a considerable overlap among different methods in terms of the final goal and mechanism, depending upon the type of a problem to be solved, some methods have advantages over the others. For example, the homogenisation methods are better applicable where an average property such as the equivalent Young's modulus of a heterogeneous material is sought, whereas the bridging-scale method is more suitable for applications where a localised behavior such as dynamic crack propagation is of interest. In a material with heterogeneity only in the continuum scale, the uncertainty in heterogeneous properties (such as elastic modulus, density) can be modeled using a random process or field. Then an uncertainty propagation tool is adopted to predict the response of the material under external loading. Some popular choices of the propagator are MC, stochastic finite element methods (SFEM), perturbation technique. Whereas in a multiscale setting, when uncertainties at different length scales are to be considered, the uncertainty propagation tools are still in their infancy. However, this issue, including applications to nanocomposites, is recently drawing interest among the researchers, for example [14-18]. One major goal of this work is to address this issue --- that is, to find a computationally efficient strategy for performing multiscale analysis of nanocomposites considering the uncertainties.

In this work, only the homogenisation methods will be explored since the current interest is limited only to the bulk properties of the nanocomposite. In a typical homogenisation method a representative volume element (RVE) is chosen first. Then based upon certain assumptions on the properties and distribution of the matrix and the reinforcements, average estimates of the material properties of this RVE are found. These properties are then fed to a finite element (FE) code to find the response at the macro scale. In the proposed work the Mori-Tanaka approach [10] will be chosen as the first candidate, and more approaches will be explored further. The quantities of interest at the nanometer level will be resolved using the methods described earlier (MD simulation). A new contribution of this proposed work over the existing literature will be to find the effect of uncertainties in the CNT properties (such as defects) to the nanocomposites. In addition to the uncertainties in the nanotubes, their random orientation and volume fraction will be taken into account. Interface bonding between CNT and alumina itself is a complex physics [19, 20] and therefore is another potential source of uncertainty. However, modeling this interface behavior will need a more detailed study. Due to the limited time and resources, this uncertainty will not be

treated in this work. Instead, a mitigating assumption such as complete or partial bonding will be assumed.

The finite element programs will initially be written in-house, primarily in C++. However, should the need arise, an open source or a commercial software (such as ABAQUS) will be adopted. Even though a commercial finite element program is used, as any multiscale analysis, a significant programming will be required.

References:

[1] Balani K, Bakshi SR, Chen Y, Laha T, and Agarwal A, Role of powder treatment and CNT dispersion in the fracture toughening of plasma-sprayed aluminum oxide–carbon nanotube ceramic nanocomposite, J. Nanosci. Nanotech. 7, 2007: 3553–3562.

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PART II - PROJECT OBJECTIVES, RESEARCH PLAN and DELIVERABLES

200. List of Objectives :

A. Investigating the effects of uncertainties at different length scales --- atomistic, and continuum to be precise --- on the behavior of a nanocomposite material.

B. Developing an efficient computational technique for uncertainty propagation in a multiscale computation.

210. Describe the yearly Research Plan and identify the Deliverables (Please see Instruction - Sr. No. 14):

A. At PI/ CI's Institution

Ist Year: Modeling and finding the effects of uncertainties in the carbon nanotubes (CNTs). Objects of interest are probabilistic nature of buckling and elastic behavior.

IInd Year: Exploring homogenisation techniques and implementation for nanocomposites.

IIIrd Year: Working on uncertainty quantification in the multiscale analysis.

B. At PC's Institution.

Ist Year:

IInd Year:

IIIrd Year:

Deliverables : The computer programs developed for the project.

211. Infrastructure facilities related to the project activity available at the PI/CI's Institute: A parallel computer with 104 cores.

212. Facilities available at the PC's institution that would be useful to this project:

PART III - BUDGET ESTIMATES

…

300. Details of budget requirements (Please see Instruction - Sr. No. 15 to 21)

Particulars ⇩ Amount in Rs.⇨	I Year	II Year	III Year	Total
310. Equipment	4,50,000	1,00,000	1,00,000	6,50,000
320. Staff Salary JRF:				
SRF:	2,80,800	2,80,800	3,12,000	8,73,600
RA:				
330. Technical Assistance				
340. Consumables	75,000	75,000	75,000	2,25,000

350. Travel PI:	55,000	55,000	55,000	1,65,000
PC/DC:				
360. Contingencies	75,000	75,000	75,000	2,25,000
370. Overheads	1,29,120	76,620	81,300	2,87,040
380. Grand Total	**10,64,920**	**6,62,420**	**6,98,300**	**24,25,640**

BUDGET DETAILS

310. Details of the budget for equipment to be procured by the PI:

Sl.No.	Item	Ist year	IInd year	IIIrd year	Total
Local:		ABAQUS License, Rs. 3,50,000/- Two desktop computers, Rs. 1,00,000/-	Parts of the existing computer cluster, including power supply. One desktop computer. ~1,00,000/-	One laptop computer and a printer/scanner. ~1,00,000/-	6,50,000/-
Imported: Mention currency conversion rate used for estimation					
Total		4,50,000/-	1,00,000/-	1,00,000/-	6,50,000/-

340. Details of budget for consumables to be procured by the PI (Amount in Rupees):

Sl. No.	Item	Ist year	IInd year	IIIrd year	Total
	Computer peripherals, printing cost, maintenance, other accessories.	75,000/-	75,000/-	75,000/-	2,25,000/-
	Total	75,000/-	75,000/-	75,000/-	2,25,000/-

350. Details of travel:

Amount in Rupees ⇨	Ist year	IInd year	IIIrd year	Total
351. Proposed number of visits of **PC/DC** to **PI's** Institute				
351A. Duration of stay (no. of days) during each visit				
351B. Total funds required				
352. Proposed number of visits	1	1	1	3

of **PI to PC/DC's** institute				
352A. Duration of stay (No. of days) during each visit	3	3	3	9
352B. Total funds required	20,000	20,000	20,000	60,000
353. Funds required by **PI** for travel to attend conferences within India.	35,000	35,000	35,000	1,05,000
354. Funds for Other visits (please give details)				

BUDGET JUSTIFICATIONS

310. Equipment: ABAQUS software license, three desktop computers, one laptop computer, a printer/scanner, parts of the existing cluster computer including power supply.

320. Staff: One SRF will be hired, desirably a candidate leading to the PhD degree. The salary includes HRA as per norms**.**

330. Technical assistance: Nil.

340. Consumables: Computer accessories, printing cost, maintenance, other accessories.

350. Travel: PI : Attending conferences and visiting PC whenever necessary.

360. Contingencies: Buying books, advertisement and selection an SRF, and his/her fees to the institute, should he/she choose to pursue PhD, local hospitality of PC during his/her visit, membership fees of professional bodies.

PART IV - OTHER PROJECTS

410. List all previous projects that are **supported by BRNS or any other funding agency** in which PI is actively participating (either as PI or as CI):

Sl. No.	Title of the project	Total cost	Agency	Present status
1.	Probabilistic behavior of modal properties of an airframe	Rs. 9.5 Lakh	ISRO–IISc Space Technology Cell	Ongoing
2.	Structural safety assessment of large structures using the spectral stochastic finite element method,	~ Rs. 13 Lakhs,	BRNS,	Ongoing.

411. List all projects submitted **during the current financial year by PI to BRNS or any other agency for**

funding. Give details on the present status of the application:

Sl. No.	Title of the project	Total cost	Agency	Present status

412. Brief description of the **project(s) submitted/sanctioned by/to PI by other agencies**. (Please see Instruction - Sr. No.22): None.

413. List all previous projects **that are supported by BRNS or any other funding agency in which CI** is actively participating (either as PI or as CI):

Sl. No.	Title of the project	Total cost	Agency	Present status
1.	Seismic Probabilistic Safety Assessment of Nuclear Power Plants (As CI, PI: Prof. C. S. Manohar)	Rs. 13,04005/=	DAE	Completed
2.	Characterization of Time Dependent Deformations in Concrete Grades Used in Nuclear Power Plants (As CI; PI Prof. A. Ramaswamy)	Rs. 34,51,000/=	DAE	Completed

414. List all projects submitted **during the current financial year by CI to BRNS or any other agency for funding**.

Project Title: Quantification of damage for residual life assessment of damaged infrastructures.

Funded by: Centre for infrastructure, sustainable transportation and urban planning, IISc., Bangalore

Project period: January 2010 to December 2011

Brief Description: This project proposal aims to quantify damage in reinforced concrete structures and to propose suitable damage indicators that would help in the assessment of the residual strength of concrete structure.

This involves quantification of the degradation of flexural stiffness in terms of a global damage index defined for the entire beam or column. The primary objective is to obtain an analytical correlation between local damage parameter and the global damage index.. A failure criterion based on fracture mechanics and damage mechanics principles in conjunction with the finite element method is proposed in order to estimate the residual strength of damaged structures**.**

415. Brief description of the project(s) submitted/sanctioned by/to CI by other agencies. (Please see Instruction - Sr.No.22): None.

PART IV - FACILITIES

416. List of **facilities** that will be extended to the investigators by the implementing institution for the project

A. **Infrastructure facilities**

Sr. No.	Item Name	Yes/No/ NR*	Sr. No.	Item Name	Yes/No/ NR*
1.	Workshop	NR	7.	Telecommunication	Partial
2.	Water & Electricity	Yes	8.	Transportation	NR
3.	Standby power supply	No	9.	Administrative l support	Yes
4.	Laboratory space & furniture	Yes	10.	Library facilities	Yes
5.	AC room for equipment	Yes	11.	Computational facilities	Partial
6.	Refrigerator	NR	12.	Animal/Glass house	NR
	NR*: Not Required				

B. **Equipment and accessories** available within the Investigator's group/Dept. which can be utilized for the project.

Sr. No.	Name of the Equipment	Model & Make	Year of Purchase
1	Cluster computer	Intel processors, 104 cores	2009

SECTION-B

(Please see Instruction - Sr. No.23 & 24)

500. Curriculum vitae (CV) of **Principal Investigator** (PI),

Name & Designation: Debraj Ghosh, Assistant Professor, Dept of Civil Engineering, Indian Institute of Science, Bangalore.

Date & Place of Birth: 4th July, 1976, West Bengal, India.

Nationality: India

Present post: Assistant Professor

Institution with address: Dept of Civil Engineering, Indian Institute of Science, Bangalore 560012.

Telephone No. (with STD code): 080-2293-2818 Fax No.: 080-2360-0404

E-mail: dghosh@civil.iisc.ernet.in

Qualifications: PhD in Civil Engineering 2005, The Johns Hopkins University, Baltimore, USA

M.E. in Civil Engineering (Structures) 2001, Indian Institute of Science, Bangalore, India.

B.E. in Civil Engineering 1997, Bengal Engineering College, Howrah, India

Experience: Postdoctoral Scholar, Dept of Mechanical Engineering, Stanford University, Stanford, USA, Oct 2005-Sept 2008.

Visiting Scholar, Dept of Civil and Environmental Engineering, University of Southern California, Jan - Sept 2005

Research Assistant, Dept of Civil Engineering, The Johns Hopkins University, 2002-2005

Teaching Assistant, Dept of Civil Engineering, The Johns Hopkins University, 2001-2003.

Software Engineer, Geometric Software Soln. Ltd., Pune, India, 2001.

Design Engineer, Arora Associates, New Delhi, India, 1997-1998.

Awards & Fellowships:

Won the USACM Travel Award to attend the 8th World Congress on Computational Mechanics, 2008. This was a nationwide competition (in US) among the young researchers.

Stood 1st in M.E. Structural Engineering, Indian Institute of Science, 2001

Ranked 5th among about 6000 examinees in national level Graduate Aptitude Test in Engineering, India, 1999.

National Scholarship from the Government of India: 1993-1997, On the basis of the performance in Higher Secondary Examination 1993

Signature with date

Publications during the last 5 years/or relevant to the project :

Journal:

Ghanem, R. and Ghosh, D. "Efficient characterization of the random eigenvalue problem in a polynomial chaos decomposition", International Journal for Numerical Methods in Engineering, Volume 72, Issue 4, 486-504, 2007

Ghosh, D. and Ghanem, R. "Stochastic convergence acceleration through basis enrichment of polynomial chaos expansion", International Journal for Numerical Methods in Engineering, Volume 73, Issue 2, 162-184, 2008

Ghosh, D. and Farhat, C. "Strain and stress computations in stochastic finite element methods", International Journal for Numerical Methods in Engineering, Volume 74, Issue 8, 1219-1239, 2008

Ghosh, D., Farhat, C. and Avery, P. "A FETI-preconditioned conjugate gradient method for large-scale stochastic finite element problems", International Journal for Numerical Methods in Engineering, Volume 80, 914-931, 2009.

Ghosh, D. ``Some interesting properties of the response covariance of stochastic linear dynamical systems", International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation, Vol 2, pp 141-149, 2010.

Conference Proceedings:

Ghosh, D. ``On Covariance of Response of an Uncertain Linear Dynamical System", IISc Centenary International Conference on Aerospace Engineering and Exhibition (ICEAE'2009), Bangalore, May 18-22, 2009.

Ghosh, D. ``Bounds of Eigenvalues of Uncertain Systems", IISc Centenary International Conference on Aerospace Engineering and Exhibition (ICEAE'2009), Bangalore, May 18-22, 2009.

Ghosh, D. and Farhat, C. ``Uncertainty quantification of large structures using domain decomposition", Inaugural International Conference of the ASCE Engineering Mechanics Institute (EM08), Minneapolis, Minnesota, May 18-21, 2008.

Ghosh, D. and Avery, P. and Farhat, C. ``Uncertainty quantification of large-scale systems using domain decomposition", 9th U.S National Congress on Computational Mechanics, San Francisco, California, July 22-26, 2007.

Reports:

Ghosh, D. and Farhat, C. and Avery, P. ``Strain and stress analysis of uncertain engineering systems", Research Briefs, Center for Turbulence Research, Stanford, 2006.

Ghosh, D. and Farhat, C. and Avery, P. ``Uncertainty analysis of large-scale systems using domain decomposition", Research Briefs, Center for Turbulence Research, Stanford, 2007.

Ghosh, D. and Iaccarino G. ``Applicability of the spectral stochastic finite element method in time dependent uncertain problems", Research Briefs, Center for Turbulence Research, Stanford, 2007.

510. Curriculum vitae (CV) of **Co-Investigator** (CI), if applicable

Name: J M Chandra Kishen
Designation: Associate Professor
Date of birth: 4th September 1964
Place of birth: Bangalore
Nationality: Indian
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Department of Civil Engineering
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Qualifications

Degree	Year	Institution/University	Subjects
BE	1988	Bangalore University	Civil Engineering
ME	1992	Indian Institute of Science, Bangalore	Civil Engineering (Structural Engg.)
PhD	1996	University of Colorado, Boulder, U.S.A.	Civil Engineering (Structural Engg.)

Experience

Positions held

Designation	Organization	Period
Site Engineer	Ranka Construction Company, Bangalore	1988-1989
Lead Graduate Teacher	University of Colorado at Boulder	1995-1996
Lecturer	IISc, Bangalore	1996-1999
Assistant Professor	IISc, Bangalore	1999-2005
Associate Professor	IISc., Bangalore	2005 - present

Areas of expertise

- Computational and experimental fracture mechanics
- Fracture Mechanics based crack propagation analysis of bi-material interface systems.
- Finite element modeling and analysis
- Structural rehabilitation

Publications of PI during the last ten years relevant to the project

1. Santosh G. Shah and J. M. Chandra Kishen, 2011, "Fracture Properties of Concrete-Concrete Interfaces Using Digital Image Correlation", International Journal of Experimental Mechanics (Springer), Vol. 55, No. 3, pp. 303-313.

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520. Curriculum vitae (CV) of **Principal Collaborator** (PC):

SECTION-C

CERTIFICATE-1 (Submit single hard copy only**)**
Certificate from the Head of the Institution of the Principal Investigator (PI) and Co-Investigator (CI) from Non-DAE Institution (Please see Instruction - Sr. No.4-6)
...

Project Title: Uncertainty quantification in multiscale analysis of nanocomposite materials

(1) Certified that this Institution agrees to the participation of

Dr. Debraj Ghosh (PI)	Prof. J M Chandra Kishen (CI)
Address: Dept of Civil Engg, IISc	Address: Dept of Civil Engg, IISc
_____	_____
_____	_____

for the above project which is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS).

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) Certified that the management takes the responsibilities for the timely submission of audited (by external Chartered Accounted or Statutory Government Auditor) statement of account (SA), utilisation certificate (UC), details of staff recruited and equipment purchased for each year as well as the audited (by external Chartered Accounted or Statutory Government Auditor) consolidated SA and UC for the final year.

(4) **Particulars of University Bank A/c are as follows (Please see Instruction - Sr. No.7):**

a) **Name of Account Holder:**

b) **Account No.:**

c) **Bank Name and Branch Address:**

d) **Branch code:**

e) **IFS Code: (16 digits)**

Date:

Place:

Name & signature of the
Head of the institution
or his authorised nominee

Seal:

Note: For Multi-Centre projects, similar certificate is needed from all the participating institutions.

CERTIFICATE-2 (Submit single hard copy only**)**

Certificate from the Head of the Institution of Principal Collaborator (PC) /Departmental Coordinator (DC) from DAE Institution

(Please see Instruction - Sr. No.7)

....

Project Title:

(1) Certified that this Institution agrees to the participation of Prof./Dr. _____ Department/Address _____ as Principal Collaborator (PC)/ Departmental Coordinator (DC) for the above project that is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS) by Prof./Dr. _____ Department/Address _____ as Principal Investigator (PI) .

The PC/ DC shall coordinate for timely submission of yearly progress reports and financial documents towards meaningful conclusion of the project as scheduled.

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) This institution assures to undertake the financial and other management responsibilities of the part of the project work that will be conducted in this institution.

(4) This Certificate is being issued with approval of the Group Board or the Group Board approval shall be taken, after the project is sanctioned by BRNS.

Date:

Place:

Name & signature of the
Head of the DAE institution/
Head of the Group

Seal:

CRP on Uncertainty Analysis of Engineering and Environmental Systems

Project-6

Stochastic modeling of groundwater flow and contaminant transport at the proposed uranium tailings pond

A project proposal submitted to

BOARD OF RESEARCH IN NUCLEAR SCIENCES
Department of Atomic Energy
Government of India

By

Professor M Sekhar (PI)
Professor C S Manohar (CI)

Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

November 2011

SECTION-A

PART I – PROJECT OVERVIEW (Please see Instruction - Sr. No. 8)

100. Advisory Committee Code Number: 36 [NRFC]

101. Title: Stochastic modeling of groundwater flow and contaminant transport at the proposed uranium tailings pond

102. Key Words & Name of 3 Referees (Please see Instruction - Sr. No. 10): Contaminant migration; mine tailing ponds; parameter uncertainty; numerical modeling

Separate Sheet: 1. Prof. B. S. Murty, IITM, Chennai
2. Prof. C. S. P. Ojha, IIT, Roorkee
3. Prof. Shashi Mathur, IIT, Delhi

103. Project Summary (Please see Instruction - Sr. No. 11):

Analysis of groundwater flow and contaminant transport near the proposed uranium tailing ponds needs to consider the uncertainties in the spatial variability of subsurface flow and transport parameters (hydraulic conductivity, porosity, dispersivity, reaction parameters of the contaminant etc.), conceptual model uncertainty and scenario uncertainty, which results in the uncertainty in the prediction of concentration fronts. The aim of this project is to analyze the probabilistic behavior of contaminant concentrations in three dimensions in the vicinity of the tailing ponds. Methods to tackle uncertainties due to parameters, conceptual model and scenario will be investigated that are applicable to this problem. Stochastic modeling will be performed using numerical models of flow and contaminant transport to simulate the prediction uncertainty in the contaminant concentrations due to the combined effects of all the three uncertainties. The field investigations carried out at the tailing pond site would be utilized for performing model calibration and parameter estimation.

Personal Details:

		Name	Address	**e-mail**	**Phone**	**Fax**
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106.	**PC**	Dr. D. Datta	HPD, BARC			
107.	**Co-PC(1)**	Shri Manish Chopra	EAD, BARC			
108.	**Co-PC(2)**	Dr. R.R. Rakesh	PSDD, BARC			

107. Total Budget: Rs. 40,75,200

108. Detailed Project Proposal Report Enclosed: **Yes**

Detailed project proposal

INTRODUCTION

BARC is focusing on characterizing the contaminant (uranium compounds) migration in the underlying aquifer originating from wastes that may be potentially discharged to the tailing ponds at the process sites. Hydrogeologic models of flow and contaminant transport often involve using the numerical models to make predictions of future concentration evolution at such sites. In order to better quantify uncertainty and provide increasingly accurate predictive capability of migration of contaminants in the heterogeneous aquifer system, it is important that subsurface modeling efforts account for both physical and chemical heterogeneities (Zinn and Harvey, 2003; Mayes et al. 2009).

There is wide body of literature dealing with numerical models (based on finite difference, finite element, finite volume) of flow and contaminant transport in groundwater system. Solute concentrations as well as the spatial or temporal moments of the concentration have been modeled in multidimensions employing diffusion type pde for flow and adevection-dispersion type partial differential equations for contaminant transport equations. General purpose codes such as MODFLOW, FEFLOW, MT3DMS have been widely used for various applications.

A variety of factors cause the predictions of hydrogeologic models uncertain, including (a) incomplete knowledge of the system, (b) variability in parameters of the system, (c) randomness in the system stresses (boundary conditions, source/sink terms) (d) measurement and sampling errors, and (e) disparity among sampling, simulation, and actual scales of the system. Other factors that may affect the degree of uncertainty in these predictions are the long time frame over which model predictions may have to be made (e.g., 1000 years or more).

The time domain over which model simulations are conducted can be viewed as two distinct periods. The history-matching period consists of the time over which observations of the system are available and model building and its calibration and validation takes place within the history matching period. The predictive period consists of the time over which the behavior of the system is to be predicted. Often for contaminant migration problems the predictive period will be much longer than the history-matching period. Under these conditions, three broad types of uncertainties emerge namely, uncertainty in model conceptualization (e.g. alternate stochastic frameworks for modeling flow and transport models, conceptualization of multiple layers or fractured media with alternate equivalent porous media models), model parameters (multiple likely estimates obtained from inverse methods) , and modeling scenarios (e.g., future irrigation schemes, ground-water extraction, natural recharge). Uncertainties in the conceptual model and parameter estimates are assessed in the history-matching period and applied on the predictive period while scenario uncertainty applies to the predictive period only.

The hydrogelogical modeling literature pertaining to flow and transport of contaminants has focused mainly with uncertainties in the parameters. This option assumed the conceptual model and scenario are known and to address parameter uncertainty only. Numerical models combining with stochastic analysis have been applied for modeling flow and transport in heterogeneous aquifers considering spatially varying parameters as spatial random fields (Postel and Xin, 1997; Ghanem, 1998; Vogel et al., 2000; Guadagnini et al., 2004; Chaudhuri and Sekhar, 2007 & 2005). However, for a realistic estimate of predictive uncertainty it is required to also consider the potential for significant conceptual model and scenario uncertainties. Although the potential importance of conceptual model uncertainty has been accepted for some time (Apostolakis 1990), practical methods to assess the impact of model uncertainty on prediction have not been widely applied.

Additional source of uncertainty that applies in the predictive period is the scenario uncertainty. A scenario is a description of the future conditions under which a model is applied. Similar to the representation of conceptual model uncertainty, the uncertainty in future site conditions can be represented as a set of alternative scenarios. In the case where future scenarios are characterized by changes in model inputs such as boundary or source terms (e.g., changes in surface recharge or pumping rates), it may also be useful to represent scenario uncertainties by treating these inputs as random.

In a quantitative uncertainty analysis, parameter uncertainty is typically characterized using continuous probability distributions. When characterizing conceptual uncertainty in hydrogeological modeling, specifying a continuum of

conceptual model possibilities is likely to be infeasible. Instead, it is generally more appropriate to postulate a discrete set of alternative conceptual models (Neuman and Wierenga 2003). This suggests a sensitivity approach to conceptual model uncertainty analogous to the sensitivity approach to addressing parameter uncertainty. Namely, each model alternative is used to simulate the desired predicted value. Each model result is represented as a probability distribution because the parameters of each model are uncertain.

A quantitative assessment of parameter uncertainty can be performed by computing the probability density function of the desired predicted value. This can be accomplished by assigning a joint probability distribution to model parameters and propagating this through the model, using a Monte Carlo simulation for example. The joint probability distribution is a measure of the degree of plausibility of the values of model parameters and is assigned based on site information.

A quantitative assessment of the combined effects of parameter and conceptual model uncertainty can be achieved by assigning a discrete probability distribution to the model alternatives. The model predictions are then combined using a weighted average with the weight for each model's prediction consisting of that model's probability (e.g., Apostolakis 1990). Similar to the case of parameter probability, the discrete model probability distribution represents the degree of plausibility of the model alternatives. The resulting model-averaged probability density function can be interpreted as a measure of the joint effect of parameter and model uncertainties. Even though the model-averaging approach has been criticized on the basis that there is only one model corresponding to the physical reality, it is argued in the literature that when appropriately formulated, each model alternative will have some merit in reproducing aspects of the physical system, which quantifies probability of each model (Ye et al. 2004).

Once the alternative scenarios are defined, the impact of scenario uncertainty can be addressed using a sensitivity approach in which the desired predictions are computed with each model alternative under each alternative scenario. Similar to the conceptual model uncertainty, it is possible to assign a discrete probability distribution to the scenario alternatives. In that case, a scenario-averaged probability distribution of the desired predicted value can be computed as a weighted average of the individual scenario (model-averaged).

METHODOLOGY

Flow and contaminant transport modeling : Theory

The governing equations of flow are given below and will be solved using numerical models for the site

$$\frac{\partial}{\partial x_i}\left(T_{ij}(\mathbf{x})\frac{\partial h(\mathbf{x},t)}{\partial x_j}\right) = S_y(\mathbf{x})\frac{\partial h(\mathbf{x},t)}{\partial t} + Q_g(\mathbf{x},t) - Q_r(\mathbf{x},t)$$

$$h(\mathbf{x},0) = h_0(\mathbf{x}) \quad \text{for } \mathbf{x} \in \Omega$$

$$h(\mathbf{x},t) = h_b(\mathbf{x},t) \quad \text{for } \mathbf{x} \in d\Omega_1$$

$$\left(T_{ij}(\mathbf{x})\frac{\partial h(\mathbf{x},t)}{\partial x_j}\right)n_{x_i} = 0 \quad \text{for } \mathbf{x} \in d\Omega_3$$

$$\left(T_{ij}(\mathbf{x})\frac{\partial h(\mathbf{x},t)}{\partial x_j}\right)n_{x_i} = f_b(\mathbf{x}) \quad \text{for } \mathbf{x} \in d\Omega_2$$

Here h(x,y,t) is the ground water level (L), T_{ij} (x) is the spatially varying anisotropic transmissivity tensor (L^2T^{-1}), S_y (x) spatial varying specific yield (LL^{-1}), Q_g (x,t) is the spatio-temporal variations in the net pumping (LT^{-1}), Q_r (x,t) is the spatial variations in the recharge.

The governing equations of contaminant transport are given below and will be solved using numerical models for the site.

$$n(\mathbf{x})\frac{\partial c(\mathbf{x},t)}{\partial t}+\rho_b\frac{\partial s(\mathbf{x},t)}{\partial t}+\frac{\partial}{\partial x_i}\left(n(\mathbf{x})v_i(\mathbf{x})c(\mathbf{x},t)-n(\mathbf{x})D_{ij}(\mathbf{x})\frac{\partial c(\mathbf{x},t)}{\partial x_j}\right)$$
$$+n(\mathbf{x})\gamma(\mathbf{x})c(\mathbf{x},t)+\rho_b\gamma_d(\mathbf{x})s(\mathbf{x},t)=0$$

$$s(\mathbf{x},t)=k_d(\mathbf{x})g(c;\mathbf{x},t)$$

$$g(c;\mathbf{x},t)=\frac{(Bc(\mathbf{x},t))^m}{1+(Bc(\mathbf{x},t))^m}$$

$$v_i(\mathbf{x})=-\frac{K_{ij}(\mathbf{x})}{n}\frac{\partial H(\mathbf{x})}{\partial x_j}$$

$$D_{ij}(\mathbf{x})=\alpha\left((1-\varepsilon)\frac{v_i(\mathbf{x})v_j(\mathbf{x})}{v(\mathbf{x})}+\varepsilon v(\mathbf{x})\delta_{ij}\right)+D_m\delta_{ij}$$

$$c(\mathbf{x},0)=c'(\mathbf{x}),\ \text{for}\ \ \mathbf{x}\in\Omega$$

$$c(\mathbf{x},t)=c_o(\mathbf{x},t),\ \text{for}\ \ \mathbf{x}\in d\Omega_1$$

$$\left(nv_i(\mathbf{x})c(\mathbf{x},t)-nD_{ij}(\mathbf{x})\frac{\partial c(\mathbf{x},t)}{\partial x_j}\right)n_{x_i}=f_b(\mathbf{x}),\ \text{for}\ \ \mathbf{x}\in d\Omega_2$$

The flow and contaminant transport will be simulated using numerical models MODFLOW or FEFLOW and MT3DMS.

Analysis of parameter uncertainty

The primary steps involved in addressing uncertainty in model parameters are: characterization of parameter uncertainty, propagation of parameter uncertainty into model output uncertainty, and parameter sensitivity analysis (Helton et al., 2006, Hill and Tiedeman, 2007). When observations of state variables (e.g., hydraulic head, radionuclide concentration) are available at a site, formal calibration methods can be used to improve parameter estimates and characterize the uncertainty of these estimates (Hill 1998; Hill and Tiedeman, 2007; Carrera and Neuman 1986). GLUE approach (Beven and Binley, 1992) is better suited and will be adopted for model inversions. This approach considers the fact that more than one set of parameters can give the same response. This problem was called equifinality problem (similar to the non-uniqueness), which considers that no single optimum set of parameters will be easily identifiable. Thus, the only way to simulate the system was by assigning the likelihood of each parameter set. This methodology was based on the Monte Carlo simulation, wherein the parameter space was sampled randomly and simulations were performed using each parameter set, and an objective function is used to assess the parameter acceptability. The GLUE methodology has been widely used for model calibration, for example, in hydrologic models (Beven, 2001), geochemical models (Zak *et al*., 1997), groundwater models (Christensen, 2004).

The GLUE approach is based on the Monte Carlo simulation. In the GLUE methodology, ensembles of parameters are sampled using Latin Hypercube Sampling (LHS) (Mckay *et al*., 1979) from a prior distribution, often taken as independent uniform distribution. These ensembles of parameters are used to simulate the model, which gives multiple sets of model output. These outputs are compared with the measured data using a goodness of fit criterion. Then a threshold of goodness of fit criterion is assumed, and set of parameters above this threshold are termed as behavioural parameters and below this are termed as non-behavioural parameters. Now these behavioural parameters are used to generate the uncertainty intervals around the model predictions. The GLUE method is summarised as follows:

1. Define a feasible range and distribution of parameters.
2. Sample the parameter space N times using LHS from their range and distribution.
3. Calculate the likelihood/goodness of fit for each set of parameters.
4. Define a threshold to separate the behavioral and non-behavioural solutions.
5. Use these behavioural solutions to generate the mean and uncertainty for the prediction.

In order to spatialise the parameters, the point estimates from lab and field experiments will be used with Kriging. This will also provide uncertainties in the interpolated spatial parameter field. Further, the outputs of behavioral parameters using GLUE can be used to develop realizations of Kriging. Similarly, as the sequential self-calibration method (Gomez- Hernandez et al. 1997) offered the advantage of producing spatially variable transmissivity fields that honor the spatial statistics of the transmissivity field. Using these approaches a calibrated, stochastic groundwater simulation can be carried out using a set of these fields in a Monte Carlo simulation.

A variety of methods for propagating parameter uncertainty are available, including Monte Carlo simulation, the first-order, second-moment method (Kunstmann et al. 2002; Vecchia and Cooley 1987), the stochastic response surface method (Isukapalli et al. 1998), stochastic moment methods (Dagan and Neuman 1997; Zhang 2001), SFEM (Chaudhuri and Sekhar, 2006). Monte Carlo simulation is the most generally applicable method. However, some of the other methods are appealing because of their potential computational advantage over Monte Carlo simulation. Hence apart from Monte Carlo simulation, investigations will be made to identify alternate method that better suited to this application.

Analysis of Conceptual model and Scenario uncertainty

Each conceptual model alternative may be identified from the assembled database of site-specific data and other relevant information (e.g. number and type of hydrogeologic units, flow and transport property characterization, system boundaries, initial conditions). Methods such as Bayesian Model Averaging to combine conceptual model and parameter uncertainties will be investigated through this study. Similarly approaches for combining parameter uncertainty and model uncertainty with scenario uncertainty will be investigated.

LAB AND FIELD DATA

Parameters (e.g. transmissivity, specific yield, rainfall-recharge factor, dispersivity, sorption parameters) will be estimated through inverse models using laboratory or field data using pump tests, tracer tests, groundwater level measurements, sorption experiments performed by agencies (e.g BARC, NGRI) and data acquired from the investigative sites.

Groundwater levels and contaminant concentrations at the study area collected at discrete locations will be utilized to calibrate and validate the numerical model during the history matching period. Access to this data will be made available for purposes of this study.

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PART II - PROJECT OBJECTIVES, RESEARCH PLAN and DELIVERABLES

200. List of Objectives (Please see Instruction - Sr. No. 13):

a. Develop and test methods for tackling the uncertainties in parameters, conceptual model and scenarios applicable to the problem of flow and contaminant transport.

b. Application of these methods near uranium mine tailing pond sites to simulate the prediction uncertainty in the contaminant concentrations due to the combined effects of these uncertainties using numerical models of flow and contaminant transport.

210. Describe the yearly Research Plan and identify the Deliverables (Please see Instruction - Sr. No. 14):

A. At PI/ CI's Institution

Ist Year: Development and testing of the methodology for handling the uncertainties in parameters. Gathering of data sets related to various field tests conducted at the uranium tailing pond site and performing model inversions to estimate model parameters and their uncertainty. Development of a numerical model for the ground water flow and contaminant transport specific to the application.

IInd Year: Developing the methodology in order to consider the uncertainties due to conceptual model and future scenarios and testing them with the numerical model developed.

IIIrd Year: Performing model simulations for analyzing the probabilistic behavior of contaminant concentrations in the vicinity of the tailing ponds. Modeling the relative role of these uncertainties and their combined effect on the prediction uncertainty of contaminant concentrations. Report and article preparation.

B. At PC's Institution.

Ist Year: Discussion of methodology and its framework. Laboratory and field data synthesis. Sampling additional field/ laboratory data.

IInd Year: Discussion of modeling results and mid-course corrections to the approach.

IIIrd Year: Discussion of modeling results, synthesis and dissemination.

211. Infrastructure facilities related to the project activity available at the PI/CI's Institute:

Existing numerical models of groundwater flow and contaminant transport and tool boxes for uncertainty analyses.

212. Facilities available at the PC's institution that would be useful to this project:

Existing numerical models of groundwater flow and contaminant transport and tool boxes for uncertainty analyses. Additional laboratory and field data sets that can be gathered for testing the modeling framework developed under this project.

PART III - BUDGET ESTIMATES

…

300. Details of budget requirements (Please see Instruction - Sr. No. 15 to 21)

Particulars ⇩ Amount in Rs ⇨	I Year	II Year	III Year	Total
310. Equipment	14,00,000			14,00,000
320. Staff Salary JRF:				
SRF:	2,80,800	2,80,800	3,12,000	8,73,600
RA:	1,87,200 (for 6 months)	1,87,200 (for 6 months)		3,74,400
330. Technical Assistance	50,000	50,000		1,00,000
340. Consumables	1,00,000	1,00,000	1,00,000	3,00,000
350. Travel PI&CI	50,000	50,000	50,000	1,50,000
PC& Co-PC:	50,000	50,000	50,000	1,50,000
360. Contingencies	75,000	75,000	75,000	2,25,000
370. Overheads	3,17,700	1,07,700	76,800	5,02,200
380. Grand Total	**25,10,700**	**9,00,700**	**6,63,800**	**40,75,200**

BUDGET DETAILS

310. Details of the budget for equipment to be procured by the PI:

Sl.No.	Item	Ist year	IInd year	IIIrd year	Total
Local:	Desktop/ Laptop – 2 nos. Desktop/workstation for computing FEFLOW software Color Laser printer	1,00,000 2,00,000 7,00,000 50,000			10,50,000
Imported: Mention currency conversion rate used for estimation	Rockware (GWB professional ver 8.0)	$6999 (Academic price)			~ 3,50,000 (1 US $ = Rs. 45) was used plus cushion is added for any changes and customs, tax etc.
Total		10,50,000+ $ 6999			14,00,000

340. Details of budget for consumables to be procured by the PI (Amount in Rupees):

Sl. No.	Item	Ist year	IInd year	IIIrd year	Total
1.	Color cartridges for printer	30,000	30,000	30,000	90,000
2.	Memory and system upgrades to existing systems	30,000	30,000	30,000	90,000
3.	Annual fee for license and upgrades for softwares	40,000	40,000	40,000	1,20,000
	Total	1,00,000	1,00,000	1,00,000	3,00,000

350. Details of travel:

Amount in Rupees ⇨	Ist year	IInd year	IIIrd year	Total
351. Proposed number of visits of **PC/DC** to **PI's** Institute	1 (2 members)	1 (2 members)	1 (2 members)	3 (2 members)
351A. Duration of stay (no. of days) during each visit	3 days	3 days	3 days	9 days
351B. Total funds required	50,000	50,000	50,000	1,50,000
352. Proposed number of visits of **PI & CI to PC/DC's** institute	1 (2 members)	1 (2 members)	1 (2 members)	3 (2 members)
352A. Duration of stay (No. of days) during each visit	3 days	3 days	3 days	9 days
352B. Total funds required	30,000	30,000	30,000	90,000
353. Funds required by **PI** for travel to attend conferences within India.		20,000	20,000	40,000
354. Funds for Other visits (please give details) Visit to Model application site (i.e. tailing pond sites)	20,000			20,000

BUDGET JUSTIFICATIONS

310. Equipment: Two simple basic computers (desktop/ laptop) are proposed for the PI and the research student (SRF). A separate computer is proposed suitable for performing model runs, which will be complimentary to the computational resources of the IISc. Modeling softwares such as FEFLOW, MT3DMS are proposed for the domain area of the project. A geochemical software (GWB professional ver 8.0) is proposed for reactive solute transport and geochemical modeling. A laser printer is proposed.

320. Staff: One doctoral research student (SRF) is proposed. One RA is proposed for one year split in the first and second year of the project, who will be a PhD student of the team to help ramping up development of uncertainty models.

330. Technical assistance:

340. Consumables: Upgrades on the existing desktop, License fee of the existing software and Refill cartridges for

the existing laser printer are proposed.

350. Travel: Travel is proposed to BARC for PI & CI of one visit for each year, travel to a conference and 1 visit to the field site related to the region where the tailing ponds investigations are being carried out. Travel is also proposed for 2 members of PC to IISc of one visit for each year.

360. Contingencies: Contingency items like books, stationary items, computer related contingency items.

PART IV - OTHER PROJECTS

410. List all previous projects that are **supported by BRNS or any other funding agency** in which PI is actively participating (either as PI or as CI):

Sl. No.	Title of the project	Total cost	Agency	Present status
1.	Near surface soil moisture retrieval using RISAT SAR data and its assimilation for root zone soil moisture estimation at watershed scale.	Rs. 21,60,000	ISRO	Ongoing 1-4-2010, Duration: 3 years
2.	Validation of MT rain rate products and its application in hydrology in the Kabini river basin.	Rs. 21,60,000	ISRO	Ongoing 1-1-2010, Duration: 3 years
3.	Assimilation of remote sensing data for modeling the land surface fluxes at watershed scale using a distributed hydrological model.	Rs. 7,46,500	ISRO-STC	Ongoing 1-4-2010, Duration: 2 Years
4.	Sustainable groundwater management in an urban environment	Rs. 25,00,000	Arghyam (NGO)	Ongoing (with extension) 1-6-2008 Duration: 3 years

411. List all projects submitted **during the current financial year by PI to BRNS or any other agency for funding.** Give details on the present status of the application:

Sl. No.	Title of the project	Total cost	Agency	Present status
1.	Assessing groundwater storage changes and sustainability due to climate change in the semi-arid watersheds of south India	Rs. 15,00,000	CSIR (under the COPEC project)	Ongoing 1-2-2011 Duration: 3 years

412. Brief description of the **project(s) submitted/sanctioned by/to PI by other agencies**. (Please see Instruction - Sr. No.22):

The projects that are currently active are in the areas of climate change impacts on groundwater systems, urban groundwater modeling, calibration of soil moisture for the upcoming RISAT satellite, calibration of rainfall for the upcoming MT satellite and ET modeling.

413. List all previous projects that are **supported by BRNS or any other funding agency** in which CI is actively participating (either as PI or as CI):

No	Title of the project	Total cost	Agency	Present status
1	Vibration based condition	Rs 28.4 lakhs	BRNS	Ongoing

	assessment and reliability analysis of existing engineering structures			2010-2013 Duration: 3 years
2	Fire resistance and repair of earthquake damaged structures	£146000=00	United Kingdom-India Education and Research Initiative.	Ongoing 2007-2011 Duration: 4 years
3	Seismic structural reliability analysis of nuclear core support structure	Rs 3.0 lakhs	IGCAR	Ongoing Duration: 1 year

The CI has completed several other funded research projects and a list of these projects is provided in section 510.

414. List all projects submitted **during the current financial year by CI to BRNS or any other agency for funding.** Give details on the present status of the application:

Asif Usmani and C S Manohar (PI-s), Making performance based structural engineering for fire resistance attainable, A collaborative proposal submitted to the UKIERI Innovative partnerships 2011 with participation from IISc and University of Edinburgh and also four industrial partners from India and the UK (total funds requested:£40000.00).

415. Brief description of the **project(s) submitted/sanctioned by/to CI by other agencies**.

The project proposal mentioned in item 414 has the following objectives:

- To develop a simple and clearly defined performance based structural engineering (PBSE) framework for structures subjected to fire including easy to use software tools that will encourage its wider adoption.
- To incorporate a more explicit treatment of uncertainty in the above framework.

The funding available here mainly supports expenses towards international travel and exchange of research students and does not provide funds for equipment/project staff.

PART IV - FACILITIES

416. List of **facilities** that will be extended to the investigators by the implementing institution for the project

A. **Infrastructure facilities**

Sr. No.	Item Name	Yes/No/ NR*	Sr. No.	Item Name	Yes/No/ NR*
1.	Workshop	NR	7.	Telecommunication	Yes
2.	Water & Electricity	Yes	8.	Transportation	Yes
3.	Standby power supply	Yes	9.	Administrative l support	Yes
4.	Laboratory space & furniture	NR	10.	Library facilities	Yes
5.	AC room for equipment	NR	11.	Computational facilities	Yes
6.	Refrigerator	NR	12.	Animal/Glass house	NR
	NR*: Not Required				

B. **Equipment and accessories** available within the Investigator's group/Dept. which can be utilized for the project.

Sr. No.	Name of the Equipment	Model & Make	Year of Purchase

SECTION-B

500. Curriculum vitae (CV) of **Principal Investigator** (PI)

CV of the PI

Name & Designation: Sekhar Muddu, Associate Professor
Date & Place of Birth: 26 August 1963; New Delhi
Nationality: Indian
Present post: Associate Professor,
Institution with address:
Department of Civil Engineering
Indian Institute of Science, Bangalore, 560 012, INDIA.
Telephone No. (work) +91 (80) 22 93 22 45 (home) +91 (80) 23 60 28 70 & +91 (80) 23 60 35 25 (mobile) +91 98450 96259 **Fax:** +91 (80) 23 60 04 04
Email: muddu@civil.iisc.ernet.in or sekhar.muddu@gmail.com
Webpage: http://civil.iisc.ernet.in/~muddu

Qualifications :

1993	Ph.D.	Indian Institute of Science	Groundwater Hydrology
1987	M.E.	Indian Institute of Science	Hydromechanics & Water Resources
1984	B.Tech	JNT University, Hyderabad, India	Civil Engineering

Experience:

12/2007-to date	Associate Professor, Indian Institute of Science, Bangalore, India
12/1996-12/2007	Assistant Professor, Indian Institute of Science, Bangalore, India
5/2010-8/2010 & 5/2009-7/2009	Visiting Scientist Fellowship of INRA, France.
4/2006-12/2006	Poste Rouge fellowship of CNRS, France
5/2005-7/2005	Visiting Scientist, University of Paul Sabatier, Toulouse, France.
6/2004-7/2004	Visiting Scientist, LMTG, Observatoire Midi-Pyrenees, Toulouse.
7/2002	Visiting Scientist, University of California, San Diego, USA
3/2001-5/2001	Visiting Scientist, Department of Mathematics and Computing Science, Technical University of Eindhoven, The Netherlands.
12/1993-12/1996	Lecturer, Indian Institute of Science, Bangalore, India.
2/1993-11/1993	Project Leader, Transoft International, Paris & Bangalore, India. (Developed "*Pollusol*" – a *Fluidyn* code)

Awards & Felowships

1. Visiting scientist fellowship of INRA, France (2009, 2010 & 2011).
2. Poste Rouge fellowship of CNRS, France.
3. Research fellowship of Indian Institute of Science for Ph.D (1987-1992).
4. Distinction, B.Tech, National scholarship of government of India for M.E. (1985-1987).
5. State recognition award for outstanding academic performance of the Government of Andhra Pradesh, India (1980-1984).

Recognitions

1. Invited by the National Academy of Engineering, USA as a speaker at the Second Indo-American Frontiers of Engineering Meeting, 28th February – 1st March, 2008, Irvine, USA.

2. Member, Central level Expert group for overall reassessment of groundwater resources of the country, 2010, Ministry of Water Resources.
3. Member of the Working group on Water Database Development and Management, Planning Commission, 2010.
4. Nominated as **Executive** Committee Member, Karnataka State Natural Disaster Monitoring Center, Government of Karnataka, India – May 2004.

Areas of Research

I work in the research areas including groundwater hydrology, numerical modeling, and environmental engineering. My interests include analysis of flow and reactive transport in groundwater systems, field-scale experiments in watershed hydrology, geospatial & geophysical methods and optimization & inverse problems

List of Relevant Publications

1. B. Siva Soumya, B., Sekhar, M., Riotte, J., Audry, S., Lagane, C., Braun, J. J. (2011). Inverse models to analyze the spatiotemporal variations of chemical weathering fluxes in a granito-gneissic watershed: Mule Hole, South India. Geoderma (In Press).
2. Suresh Kumar, G., Sekhar, M. and Misra, D. (2011). Spatial and temporal moment analyses of decaying solute transport in a single fracture with matrix diffusion. Journal of Petroleum and Geosystems Science and Engineering (In Press).
3. Sat Kumar, Sekhar, M., Mohan Kumar and Reddy, D. V. (2010). Estimation of soil hydraulic properties and their uncertainty: comparison between laboratory and field experiment. Hydrological processes. DOI: 10.1002/hyp.7775.
4. Sat Kumar, Sekhar, M., Bandyopadhyay, S. (2009). Assimilation of remote sensing and hydrological data using adaptive filtering techniques for watershed modeling. Current Science, Vol.97(8), pp.1196-1202 (Invited article in Section: Civil engineering Research).
5. Ruiz, L., Murari, R. R. V., Mohan Kumar, M. S., Sekhar, M., Maréchal, J-C., Descloitres, M., Riotte, J., Sat Kumar, Kumar, C. and Braun, J-J. (2009). Water balance modelling in a tropical watershed under deciduous forest (Mule Hole, India) : regolith matric storage buffers the groundwater recharge process. Journal of Hydrology. 10.1016/j.jhydrol.2009.11.020.
6. Sat Kumar, Sekhar, M. and Reddy, D. V. (2009). Improving the disaggregation of daily rainfall into hourly rainfall using hourly soil moisture. Hydroinformatics in hydrology, hydrogeology and water resources. IAHS Publication. 331, pp.236-244.
7. Javeed, Y., Sekhar, M., Bandyopadhyay, S. and Mangiarotti, S. (2009). EOF and SSA analyses of hydrological time series to assess climatic variability and land use effects: a case study in the Kabini River basin of South India. IAHS Publication. 329, pp.167-177.
8. Majumdar, P. K., Sekhar, M., Sridharan, K, Mishra, G. C. (2008). Numerical simulation of groundwater flow with gradually increasing heterogeneity due to clogging. Journal of Irrigiation and Drainage Engineering (ASCE), Vol. 134(3), pp. 400-404.
9. Sekhar, M., Braun, J. J., Rao, K.V. H., Ruiz, L., Robain, H., Viers, J., Ndam, J. R., Dupre, B. (2008). Hydrogeochemical modeling of organo-metallic colloids in the Nsimi experimental watershed, South Cameroon. Environmental Geology, Vol. 54(4), pp. 831-841.
10. Descloitres, M., Ruiz, L., Sekhar, M., Legchenko, A., Braun, J. J., Kumar, M. S. M., Subramanian, S. (2008). Characterization of seasonal local recharge using electrical resistivity tomography and magnetic resonance sounding. Hydrological Processes, Vol. 22(3), pp. 384-394.
11. Chaudhuri, A., Sekhar, M. (2008). Modelling of solute transport in a mild heterogeneous porous medium using stochastic finite element method: Effects of random source conditions. International Journal for Numerical Methods in Fluids, Vol. 56(5), pp.557-586.
12. Kumar, G. S., Sekhar, M., Misra, D. (2008). Time-dependent dispersivity of linearly sorbing solutes in a single fracture with matrix diffusion. Journal of Hydrological Engineering (ASCE), Vol.13(4), pp. 250-257.
13. Chaudhuri, A. and Sekhar, M. (2007) Analysis of biodegradation in a 3-D heterogeneous porous medium using nonlinear stochastic finite element method. Advances in Water Resources, V. 30, pp.589-605.
14. Chaudhuri, A. and Sekhar, M. (2007) Stochastic finite element method for analysis of transport of nonlinearly sorbing solutes in 3-D heterogeneous porous media. Water Resources Research, 43, W07442, doi:10.1029/2006WR004892.

15. Sekhar, M., Suresh Kumar, G., and Misra, D. (2006). Numerical Modeling and Analysis of Solute Velocity and Macrodispersion for Linearly and Nonlinearly Sorbing Solutes in a Single Fracture with Matrix Diffusion. Journal of Hydrological Engineering, ASCE, V. 11 (4), pp.319-328.
16. Sekhar, M. and Suresh Kumar, G. (2006) Modelling transport of linearly sorbing solutes in a single fracture: Asymptotic behavior of solute velocity and dispersivity. International Journal of Geotechnical and Geological Engineering, V.24, pp.183-201.
17. Chaudhuri, A. and Sekhar, M. (2006). Stochastic modeling of solute transport in 3-D heterogeneous media with random source condition. Stochastic Environmental Research and Risk Assessment, V.21, pp.159-173.
18. Legchenko, A., Descloitres, M., Bost, A., Ruiz, L., Reddy, M., Girard, J-F., Sekhar, M., Mohan Kumar, M.S., Braun, J-J. (2006). Efficiency of Magnetic Resonance Soundings applied to characterization of anisotropic crystalline basement aquifers. Journal of Groundwater, V. 44 (4), pp.547-554.
19. Suresh Kumar, G., Sekhar, M. and Misra, D. (2006). Time dependent dispersivity behavior of non-reactive solutes in a system of parallel fractures. Hydrology and Earth System Science Discussions, V. 3 (3), pp. 895-923.
20. Sekhar, M., Rasmi, S.N., Javeed, Y., Gowrisankar, D., and Ruiz, L. (2006). Modeling the groundwater dynamics in a semi-arid hard rock aquifer influenced by boundary fluxes, spatial and temporal variability in pumping/recharge. Advances in Geoscience, Hydrological Sciences (ed) Park, N., V. 4, p. 173-181.
21. Chaudhuri, A. and Sekhar, M. (2005) Stochastic finite element method for probabilistic analysis of flow and transport in a 3-D heterogeneous porous formation. Water Resources Research, V.41, W09404.
22. Suresh Kumar, G. and Sekhar, M. (2005) Spatial Moment analysis for transport of non-reactive solutes in a fracture-matrix system. Journal of Hydrologic Engineering, ASCE, V.10 (3), pp.192-199.
23. Chaudhuri, A. and Sekhar, M. (2005). Analytical solutions for macrodispersion in 3-D heterogeneous porous medium with random hydraulic conductivity and dispersivity. Transport in Porous media, V.58 (3), pp.217-241.
24. Chaudhuri, A and Sekhar, M. (2005). Probabilistic analysis of pollutant migration from a landfill using stochastic finite element method. Journal of Geotechnical and Geoenvironmental Engineering, ASCE , V.131, No.8, pp.1042-1049.
25. Hari Prasad, K. S., Mohan Kumar, M. S., Sekhar, M., (2005) Analysis of saturated-unsaturated flow near a pumping well in an aquifer-water table aquitard system. Hydrology Journal, V. 28, No.1-2, pp. 19-32.
26. Sekhar, M., Rasmi, S.N., Sivapullaiah, P.V. and Ruiz, L. (2004) Groundwater flow modeling of Gundal sub-basin in Kabini river basin, India. Asian Journal of Water, Environment and Pollution, V. 1(1-2), pp. 65-77.
27. Hari Prasad, K.S., Mohan Kumar, M.S. and Sekhar, M. (2001) Modelling Flow Through Unsaturated Zones: Sensitivity Unsaturated Soil Properties, Sadhana, Proceedings of Indian Academy of Sciences in Engineering Sciences, V. 26(6), 2001, pp.517-528.

510. Curriculum vitae (CV) of **Co-Investigator** (CI)

C S Manohar
Professor and Chairman
Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012 INDIA

Born : 11th May 1959, Hubli (Karnataka)
Indian National
Phone: +91 80 2293 3121 Fax: +91 80-23600 404
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Web: http://civil.iisc.ernet.in/fac/~manohar

Education

- BE (Civil Engg.), 1982, Karnatak University, India, First Class with Distinction.
- ME (Civil Engg.), 1984, Indian Institute of Science, First Class with Distinction.
- PhD (Faculty of Engineering), 1989, Indian Institute of Science, Bangalore.

Work Experience

Academic positions held at the Indian Institute of Science

- Professor, May 2005-present, Department of Civil Engineering.
- Associate Professor, May 1999-May 2005, Department of Civil Engineering.
- Assistant Professor, May 1993-May 1999, Department of Civil Engineering.

Other positions held at the Indian Institute of Science

- Chairman, December 2010- present, Department of Civil Engineering.
- Chairman, July 2007- December 2010, Centre for Earth Sciences.
- Associate Faculty Member, 2007-present, Centre for Earth Sciences.
- Member Secretary, IISc-IGCAR R & D Cell, 2011-present

Positions held outside the Indian Institute of Science

- Visiting Professor, October 2011, Carleton University, Ottawa, Canada.
- Visiting Scientist, May 2003, Dept. of Civil Engineering, University of Delaware, USA.
- Visiting Associate Professor, June-July, 2003, Dept. of Civil Engineering, The Johns Hopkins University, USA.
- Research Assistant, May 1991-May 1993, Dept. of Engineering Sciences, University of Oxford, UK.
- Scientist, Oct 1990-May 1991, Structural Engineering Research Centre, Chennai, India

Honors

- Member, Editorial Board, Probabilistic Engineering Mechanics (Elsevier)
- Member, Editorial Board, Structural Control and Health Monitoring (Wiley)
- Associate Editor (Structural Dynamics), ISET Journal of Earthquake Technology, (since 2007).
- Associate Editor, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation (Serial Publications).
- Member, Editorial Board, Earthquakes and Structures (from 2010) (Techno Press).
- Sir C V Raman award for young scientists for the year 1999, Instituted by Government of Karnataka, India.
- Member, Technical Committee of Dynamics, Engineering Mechanics Division, American Society of Civil Engineers, 2003-2007.
- Invitations to IUTAM symposia on Nonlinear Stochastic Mechanics, 1995, 2001, 2009.

Research interests

- Structural dynamics: modeling of nonlinearity and uncertainties; computational and experimental methods; inverse problems: structural system identification and damage detection using measured vibration data; statistical energy analysis.
- Stochastic structural mechanics: stochastic FEM; random vibrations; Bayesian filtering; Monte Carlo simulations & variance reduction schemes; structural reliability modeling.
- Earthquake engineering: seismic safety of large scale structures; science of earthquake simulations: hybrid test methods; real time substructuring; fire following earthquakes.

Papers in refereed journals (last ten years)

1. B Radhika and C S Manohar, 2011, Updating response sensitivity models of nonlinear vibrating structures using particle filters, Computers and Structures, 89(11-12), 901-911.
2. H A Nasrellah and C S Manohar, 2011, Finite element method based Monte Carlo filters for structural system identification, Probabilistic Engineering Mechanics, 26 (2011) 294–307.
3. H A Nasrellah and C S Manohar, 2011, Particle filters for structural system identification using multiple test and sensor data: a combined computational and experimental study, Structural Control and Health Monitoring, 18, 99–120.
4. B Radhika and C S Manohar, 2010, Reliability models for existing structures based on dynamic state estimation and data based asymptotic extreme value analysis, Probabilistic Engineering Mechanics, 25, 393-405.
5. H A Nasrellah and C S Manohar, 2010, A particle filtering approach for structural system identification in vehicle-structure interaction problems, Journal of Sound and Vibration. 329(9), 1289-1309.
6. R Sajeeb, C S Manohar and D Roy, 2010, A semi-analytical particle filter for identification of nonlinear oscillators, Probabilistic Engineering Mechanics, 25, 35-48
7. R Sivaprasad, S Venkatesha, and C S Manohar, 2009, Identification of dynamical systems with fractional derivative damping models using inverse sensitivity analysis, Computers, Materials and Continua, 9 (3), 179-207.
8. R Tipireddy, H A Nasrellah and C S Manohar, 2009, A Kalman filter based strategy for linear structural system identification based on multiple static and dynamic test data, Probabilistic Engineering Mechanics, 24, 60-74.
9. R Sajeeb, C S Manohar and D Roy, 2009, A Conditionally linearized Monte Carlo filter in nonlinear structural dynamics, International Journal of Nonlinear Mechanics, 44(7), 776-790.

10. R Sajeeb, C S Manohar and D Roy, 2009, Rao-Blackwellization with substructuring for state and parameter estimations of a class of nonlinear dynamical systems, International Journal of Engineering Under Uncertainty: Hazards, Assessment and Mitigation, 1(1-2) 2009.
11. S Venkatesha, R Rajender, and C S Manohar, 2008, Inverse sensitivity analysis of singular solutions of FRF matrix in structural system identification, CMES: Computer Modeling in Engineering and Science, 37(2), 113-152.
12. V Namdeo and C S Manohar, 2008, Force state maps using reproducing kernel particle method and kriging based functional representations, CMES: Computer Modeling in Engineering and Science, 32(3), 123-160.
13. S S Panda and C S Manohar, 2008, Applications of meta-models in finite element based reliability analysis, CMES: Computer Modeling in Engineering and Sciences, 28, N0. 3, 161-184.
14. B Radhika, S S Panda and C S Manohar, 2008, Time variant reliability analysis using data based extreme value analysis, CMES: Computer Modeling in Engineering and Sciences, 27(1-2),79-110.
15. S Ghosh, C S Manohar and D Roy, 2008, Sequential importance sampling filters with a new proposal distribution for parameter identification of structural systems, Proceedings of Royal Society of London, A, 464, 25-47.
16. V Namdeo and C S Manohar, 2007, Nonlinear structural dynamical system identification using adaptive particle filters, Journal of Sound and Vibration, 306, 524-563.
17. R Sajeeb, C S Manohar and D Roy, 2007, Control of Nonlinear Structural Dynamical Systems with Noise Using Particle Filters, Journal of Sound and Vibration, 306, 25, 111-135.
18. S Ghosh, D Roy and C S Manohar, 2007, New forms of extended Kalman filter via transversal linearization and applications to structural system identification, Computer Methods in Applied Mechanics and Engineering, 196, 5063-5083.
19. M Manjuprasad and C S Manohar, 2007, Adaptive random field mesh refinements in stochastic finite element reliability analysis of structures, CMES: Computer Modeling in Engineering and Sciences, 19(1), 23-54.
20. R Sajeeb, D Roy and C S Manohar, 2007, Numerical aspects of a real-time substructuring technique in structural dynamics, International Journal of Numerical Methods in Engineering, 72, 1261-1313.
21. A M Abbas and C S Manohar, 2007, Critical vector random earthquake loads for parametrically excited structures, Structural Safety, 29(1), 32-48.
22. Sayan Gupta and C S Manohar, 2006, Reliability analysis of randomly parametered linear vibrating systems subjected to stochastic excitations, Journal of Sound and Vibration, 297(3-5), 1000-1024.
23. C S Manohar and D Roy, 2006, Nonlinear structure system identification using Monte Carlo filters, Sadhana, Academy Proceedings in Engineering, Indian Academy of Science, 31(4), 399-427.
24. Sayan Gupta and C S Manohar, 2005, Extreme value distribution of von Mises stress in randomly vibrating structures, Journal of Vibration and Acoustics, Transaction of ASME, 127 (6), 547-555.
25. Sayan Gupta and C S Manohar, 2005, Development of multivariate extreme value distributions for random vibration applications, Journal of Engineering Mechanics, ASCE. 131(7), 712-720.
26. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part I: Linear structures, Journal of Sound and Vibration, 287, 865-882.
27. A M Abbas and C S Manohar, 2005, Reliability based critical excitation models. Part II: Nonlinear structures, Journal of Sound and Vibration, 287, 883-900.
28. C S Manohar and R Ghanem, 2005, Multivariate probability distribution of ordered peaks of vector Gaussian random processes, Probabilistic Engineering Mechanics, 20, pp 87-96.
29. Saikat Saha and C S Manohar, 2005, Inverse reliability design of structures subjected to partially specified earthquake loads, Probabilistic Engineering Mechanics, 20, 19-31.
30. Sayan Gupta and C S Manohar, 2004, Response surface method for time variant reliability analysis of nonlinear random structures under nonstationary excitations, 36, 267-280, Nonlinear Dynamics.
31. Sayan Gupta and C S Manohar, 2004, Improved response surface method for structural reliability analysis, 123-139, Structural safety.
32. S Ammanagai, S Venkatesha, and C S Manohar, 2004, Analytical and experimental investigations of structural damages in beams and built-up structures using vibration data, 31(1), 73-84, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.
33. Luna Majumder and C S Manohar, 2003, A time domain approach for damage detection in bridge structures using vibration data with moving vehicle as an excitation source, 268, 699-716, Journal of sound and Vibration.
34. C S Manohar, S Venkatesha and S Sadasivan, 2003, Finite element analysis of vehicle-structure interactions during launching of remotely piloted air-vehicles, 30(1), 1-6, Journal of Structural Engineering, Structural Engineering Research Centre, Madras.

35. C S Manohar, R Ravi and Ch Srinivas, 2003, Nonlinear structures under random differential support motions and determination of critical input models, 2(3), 171-198, Advances in vibration engineering, Vibration Institute of India.
36. Luna Majumder and C S Manohar, 2002, Nonlinear reduced models for beam damage detection using data on moving oscillator-beam interactions, 82, 301-314, Computers and Structures.
37. Sayan Gupta and C S Manohar, 2002, Dynamic stiffness method for circular stochastic Timoshenko beams: response variability and reliability analyses, Journal of Sound and Vibrations, 253(5), 1051-085.
38. Abbas M and C S Manohar, 2002, Investigations into critical excitation models within deterministic and probabilistic frameworks: single point excitations, Earthquake Engineering and Structural Dynamics 31, 813-832.
39. A M Abbas and C S Manohar, 2002, Critical spatially varying earthquake load models, Journal of Structural Engineering, Structural Engineering Research Centre, Madras, 29, 39-52.

List of funded projects (last ten years)

1. C S Manohar and S Venkatesha, 2010-2013, Vibration based condition assessment and reliability analysis of existing structures', Funded by Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India.
2. C S Manohar, 2010, Development of a video based course on Stochastic Structural Dynamics, funded by National Programme on Technology Enhanced Learning, Government of India.
3. 2007-2010, Fire resistance and repair of earthquake damaged structures, United Kingdom-India Education and Research Initiative (UKIERI) Collaborative Research Awards 2007, Jointly developed with University of Edinburgh, IIT Roorkee and IISc, Bangalore; Team: Edinburgh: A S Usmani, J L Torero, P Pankaj, J F Chen, and M Gillie; IIT Roorkee: Pradeep Bhargava, Yogendra Singh, Umesh Kumar Sharma; IISc: C S Manohar and Ananth Ramaswamy.
4. C S Manohar and K Venkatraman, 2006-2008, Analytical prediction of squeak and rattle noise intensity in a seat belt retractor system, Funded by Delphi Automotive Systems, India.
5. C S Manohar, 2006-2008, Structural Reliability Under Seismic Loads, Funded by Cranes Software India Limited.
6. C S Manohar and V R Sonti, and A R Upadhya, 2005-2009, Modeling of nonlinearity in experimental structural dynamics, Aeronautical Research and Development Board, Government of India.
7. J M Chandra Kishen, Ananth Ramaswamy, C S Manohar, and D Roy, 2006-2009, Condition monitoring of railway bridges, Funded by Indian Railways (South Central Division).
8. C S Manohar and K Venkatraman, 2006, Acoustic vibration of sodium to air heat exchangers, Funded by IGCAR.
9. C S Manohar and K Venkatraman, 2008, Dynamic analysis of rotating parts of a turbine, Funded by Bharath Heavy Electricals Limited, Bhopal.
10. D Roy and C S Manohar, 2004-2007, Development of numerical methods for structural reliability analyses, Funded by Board of Research in Nuclear Studies, Department of Atomic Energy, Government of India.
11. C S Manohar and J M Chandra Kishen, 2002-2006, Seismic Probabilistic Safety Assessment (PSA) of nuclear power plants, Funded by Board of Research in Nuclear Studies, Department of Atomic Energy, Government of India.
12. C S Manohar and S Venkatesha, 2006, Testing and model validation for simple brackets and lectures on techniques and method used**,** Funded by John F Welch Technology Centre, General Electricals India, Bangalore.
13. C S Manohar, D Roy, and S Venkatesha, 2006, Environmental vibration survey at the National Centre for Biological Sciences at the proposed site for installing an electronic microscope, Bangalore.
14. C S Manohar and V R Sonti, 2003-2005, Bayesian updation of finite element sub-structure assemblies using qualification test data, Funded by Indian Space Research Organization-Indian Institute of Science Space Technology Cell.
15. C S Manohar, 2001-2004, Structural damage detection using vibration data and probabilistic health assessment, Funded by Council of Scientific and Industrial Research, Government of India.
16. C S Manohar and Kartik Venkatraman, 2002-2004, Vibration response prediction in a flight vehicle, Funded by Environmental Test Laboratory, Regional Research Centre, Hyderabad, Defence R & D Organization, Government of India.

SECTION-C

CERTIFICATE-1 (Submit single hard copy only**)**
Certificate from the Head of the Institution of the Principal Investigator (PI) and Co-Investigator (CI) from Non-DAE Institution (Please see Instruction - Sr. No.4-6)

...

Project Title:

Stochastic modeling of groundwater flow and contaminant transport at the proposed uranium tailings pond

(1) Certified that this Institution agrees to the participation of

	Prof. M. Sekhar (PI)	Prof. C. S. Manohar (CI)
Address	Department of Civil Engineering Indian Institute of Science Bangalore, 560012	Department of Civil Engineering Indian Institute of Science Bangalore, 560012

for the above project which is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS).

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) Certified that the management takes the responsibilities for the timely submission of audited (by external Chartered Accounted or Statutory Government Auditor) statement of account (SA), utilisation certificate (UC), details of staff recruited and equipment purchased for each year as well as the audited (by external Chartered Accounted or Statutory Government Auditor) consolidated SA and UC for the final year.

(4) **Particulars of University Bank A/c are as follows (Please see Instruction - Sr. No.7):**

a) Name of Account Holder:

b) Account No.:

c) Bank Name and Branch Address:

d) Branch code:

e) IFS Code: (16 digits)

Date:

Place:

Name & signature of the
Head of the institution
or his authorised nominee

Seal:

CERTIFICATE-2 (Submit single hard copy only**)**

Certificate from the Head of the Institution of Principal Collaborator (PC) /Departmental Coordinator (DC) from DAE Institution

(Please see Instruction - Sr. No.7)

....

Project Title:

Stochastic modeling of groundwater flow and contaminant transport at the proposed uranium tailings pond

(1) Certified that this Institution agrees to the participation of Dr. _____ Department/Address _____ as Principal Collaborator (PC)/ Departmental Coordinator (DC) for the above project that is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS) by Prof./Dr. _____ Department/Address _____ as Principal Investigator (PI) .

The PC/ DC shall coordinate for timely submission of yearly progress reports and financial documents towards meaningful conclusion of the project as scheduled.

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) This institution assures to undertake the financial and other management responsibilities of the part of the project work that will be conducted in this institution.

(4) This Certificate is being issued with approval of the Group Board or the Group Board approval shall be taken, after the project is sanctioned by BRNS.

Date:

Place:

Name & signature of the
Head of the DAE institution/
Head of the Group

Seal:

CRP on Uncertainty Analysis of Engineering and Environmental Systems

Project-7

Development of probabilistic design and analysis procedures in radioactive waste disposal in NSDF and design of NSDF closure

A project proposal submitted to

BOARD OF RESEARCH IN NUCLEAR SCIENCES
Department of Atomic Energy
Government of India

By

Professor G L Sivakumar Babu (PI)
Professor M Sekhar (CI)

Department of Civil Engineering
Indian Institute of Science
Bangalore 560 012

February 2012

SECTION-A

PART I – PROJECT OVERVIEW (Please see Instruction - Sr. No. 8)

100. Advisory Committee Code Number (Please see Instruction - Sr. No. 9): **36**

101. Title: **Development of Probabilistic design and analysis procedures in radioactive waste disposal in NSDF and design of NSDF closure**

102. Key Words & Name of 3 Referees (Please see Instruction - Sr. No. 10):

Radioactive waste disposal, containment, closure, risk, geotechnical

Prof. D N Singh
Department of Civil Engineering
Indian Institute of Technology
IIT Mumbai

Prof. M Sudhakar Rao
Department of Civil Engineering
Indian Institute of Science
Bangalore

Prof. D S N Murty
Department of Civil Engineering
Indian Institute of Technology
IIT Mumbai

103. Project Summary (Please see Instruction - Sr. No. 11):

Low and intermediate level radioactive waste generated at various stages of nuclear fuel cycle and from other applications (e.g. medical, agriculture and various research labs) are treated, conditioned and disposed off in engineered disposal modules of Near Surface Disposal Facility (NSDF). In India this practice is being adopted successfully since over five decades. The multi barrier approach adopted in disposal programme minimizes the risk to humans and the environment from the harmful effects of radioactive waste. A number of geotechnical and geo-environmental parameters are used in the design of multi barrier disposal modules, liners as well as cover system, and in the assessment of stability and settlement response of cover material as well as migration of contaminants. These parameters have significant variability and are correlated and hence considerably influence decisions pertaining to design, analysis as well as performance. The implications also have significant influence on the risk assessment. In the proposed research, waste disposal modules currently being used for disposal of radioactive wastes in NSDF will be examined. Field and laboratory test results provided by BARC will be used to obtain relevant properties for modeling and their variations. Reliability analysis of covers, lining systems, slope stability, settlement predictions and contaminant migration will be performed. Probabilistic analysis using simple first order methods, using Monte Carlo simulations and numerical analysis using FLAC will be performed. The results of the study will be used to examine the current guidelines of disposal modules design and construction.

Personal Details:

		Name	Address	e-mail	Phone	Fax
104.	**PI**	G L Sivakumar Babu	Professor Department of Civil Engineering Indian Institute of Science Bangalore 560012	gls@civil.iisc.ernet.in	22933124	23600404
105.	**CI**	M Sekhar	Professor Department of Civil Engineering Indian Institute of Science Bangalore 560012	muddu@civil.iisc.ernet.in	22932245	23600404
106.	**PC**	R R Rakesh	Scientific officer grade(F), Process Development Div. Nuclear Recycle Group, BARC, Mumbai		9869233577 25591067	
107.	**PC**	V S Phanikanth	Scientific officer grade(F), A&CED,BARC, Mumbai		9833917524	

107. Total Budget **Rs. 38,41,000**

108. Detailed Project Proposal Report Enclosed: **Yes**

PART II - PROJECT OBJECTIVES, RESEARCH PLAN and DELIVERABLES

200. List of Objectives (Please see Instruction - Sr. No. 13):

1) Literature review in design of radioactive waste disposal modules
2) Collection of data pertaining to waste characteristics, NSDF field condition and laboratory testing, also collect data from literature on properties and variations
3) Analysis of data of laboratory/field test results.
4) Analysis of typical designs using various computational software such as Pollute, Hydrous 2D, HELP and FLAC
5) Analysis of role of variability and uncertainties and formulation of limit state functions for different designs in landfills and reliability analysis.
6) Report preparation.

210. Describe the yearly Research Plan and identify the Deliverables (Please see Instruction - Sr. No. 14):

The following is the time frame proposed. Work plans as well as deliverables are indicated.

Task	Months					
Literature survey	6					
Collection and characterization of landfill wastes		18				
Laboratory and field testing			24			
Analysis of landfill designs				28		
Variability and reliability analysis					33	
Report preparation						36

211. Infrastructure facilities related to the project activity available at the PI/CI's Institute:

Facilities for basic testing (index properties, shear and compressibility tests) of site specific soil are available. FLAC 2D software is available.

212. Facilities available at the PC's institution that would be useful to this project:

PART III - BUDGET ESTIMATES

…

300. Details of budget requirements (Please see Instruction - Sr. No. 15 to 21)

Particulars ⇩ Amount in Rs.⇨	I Year	II Year	III Year	Total
310. Equipment	4,60,000	-	-	4,60,000
320. Staff Salary two SRFs at RS.20,000/- pm	4,80,000	4,80,000	4,80,000	14,40,000
330. Technical Assistance At Rs.15,000/ pm	1.80,000	1.80,000	1.80,000	5,40,000
340. Consumables	2,00,000	2,00,000	2,00,000	6,00,000
350. Travel PI:	50,000	50,000	50,000	1,50,000
PC/DC:				
360. Contingencies	50,000	50,000	50,000	1,50,000
370. Overheads (15%)	2,13,000	1,44,000	1,44,000	3,00,000
380. Grand Total	**16,33,000**	**11,04,000**	**11,04,000**	**38,41,000**

BUDGET DETAILS

310. Details of the budget for equipment to be procured by the PI:

Sl.No.	Item	Ist year	
Local:	FLAC software HELP	All will be procured in ist year	1) FLAC software upgradation 1,75,978 2) Hydrous 2D 81,600 3) Pollute ver 7 44,775 4) HELP 56,160 5) and two state of the art PCs for project staff at Rs 50,000/-
Imported: Mention currency conversion rate used for estimation	Hydrous 2D 1200 EUx68= 81,600 Pollute ver 7 995 USDx45= 44,775		
Total			**Total, 4,58,513**

340. Details of budget for consumables to be procured by the PI (Amount in Rupees):

Sl. No.	Item	Ist year	IInd year	IIIrd year	Total
	expenditure for field testing, fabrication of set up for laboratory tests, laboratory tests,	2,00,000	2,00,000	2,00,000	
	Total	2,00,000	2,00,000	2,00,000	

350. Details of travel: RS.50,000/- in each year is earmarked for the PI.

Amount in Rupees ⇨	Ist year	IInd year	IIIrd year	Total
351. Proposed number of visits of **PC/DC** to **PI's** Institute				
351A. Duration of stay (no. of days) during each visit				
351B. Total funds required				
352. Proposed number of visits of **PI to PC/DC's** institute				
352A. Duration of stay (No. of days) during each visit				
352B. Total funds required				
353. Funds required by **PI** for travel to attend conferences within India.				
354. Funds for Other visits (please give details)				

BUDGET JUSTIFICATIONS

310. Equipment: The indicated software are very essential for analysis in the project and hence necessary.

320. Staff: Two SRFs are required to do analysis, uncertainty modeling, compilation of data, report preparation etc.

330. Technical assistance: On assistant is required to do testing and characterization of waste

340. Consumables: Consumables will be used for experimental work which includes fabrication of test set up.

350. Travel: Only travel for PI is included in the proposal.

360. Contingencies: For miscellaneous expenditure Rs.50,000/ is proposed.

PART IV - OTHER PROJECTS

410. List all previous projects that are **supported by BRNS or any other funding agency** in which PI is actively participating (either as PI or as CI**): None.**

411. List all projects submitted **during the current financial year by PI to BRNS or any other agency for funding.** Give details on the present status of the application: None.

412. Brief description of the **project(s) submitted/sanctioned by/to PI by other agencies**. (Please see Instruction - Sr. No.22):

At present, two projects Experimental and analytical studies on fiber reinforced soils, Engineering behavior of fly ash composites both sponsored by DST does not have any overlap with the proposed project.

413. List all previous projects **that are supported by BRNS or any other funding agency in which CI** is actively participating (either as PI or as CI):

No	Title	Total cost	Agency	Status
1.	Near surface soil moisture retrieval using RISAT SAR data and its assimilation for root zone soil moisture estimation at watershed scale.	Rs. 21,60,000	ISRO	Ongoing 1-4-2010, Duration: 3 years
2.	Validation of MT rain rate products and its application in hydrology in the Kabini river basin.	Rs. 21,60,000	ISRO	Ongoing 1-1-2010, Duration: 3 years
3.	Assimilation of remote sensing data for modeling the land surface fluxes at watershed scale using a distributed hydrological model.	Rs. 7,46,500	ISRO-STC	Ongoing 1-4-2010, Duration: 2 Years
4.	Sustainable groundwater management in an urban environment	Rs. 25,00,000	Arghyam (NGO)	Ongoing (with extension) 1-6-2008 Duration: 3 years

414. List all projects submitted **during the current financial year by CI to BRNS or any other agency for funding**. Give details on the present status of the application:

No	Title	Total cost	Agency	Status
1.	Assessing groundwater storage changes and sustainability due to climate change in the semi-arid watersheds of south India	Rs. 15,00,000	CSIR (under the COPEC project)	Ongoing 1-2-2011 Duration: 3 years

415. Brief description of the project(s) submitted/sanctioned by/to CI by other agencies.

The projects that are currently active are in the areas of climate change impacts on groundwater systems, urban groundwater modeling, calibration of soil moisture for the upcoming RISAT satellite, calibration of rainfall for the upcoming MT satellite and ET modeling.

PART IV - FACILITIES

416. List of **facilities** that will be extended to the investigators by the implementing institution for the project

A. **Infrastructure facilities.**

Sr. No.	Item Name	Yes/No/ NR*	Sr. No.	Item Name	Yes/No/ NR*
1.	Workshop	Yes	7.	Telecommunication	Yes
2.	Water & Electricity	Yes	8.	Transportation	
3.	Standby power supply		9.	Administrative l support	Yes
4.	Laboratory space & furniture	Yes	10.	Library facilities	
5.	AC room for equipment		11.	Computational facilities	
6.	Refrigerator		12.	Animal/Glass house	No
	NR*: Not Required				

B. **Equipment and accessories** available within the Investigator's group/Dept. which can be utilized for the project.

Sr. No.	**Name of the Equipment**	**Model & Make**	**Year of Purchase**
	FLAC ver.5 which is available will be upgraded to version 7. Direct shear, compressibility testing and tri-axial testing	FLAC ver 5	2007

SECTION-B

500. Curriculum vitae (CV) of **Principal Investigator** (PI)

G. L. SIVAKUMAR BABU
Professor
Department of Civil Engineering Department of Civil Engineering
Associate faculty
Centre for Infrastructure, Sustainable Transportation and Urban Planning (CiSTUP),
Centre for Sustainable Technologies (CST)
Indian Institute of Science, Bangalore - 560 012
Email: gls@civil.iisc.ernet.in, glsivakumar@gmail.com

Academic qualifications

Ph.D.	Geotechnical Engineering Indian Institute of Science, Bangalore, India	1991
M.E.	Soil Mechanics Foundation Engg. Anna University, Madras	1987
B.Tech.	Civil Engineering Sri Venkateswara University, Tirupati	1983

Professional experience

10/2009- Present	Professor, Indian Institute of Science, Bangalore
10/2003 – 10/2009	Associate Professor, Indian Institute of Science, Bangalore
11/96 - 10/2003	Assistant Professor, Indian Institute of Science, Bangalore
5/92 - 11/96	Scientist, Central Road Research Institute, New Delhi
9/89 - 5/92	Scientific Officer, Indian Institute of Science, Bangalore
2/83 - 7/85	Engineer, International Airports Authority of India, N. Delhi

Assignments abroad

06/99 - 07/2000	Humboldt Fellow & Visiting Scientist, Germany
2/95 - 2/96	Visiting Scholar, Purdue University, Lafayette, USA

Countries visited for long/short stays

USA, Germany, Japan, Thailand, Australia, Finland, Italy, Norway, France, Austria, Singapore and many other countries

Research guidance

Ph.D -8, M. Sc (Engg.)-3, PhD (9 students presently doing research)

Publications

Book – (on soil reinforcement and geosynthetics), Edited books and proceedings 6
International and national Journals -99, International and national conf. over 100 Total over 200.

Research activities

Risk and reliability applications in Geotechnical engineering, Ground Improvement, Geotechnics for infrastructure, Geosynthetics and reinforced soil structures, Earthquake Geotechnical engineering, Geotechnics for disaster mitigation and Geoenvironmental Engineering

Awards and Recognitions
International

1. **Excellent Contributions Award** of International Association for Computer Methods and Advances in Geomechanics (IACMAG), USA "for excellent scientific contributions in the application of probabilistic methods in geotechnical engineering practice, geomechanics, constitutive modeling and ground improvement".
2. Best paper award of International Association for Computer Methods and Advances in Geomechanics (IACMAG) USA for the paper G L Sivakumar Babu and B. Munwar Basha (2008). Optimum design of cantilever retaining walls using target reliability approach. International Journal of Geomechanics, Journal of American Society for Civil Engineers (ASCE), 8(4): 240-252.
3. Best paper award of International Association for Computer Methods and Advances in Geomechanics (IACMAG) USA for the paper Sumanta Haldar and G. L. Sivakumar Babu (2010) Failure Mechanisms of Pile Foundations in Liquefiable Soil: Parametric Study published in International Journal of Geomechanics, ASCE , 10(2).74-84.
4. Best Theoretical Oriented Paper Award of the EWRI (Environmental and Water Resources Institute, USA) -ASCE for 2011 for the paper G L Sivakumar Babu, Reddy Krishna, R, Sandeep Kumar Chouksey and Hanumanth Kulkarni (2010) Prediction of Long-Term Municipal Solid Waste Landfill Settlement Using Constitutive Model. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, ASCE, Vol.14 (2).139-150
5. Editorial Board Member, International Journal of GEORISK -Assessment and Management of Risk for Engineered Systems and Geohazards, Taylor & Francis Group
6. Editorial Board Member, GROUND IMPROVEMENT Journal, Journal of Institution of Civil Engineers, UK published by Thomas Telford publishers
7. Editorial Board Member, Editorial Board Member of **The** Open Transportation Journal Bentham Science Publishers
8. Alexander von Humboldt Fellowship (Visiting Scientist, Geotechnical Institute, Landesgewerbeanstalt Bayern, Nuremberg) for the year 1999-2000.
9. Visiting Scholar, Purdue University, West Lafayette IN during 1995-96.
10. Secretary, International Technical Committee (TC-40) on Forensic Geotechnical Engineering (FGE), a body of International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE).
11. Member, International Technical Committee (TC-32) on Risk assessment in Geotechnical Engineering, a body of International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) for 1997-2001 and 2001-2005.
12. Served as *Chairman/Co-chairman/expert for technical sessions in various international/national conferences in India and abroad*
13. Reviewer for many international journals such as American Society for Civil Engineers (ASCE), Canadian Geotechnical Journal, Geotechnique, Computers and Geotechnics, Georisk, Engineering Structures and national journals such as Indian Geotechnical Journal, Sadhana etc.

National

14. Member, Sectoral Innovation Council, Ministry of Road Transport and Highways, Government of India

15. Editor, Indian Geotechnical Journal of the Indian Geotechnical Society, New Delhi.
16. IGS-AFCONS Biennial Award for the best paper on Case Histories" published through the Indian Geotechnical Society Back on Analysis of the Chang Dam Section in the Kachchh Region of Gujarat, India" published in the Proceedings of 17 ICSMGE-2009, Alaxendria, Egypt. The best Doctoral thesis in Geotechnical Engineering in India for the year 1991, by the Indian Geotechnical Society, New Delhi.
17. T Narayana Reddy Memorial Lecture on Geotechnics for Infrastructure Improvement, 27th November 2008, Institution of Engineers (India), Tirupati.
18. Smt. Indra Joshi biennial best paper award by Indian Geotechnical Society (IGS) on case studies for the paper titled Underpass at Air Force Station, Yelahanka, Bangalore, published in the proceedings of IGC-2006.
19. Committee Member, Special Committee on suggestion of appropriate remedial measures for Tungabhadra Left Bank Canal Government of Karnataka 2005B N Gupta Best paper award for the paper on shallow foundations for the paper Reliability analysis of bearing capacity of shallow foundations, published in the proceedings of IGC-2003.
20. IGS-AIMIL Annual Prize for the best paper on Instrumentation for the paper Instrumentation, and Monitoring of Slope Movements at Powari landslide, Proc. Of IGC 95.
21. BOYSCAST Fellowship for one year by the Department of Science and Technology, Government of India to conduct research at Purdue University, U.S.A., 1994.
22. Represented India at II Young Asian Geotechnical Engineers, Conference, 1994 at Bangkok.
23. Young Engineer Prize for the year 1993, by Central Board of Irrigation and Power, Ministry of Water Resources, New Delhi.
24. Certificate of Merit for the paper Prediction of engineering behavior of tropical residual soils during 56th annual session from the CBI &P, New Delhi (1989).

Membership of professional bodies

Fellow of Institution of Engineers India, Fellow of Indian Geotechnical Society, Fellow of Association of Consulting Engineers (ACCE), Member of American Society of Civil Engineers (ASCE), Member of International Geosynthetics Society (IGS), Life Member of Indian Roads Congress, etc

510. Curriculum vitae (CV) of **Co-Investigator** (CI)

CV of the CI

Name & Designation: Sekhar Muddu, Associate Professor
Date & Place of Birth: 26 August 1963; New Delhi
Nationality: Indian
Present post: Associate Professor,
Institution with address:
Department of@ngineering
Indian Institute of Science, Bangalore, 560 012, INDIA.
Telephone No.
(work) +91 (80) 22 93 22 45 (home) +91 (80) 23 60 28 70 & +91 (80) 23 60 35 25
(mobile) +91 98450 96259 **Fax:** +91 (80) 23 60 04 04
Email: muddu@civil.iisc.ernet.in or sekhar.muddu@gmail.com
Webpage: http://civil.iisc.ernet.in/~muddu

Qualifications :

1993	Ph.D.	Indian Institute of Science	Groundwater Hydrology
1987	M.E.	Indian Institute of Science	Hydromechanics & Water Resources
1984	B.Tech	JNT University, Hyderabad, India	Civil Engineering

Experience:

12/2007-to date	Associate Professor, Indian Institute of Science, Bangalore, India
12/1996-12/2007	Assistant Professor, Indian Institute of Science, Bangalore, India
5/2010-8/2010 & 5/2009-7/2009	Visiting Scientist Fellowship of INRA, France.
4/2006-12/2006	Poste Rouge fellowship of CNRS, France
5/2005-7/2005	Visiting Scientist, University of Paul Sabatier, Toulouse, France.
6/2004-7/2004	Visiting Scientist, LMTG, Observatoire Midi-Pyrenees, Toulouse.
7/2002	Visiting Scientist, University of California, San Diego, USA
3/2001-5/2001	Visiting Scientist, Department of Mathematics and Computing Science, Technical University of Eindhoven, The Netherlands.
12/1993-12/1996	Lecturer, Indian Institute of Science, Bangalore, India.
2/1993-11/1993	Project Leader, Transoft International, Paris & Bangalore, India. (Developed "*Pollusol*" – a *Fluidyn* code)

Awards & Felowships

1. Visiting scientist fellowship of INRA, France (2009, 2010 & 2011).
2. Poste Rouge fellowship of CNRS, France.
3. Research fellowship of Indian Institute of Science for Ph.D (1987-1992).
4. Distinction, B.Tech, National scholarship of government of India for M.E. (1985-1987).
5. State recognition award for outstanding academic performance of the Government of Andhra Pradesh, India (1980-1984).

Recognitions

1. Invited by the National Academy of Engineering, USA as a speaker at the Second Indo-American Frontiers of Engineering Meeting, 28th February – 1st March, 2008, Irvine, USA.
2. Member, Central level Expert group for overall reassessment of groundwater resources of the country, 2010, Ministry of Water Resources.
3. Member of the Working group on Water Database Development and Management, Planning Commission, 2010.
4. Nominated as **Executive** Committee Member, Karnataka State Natural Disaster Monitoring Center, Government of Karnataka, India – May 2004.

Areas of Research

I work in the research areas including groundwater hydrology, numerical modeling, and environmental engineering. My interests include analysis of flow and reactive transport in groundwater systems, field-scale experiments in watershed hydrology, geospatial & geophysical methods and optimization & inverse problems

List of Relevant Publications

1. B. Siva Soumya, B., Sekhar, M., Riotte, J., Audry, S., Lagane, C., Braun, J. J. (2011). Inverse models to analyze the spatiotemporal variations of chemical weathering fluxes in a granito-gneissic watershed: Mule Hole, South India. Geoderma (In Press).
2. Suresh Kumar, G., Sekhar, M. and Misra, D. (2011). Spatial and temporal moment analyses of decaying solute transport in a single fracture with matrix diffusion. Journal of Petroleum and Geosystems Science and Engineering (In Press).
3. Sat Kumar, Sekhar, M., Mohan Kumar and Reddy, D. V. (2010). Estimation of soil hydraulic properties and their uncertainty: comparison between laboratory and field experiment. Hydrological processes. DOI: 10.1002/hyp.7775.
4. Sat Kumar, Sekhar, M., Bandyopadhyay, S. (2009). Assimilation of remote sensing and hydrological data using adaptive filtering techniques for watershed modeling. Current Science, Vol.97(8), pp.1196-1202 (Invited article in Section: Civil engineering Research).
5. Ruiz, L., Murari, R. R. V., Mohan Kumar, M. S., Sekhar, M., Maréchal, J-C., Descloitres, M., Riotte, J., Sat Kumar, Kumar, C. and Braun, J-J. (2009). Water balance modelling in a tropical watershed under deciduous forest (Mule Hole, India) : regolith matric storage buffers the groundwater recharge process. Journal of Hydrology. 10.1016/j.jhydrol.2009.11.020.
6. Sat Kumar, Sekhar, M. and Reddy, D. V. (2009). Improving the disaggregation of daily rainfall into hourly rainfall using hourly soil moisture. Hydroinformatics in hydrology, hydrogeology and water resources. IAHS Publication. 331, pp.236-244.
7. Javeed, Y., Sekhar, M., Bandyopadhyay, S. and Mangiarotti, S. (2009). EOF and SSA analyses of hydrological time series to assess climatic variability and land use effects: a case study in the Kabini River basin of South India. IAHS Publication. 329, pp.167-177.
8. Majumdar, P. K., Sekhar, M., Sridharan, K, Mishra, G. C. (2008). Numerical simulation of groundwater flow with gradually increasing heterogeneity due to clogging. Journal of Irrigiation and Drainage Engineering (ASCE), Vol. 134(3), pp. 400-404.
9. Sekhar, M., Braun, J. J., Rao, K.V. H., Ruiz, L., Robain, H., Viers, J., Ndam, J. R., Dupre, B. (2008). Hydrogeochemical modeling of organo-metallic colloids in the Nsimi experimental watershed, South Cameroon. Environmental Geology, Vol. 54(4), pp. 831-841.
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12. Kumar, G. S., Sekhar, M., Misra, D. (2008). Time-dependent dispersivity of linearly sorbing solutes in a single fracture with matrix diffusion. Journal of Hydrological Engineering (ASCE), Vol.13(4), pp. 250-257.
13. Chaudhuri, A. and Sekhar, M. (2007) Analysis of biodegradation in a 3-D heterogeneous porous medium using nonlinear stochastic finite element method. Advances in Water Resources, V. 30, pp.589-605.
14. Chaudhuri, A. and Sekhar, M. (2007) Stochastic finite element method for analysis of transport of nonlinearly sorbing solutes in 3-D heterogeneous porous media. Water Resources Research, 43, W07442, doi:10.1029/2006WR004892.
15. Sekhar, M., Suresh Kumar, G., and Misra, D. (2006). Numerical Modeling and Analysis of Solute Velocity and Macrodispersion for Linearly and Nonlinearly Sorbing Solutes in a Single Fracture with Matrix Diffusion. Journal of Hydrological Engineering, ASCE, V. 11 (4), pp.319-328.
16. Sekhar, M. and Suresh Kumar, G. (2006) Modelling transport of linearly sorbing solutes in a single fracture: Asymptotic behavior of solute velocity and dispersivity. International Journal of Geotechnical and Geological Engineering, V.24, pp.183-201.
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20. Sekhar, M., Rasmi, S.N., Javeed, Y., Gowrisankar, D., and Ruiz, L. (2006). Modeling the groundwater dynamics in a semi-arid hard rock aquifer influenced by boundary fluxes, spatial and temporal variability in pumping/recharge. Advances in Geoscience, Hydrological Sciences (ed) Park, N., V. 4, p. 173-181.
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24. Chaudhuri, A and Sekhar, M. (2005). Probabilistic analysis of pollutant migration from a landfill using stochastic finite element method. Journal of Geotechnical and Geoenvironmental Engineering, ASCE , V.131, No.8, pp.1042-1049.
25. Hari Prasad, K. S., Mohan Kumar, M. S., Sekhar, M., (2005) Analysis of saturated-unsaturated flow near a pumping well in an aquifer-water table aquitard system. Hydrology Journal, V. 28, No.1-2, pp. 19-32.
26. Sekhar, M., Rasmi, S.N., Sivapullaiah, P.V. and Ruiz, L. (2004) Groundwater flow modeling of Gundal sub-basin in Kabini river basin, India. Asian Journal of Water, Environment and Pollution, V. 1(1-2), pp. 65-77.

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Sensitivity Unsaturated Soil Properties, Sadhana, Proceedings of Indian Academy of Sciences in Engineering

Sciences, V. 26(6), 2001, pp.517-528.

520. Curriculum vitae (CV) of **Principal Collaborator** (PC)

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Qualifications:

Sl. No.	Degree	Institute/University	Year of passing	Subject of specialization	%/CPI Class/grades
1	B. Tech.	Bihar Institute of Technology, Sindri, Dhanbad	1989	Civil Engineering	74.75% First class with distinction
2	M. Tech.	I. I. T. Kanpur	1991	Geotechnical Engineering	8.25/10
3	Ph. D.	I. I. T. Bombay	2005	Geotechnical Engineering	7.5/10

I. Refereed Journals:

(a) International Journals

1. Rao, B. Hanumantha., Sridhar, V., **Rakesh, R. R.**, Singh, D. N., Narayan, P. K., and Wattal, P. K. (2011). "Modelling Radioactive Contaminant Transport in Soils", International Journal of Environment and Waste Management, in print.

2. **Rakesh, R. R.**, Singh, D. N., Nair, R. N. (2009). "A methodology for simulating radionuclide diffusion in unsaturated soils", Journal of Geotechnical and Geological Engineering. 27(1), 13-21.

3. B. Hanumantha Rao, V. Sridhar, **R. R. Rakesh**, D. N. Singh, P. K. Narayan, P. K. Wattal (2009) "Application of In-situ Lysimetric Studies for Determining Soil Hydraulic Conductivity", Journal of Geotech Geol Eng. 27(5), 595-606.

II. Publications in the Conference Proceedings:

(a) International Conferences

1. A. Rawat**, ,R. R. Rakesh**, J. N. Mandal (2011) "A Study on Inclusion of Different Types of Fibers in Cover Soil for Low Level Radioactive Waste Disposal Facilities", *In the Proc. of 12th IACMAG International Conference held in Melbourne, Australia*, 9-11, May 2011. pp:724-729.
2. **R. R. Rakesh**, P. K. Wattal, R. N. Nair, D. N. Singh (2011) 'Some studies on soil-radionuclide interaction under varied experimental conditions', In the Proc. of 13th IACMAG International Conference, Melbourne, Australia, 9-11, May 2011.
3. **R R Rakesh**, P K Wattal (2011) 'Service Life Prediction of Reinforce Concrete Trenches' In the Proc. Of International Conference SMiRT 21, Nov. 06-11, 2011, New Delhi India.
4. A. Rawat**, ,R. R. Rakesh**, J. N. Mandal (2011) "A Study on Inclusion of Different Types of Fibers in Cover Soil for Low Level Radioactive Waste Disposal Facilities", *In the Proc. of 12th IACMAG International Conference held in Melbourne, Australia*, 9-11, May 2011. pp:724-729.
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6. Rawat A, **Rakesh R. R.** and Mandal J. N. (2010) "Effect of Glassgrid Geocell Inclusion on Flexural Behavior of Cover Soil for Low Level Radioactive Waste Disposal Facility", *In the Proc. of 6th International Congress on Environmental Geotechnics at New Delhi, India*, 08-12. pp: 402-408.
7. **R. R. Rakesh**, P. K. Narayan, P. K. Wattal, S. Anil Kumar, B. Hanumantha Rao, and D. N. Singh. (2008). "In-Situ Lysimeter Studies for Radionuclide Migration In Undisturbed Unsaturated Soil Under Geo-Environmental Condition", In the Proc. of 12th IACMAG International Conference held in Goa from 1-6, October-2008, India, pp: 2320-2326.
8. Shirole, A., **Rakesh, R. R.**, Raj, K. and Bansal, N. K. (2005). "Condition Monitoring and Service Life Prediction of Near Surface Disposal Module Located at Three Different Sites in India", *International Conference on the Safety of Radioactive Waste Disposal*, IAEA-CN-135/40, Tokyo, Japan, October 03-07., pp. 157-161.

(b) Indian Conferences

1. **R. R. Rakesh**, M. R. Joshi, D. N. Yadav, K. K. Narayan and S. Anil Kumar (2007). – "In-situ studies of Radionuclide Migration at Near Surface Waste Disposal Facility, Trombay", Mitigation of Pollutants for Clean Environment - *Proceedings of the Fifteenth National Symposium on Environment (NSE-15)*, Bharathiar University, Coimbatore, India, June 05-07,pp. 235-240.
2. Singh, D. N., Rao, H. and **Rakesh R. R.** (2007). "In-situ Studies on Hydraulic Conductivity of Unsaturated Soils", *Proceedings of 9th Technical Programme Discussion Meeting of BRNS Projects*, organized by NRFCC BRNS, Mumbai, February 23-24, pp. 94-98.
3. **Rakesh, R. R.** (2007). "Radionuclide Transport through Fractured Porous Media: Analytical Solutions for Single and Parallel Fractures", *Proceedings of DAE-BRNS Theme Meeting on Modelling of Groundwater Contamination,* organized by HS & EG, BARC, Mumbai, January 08-12, pp 176-189.

4. **Rakesh, R. R.**, Joshi, M. R., Pawar, V. M. and Narayan, P. K. (2005). "Sorption Behaviour of Selected Fission and Activation Products with Soils and Rocks of Some Near Surface Radioactive Waste Disposal Facilities." *Proceedings of DAE-BRNS Symposium on Nuclear and Radiochemistry 'NUCAR - 2005'*, Amritsar, India, 641-642.

5. **Rakesh, R. R**., Narayan, P. K. and Mathur, R. K. (1995). "Development of a Radionuclide Leach and Transport Model for a Cylindrical Waste Form", Symposium on Management of Radioactive and Toxic Waste (SMART), Trombay, India, 1995.

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(c) IAEA Meetings

1. R. G. Yeotikar, **R. R. Rakesh**, Ajay Shirole, Biplob Paul, T. P. Valsala and D. K. Choudhury. (2010). 'Characterization, improvement and long term evaluation of cementitious waste products –An Indian Scenario', 3rd RCM of IAEA CRP on 'Behaviour of Cementitious Materials in Long Term Storage and Disposal of Radioactive Waste' *at Safety Research Institute, Kalpakkam, Oct. 18-22, 2010.*

2. **Rakesh R. R**. and Narayan, P. K. (2008). "Thermo-mechanical Analysis and Performance Assessment of Conceptual Geological repository", 2nd RCM of IAEA CRP on 'Use of Numerical Models in Support of Site Characterization and Performance Assessment of Geological Repository', Daejeon, Republic of Korea during May 19-23, 2008.

3. Narayan, P. K., **Rakesh R. R**., Ranjan Rajeev and Bajpai, R. K. (2006). "Thermo-mechanical Models in Conceptual Design and Performance Assessment of Geological Repository", 1st RCM of IAEA CRP on 'Use of Numerical Models in Support of Site Characterization and Performance Assessment of Geological Repository', Beijing, China, Sep. 11-15, 2006.

4. Kumar S., Satya Sai, P. M., Manohar S. and **Rakesh, R. R.** (2006). "Studies for onsite Disposal of Waste from Decommissioning/Revamping on Nuclear Facilities and NPPs in India", 3rd RCM of IAEA-CRP at Vienna, Austria, Feb. 20-24, 2006.

5. Bansal, N. K., Kumar, S., Kaushik, C. P., Rakesh, R. R., Galande, S. M. (2004). 'Safety Assessment of Radioactive Waste Packages for Disposal in Near Surface Disposal Facilities', 'Long Term Behaviour of Low and Intermediate Level Waste Packages Under Repository Conditions', IAEA-TECDOC-1397, 2004. pp. 101-118.

6. **Rakesh, R. R.** et. al. (2004). 'Safety Assessment Methodologies for Near Surface Disposal Facilities, Results of a Coordinated Research Project Vol.1: Review and enhancement of safety assessment approaches and tools. Vol.2: Test cases, IAEA, Vienna, 2004. ISBN 92-0-104004-0, ISSN 1011-4289.

7. **Rakesh R. R.**, Narayan, P.K. and Raj. K. (2001). "Safety aspects of Radioactive Waste Management Practices and Activities in India", in international training programme on 'Safety Assessment Methodology for Near Surface Radioactive Waste Disposal facilities,' Singapore, November 26 – December 07, 2001.

8. **Rakesh, R. R**., Narayan, P. K. and Nair, R. N. (2000). "Safety Assessment Activities in India", 3rd RCM of IAEA - CRP on Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM), Vienna, Austria, September 25-29, 2000.

9. Bansal, N. K; **Rakesh, R. R.** et. al. (1999). "Long Term behaviour of Low and Intermediate Level Waste Packages Under Repository Conditions", 2nd RCM of IAEA - CRP at Cordoba (Spain), April 19-23, 1999.

10. **Rakesh, R. R**., Narayan, P. K. and Nair, R. N. (1999). "Safety Analysis of Radioactive Waste Storage and Management Site, Trombay", 2nd RCM of IAEA - CRP on Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM), Vienna, Austria, Feb. 01 – 05, 1999.

11. Kumra, M. S., **Rakesh, R. R.** et. al. (1997). "Long Term behaviour of Low and Intermediate Level Waste Packages Under Repository Conditions", first RCM of IAEA - CRP at Moscow, November 24-28, 1997.
12. Krishnamoorthy, T. M., **Rakesh, R. R.** et. al. (1994). "The Safety Assessment of Near Surface Radioactive Waste Disposal Facilities (NSARS) - Results of Test case - 2B", 3rd RCM of IAEA - CRP on NSARS at Seville, Spain, April 1994.
13. Kumra, M. S., **Rakesh, R. R.** et. al. (1992). "The Safety Assessment of Near Surface Radioactive Waste Disposal Facilities (NSARS) - Results of Test Case - 2A", 2nd RCM of IAEA - CRP on NSARS at Augusta (Georgia) U. S. A., October 1992.

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(BARC Library reports)

1. **Rakesh, R. R., Yadav, D. N., Narayan, P. K., Wattal, P. K., P. Pal. and S. Vedamoorthy (2007). – "Post-closure Safety Assessment of Solid Waste Management Plant, Kota, Rajasthan", Report No. BARC/2007/I/001.**
2. **Rakesh, R. R.**, Yadav, D. N., Narayan, P. K. and Nair, R. N. (2005). – "Post Closure Safety Assessment of Radioactive Waste Storage and Management Site, Trombay", Report No. BARC/2005/I/010.
3. Mathur, R. K., **Rakesh, R. R.** et. al. (1998). "In-situ Multi-heater Thermo-mechanical Experiment in Mysore Mines, Kolar Gold Fields", Rep. No. BARC/1998/I/015.

(Sectional Reports)

1. **R. R. Rakesh**, R. B. Sastry, A. Shirole, S. B. Patil (2011) 'Two-Tier RCC Trenches for Solid Radioactive Waste Disposal', Task force report, NRG, BARC Trombay.
2. **R. R. Rakesh**, R. B. Sastry, A. Shirole, S. B. Patil (2010) 'Above ground RCC dyke at RSMS Trombay', Task force report, NRG, BARC Trombay.
3. **Rakesh, R. R.** and Yadav, D. N. (2009). "Post-closure Safety Assessment of NSDF, Kakrapar Atomic Power Station, Gujrat', an internal report of BETDD/RPS, report submitted to NPCIL.
4. Yadav, D. N., **Rakesh, R. R.**, Joshi, M. R. Pawar, V. M. (2005). 'Preliminary Report on Estimation of Groundwater Recharge Using ^{3}H as a Tracer at Gamma Garden, Trombay', an internal report of RPS/BETDD/NRG, BARC, Trombay .
5. **Rakesh, R. R.**, Yadav. D. N., Narayan, P. K. (2004). 'Preliminary Report on Radionuclide Migration based on Monitoring of Borehole Data from SWMF, Tarapur, an internal report of RPS/BETDD/NRG, BARC, Trombay.
6. **Rakesh R. R.**, and Narayan, P.K. (2002). "Post Closure Safety Analysis of Solid Waste Management Facility, Tarapur", an internal report of RPS/BETDD/NRG, BARC, Trombay.
7. **Rakesh R. R.**, Narayan, P.K. and Mathur, R. K. (2000). "Preliminary Safety Analysis of Proposed Beryllium Disposal at Trombay", Internal report of RPS/NRG.
8. **Rakesh, R. R**., Narayan, P. K. and Mathur, R. K.(1993). "Safety Analysis and Modelling of Migration of Radionuclides through Geologic Media for Nuclear Waste Disposal Site, Kiaga",

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List of Publications of Shri VS Phanikanth as on 29-08-2011:

International Journals

1) Phanikanth V.S., Srinivas K., and Reddy G.R. (2010). "Floor Response Spectrum Generation Using Simplified Procedures- Case Study of an Underground structure". ***International Journal of Earth sciences and Engineering***, (ISSN 0974-5904), Vol. 03, No. 04- Spl. issue, July 2010, pp. 643-651.
2) Phanikanth V.S., Choudhury D. and Reddy G.R. (2010). "Response of single pile under lateral load in cohesionless soils", ***Electronic Journal of geotechnical Engineering***, (*ISSN: 1089-3032*), USA, Vol. 15, Bundle H, pp. 813-830.
3) Phanikanth V.S., Choudhury D. and Reddy G.R. (2010). "Behaviour of Fixed head single pile in cohesionless soil under lateral loads", ***Electronic Journal of geotechnical Engineering***, *(ISSN: 1089-3032)*, USA, Vol. 15, Bundle M, pp. 1243-1262.
4) Phanikanth V.S., Choudhury D. and Reddy G.R. (2010). "Equivalent linear ground response analysis of some typical sites in Mumbai city", ***Geotechnical and Geological Engineering,*** (*ISSN: 0960-3182*) Springer, Netherlands, (accepted, in press for publication).
5) Phanikanth V.S., Choudhury D. and Reddy G. R. (2011). "Behaviour of single pile in liquefied deposits during earthquakes", (Under review process in ***International Journal of Geomechanics, ASCE***).

National Journals

6) Deepankar Choudhury, Phanikanth V. S., Reddy G.R.(2009). "Recent advances in analysis and design of pile foundations in liquefying soils during earthquake: a review ". *Proceedings of the National Academy of Sciences, (Section A, Part II)*, Vol. LXXIX, India.

International Conferences

7) Phanikanth V.S., Choudhury D. and Reddy G.R. (2011). "Behaviour of Single Piles in Cohesiove Soils under Lateral Loads", *13th International Association for Computer Methods and advances in Geomechanics*, Melbourne, Australia, May, 2011, Paper ID 1073,pp.899-904.
8) Phanikanth V. S., Srinivas K., Reddy G.R. (2009). "Floor response spectrum generation using Simplified procedures- Case study of an underground structure". *Advances in Concrete Structural and Geotechnical Engineering* (*ACSGE*).
9) Phani Kanth V.S., Srinivas K., Ratwani S.S, Reddy G.R., Vaze K.K.,(2008). "Seismic Analysis of underground Structure Considering Soil Structure Interaction." *12th International Conference on International Association for computer methods and advances in Geomechanics* (*IACMAG*), *Goa, India, October*, 2008.
10) Mukhopadhyay M., Choudhury D., Phanikanth, V.S. and Reddy G.R. (2008). "Pushover analysis of piles in stratified soil", *Proceedings of 14th World Conference on Earthquake Engineering* (*14WCEE*), October 12 - 17, 2008, Beijing, China, in CD paper number 04-01-0060.
11) Soil Structure Interaction analysis of a reinforced concrete Stack (2008). Phanikanth V.S. *Indian Geotechnical Conference (IGC)*, IISc Bangalore, India.
12) Seismic/wind analysis of a reinforced concrete chimney-comparative study of A.C.I & IS. Codes. Phani Kanth V.S., Jain R.C., and Ramanujam S. (2003). *International Conference on Structural Engineering Convention*, December, IIT, Kharagpur, India.
13) Computer aided analysis of a machine foundation (2002). Phanikanth V.S., Patnaik R., Ramanujam S., *Proc. of the Second International Conference on Vibration Engineering and Technology of Machinery, VETOMAC-II*, December, BARC Mumbai, India.
14) Evaluation of Seismic Fragility of Structures - A Case Study. Bhargava K., Agrawal M.K., Phanikanth V. S., Reddy G.R., Ghosh A.K., Patnaik R., Ramanujam S. and Kushwaha H.S.(1999). *15th International Conference on Structural Mechanics in Reactor Technology*, August.

Date: 29-08-2011

Place: Mumbai-94

Signature:

(Dr.VS. Phanikanth)

SECTION-C

CERTIFICATE-1 (Submit single hard copy only**)**
Certificate from the Head of the Institution of the Principal Investigator (PI) and Co-Investigator (CI) from Non-DAE Institution (Please see Instruction - Sr. No.4-6)
...

Project Title: **Development of Probabilistic design and analysis procedures in radioactive waste disposal in NSDF and design of NSDF closure**

(1) Certified that this Institution agrees to the participation of

Prof.G L Sivakumar Babu(PI)	Prof./M Sekhar (CI)
Department of Civil Engineering	Department of Civil Engineering
Indian Institute of Science	Indian Institute of Science
Bangalore	Bangalore

for the above project which is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS).

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) Certified that the management takes the responsibilities for the timely submission of audited (by external Chartered Accounted or Statutory Government Auditor) statement of account (SA), utilisation certificate (UC), details of staff recruited and equipment purchased for each year as well as the audited (by external Chartered Accounted or Statutory Government Auditor) consolidated SA and UC for the final year.

(4) **Particulars of University Bank A/c are as follows (Please see Instruction - Sr. No.7):**

a) Name of Account Holder:

b) Account No.:

c) Bank Name and Branch Address:

d) Branch code:

e) IFS Code: (16 digits)

Date:

Place:

Name & signature of the
Head of the institution
or his authorised nominee

Seal:

Note: For Multi-Centre projects, similar certificate is needed from all the participating institutions.

CERTIFICATE-2 (Submit single hard copy only**)**

Certificate from the Head of the Institution of Principal Collaborator (PC) /Departmental Coordinator (DC) from DAE Institution

(Please see Instruction - Sr. No.7)

....

Project Title: **Development of Probabilistic design and analysis procedures in radioactive waste disposal in NSDF and design of NSDF closure**

(1) Certified that this Institution agrees to the participation of Prof./Dr. _____ Department/Address _____ as Principal Collaborator (PC)/ Departmental Coordinator (DC) for the above project that is being submitted for financial support to the Board of Research in Nuclear Sciences (BRNS) by Prof./Dr. _____ Department/Address _____ as Principal Investigator (PI) .

The PC/ DC shall coordinate for timely submission of yearly progress reports and financial documents towards meaningful conclusion of the project as scheduled.

(2) Certified that the infrastructural facilities related to the project activity available in this institution and in Part II of the proposal (including equipment, manpower and other facilities) will be extended for the project.

(3) This institution assures to undertake the financial and other management responsibilities of the part of the project work that will be conducted in this institution.

(4) This Certificate is being issued with approval of the Group Board or the Group Board approval shall be taken, after the project is sanctioned by BRNS.

Date:

Place:

Name & signature of the
Head of the DAE institution/
Head of the Group

Seal:

Detailed Proposal

Development of Probabilistic design and analysis procedures in radioactive waste disposal in NSDF and design of NSDF closure

Introduction

Performance of NSDF disposal modules as effective barriers/engineered systems to prevent possible radionuclide leaching to ground water followed by migration to geo-environment essentially depends on total isolation of wasteform material using engineered disposal modules. The engineered disposal modules consist of liners at the bottom, disposal modules (Stone Lined Trench (SLT)/Reinforced Cement Concrete Trench (RCT)/Tile Holes(TH)) followed by proposed clay covers at the top. The basic design objective of engineered disposal system is to design and develop barrier systems that minimize the waste water interaction. Based on extensive research, design and feedback from field experience, regulations are developed in many developed and developing countries for the design of disposal system. Raj et al (2006) provide details on radioactive waste management practices in india. Enforcement of regulations is based on both prescriptive designs (minimum) and performance based designs with appropriate justifications. Once the disposal system operationally closed i.e. it stops receiving the waste, a designed multi layer cover is placed over the top of the disposal modules to prevent water infiltration into disposal modules from top. There are number of issues related with the design of liner and top cover that need to be addressed for the effective isolation of radioactive waste for a sufficiently long period. The proposal seeks to address these issues based on collection of data from the field and in experimentation and analysis using probabilistic considerations.

Issues

A few issues of concern are a) characterization of waste forms b) understanding of engineering behavior of wasteform in the field c) placement of waste during filling and corresponding specifications d) development of design procedures for clay liners and covers and e) performance assessment of the disposal system components as a individual unit and as an integrated system. It is known that many properties involved in design are vary from point to point both in time and space scales and hence have a significant role in all the above issues. Hence use of probabilistic analysis is necessary.

a) Characterization of waste

The geotechnical properties of radioactive wasteforms are of paramount importance in designing and assessing the performance of integrated disposal system and in ensuring safe long-term containment of radioactive waste to prevent human health and the environment from any undue risk. Rao et al (2009), Rakesh et al (2009) extensively studied the transport phenomena related to radioactive contaminants using modeling and also using lysimeter tests. Solid wastes are divided into four categories and category I which consists of treated paper trash etc. This category is similar to Municipal Solid waste (MSW) and knowledge of unit weight, vertical compressibility, shear strength, lateral stiffness, in situ stresses and hydraulic conductivity is fundamental to the assessment of waste disposal stability and integrity of both geosynthetic and mineral lining components. An internationally agreed classification system and test standards are required to allow interpretation of published results. This will lead to development of appropriate constitutive models for waste and hence to optimization of disposal modules designs by considering waste/lining system interaction in full. Often, it is less realized that the variation and range of properties control the performance as well as stability. The safety and stability of the disposal system need to be assessed based on probabilistic considerations.

b) Engineering behavior of Waste

Engineering behaviour of the waste body controls many aspects of lining system design and performance, including stability issues and integrity of the geosynthetic and mineral lining components. The response of radioactive waste in terms of stability, settlement and stability under flow and circulation of leachate depends on the engineering properties. Knowledge of shear strength is required in order to assess waste slope stability. Mechanisms resulting in settlement of waste include physical compression and creep, raveling and decomposition due to biodegradation of organic components. For simplicity, the total settlement of a waste in disposal modules can be taken as the combination of primary and secondary compression. Primary compression includes the physical compression of components and consolidation. Secondary compression includes all creep effects and those relating to degradation. It is well recognized that the compression and shear strength of waste forms are interrelated and there is a need to study the coupled compression-strength behavior. Several researchers have begun to use advanced mathematical models to assess the coupled stability and settlement and strength of landfills by attempting to account for the complex behavior of wasteforms. For example, Reddy et al. (1996) demonstrated that displacement-based analysis provides a better understanding of the shear stress–displacement behavior of MSW and liner systems under incremental. The properties of MSW were found to have a significant effect on the shear stress–displacement of composite geosynthetic liner systems. The main drawback of such advanced analyses is the use of a constitutive model that does not accurately describe the coupled compression-strength response of MSW under drained or undrained conditions. Recognizing the above, Babu et al (2010a, 2010b and 2011) developed and validated constitutive model that accounts for primary compression and time dependent mechanical creep and biodegradation is used for parametric study to investigate the effects of model parameters on the predicted settlement of municipal solid waste (MSW) with time. The model enables the prediction of stress strain response and yield surfaces for three components of settlement: primary compression, mechanical creep, and biodegradation. The similar studies have to be performed for different radioactive wasteforms being disposed in NSDF disposal modules. MSW parameters investigated include compression index, coefficient of earth pressure at-rest, overconsolidation ratio, and biodegradation parameters of MSW. Overall, the study shows that the variation in the model parameters can lead to significantly different results; therefore, the model parameter values should be carefully selected to predict settlements accurately. However, the parametric analysis using a set of deterministic parameters cannot capture the effects of variations and correlations between properties in a rational manner and hence probabilistic analysis of engineering response is necessary.

c) Placement of waste during filling and corresponding specifications

Normally waste material needs to be placed during disposal in a manner that reduces further settlements. In addition, the material is expected to have good strength properties and should be able to support the loads that are expected later. For this purpose, specifications indicate that compaction of waste material is desirable. However, the specifications are not clear with regard to the compaction lift requirements etc. Recently an attempt is made by Babu et al (2011) to examine the role of compaction thickness on the ultimate settlement of MSW based on the constitutive model approach. Results clearly highlight the importance of compaction in the settlement analysis. There is a need to examine the above for radioactive wasteforms using probabilistic considerations as the properties involved in the analysis are variable.

d) Development of design procedures for clay liners and covers

The design of clay liner thickness is based on permeability characteristics of the clays, as well as that of natural materials below, diffusion characteristics of clay soil liner as well as that of natural material, thickness of the liner, and resistance to desiccation cracking. Similarly the design of clay cover is a function of the permeability of the clay, soil moisture storage capacity of the clay reflected in terms of

soil water characteristics, as local atmospheric conditions. These aspects can be modeled by HELP programme. Desiccation of clay liners and clay covers is another important aspect in design and these aspects investigated and presented in Babu et al (2001, 2002). In addition, properties of geomembranes also play a significant role. The design of Leachate collection system depends on hydraulic head due to leachate and permeability of waste. Design of gas collection system depends on air pressure generated as well as circulation in the body of the landfill. All the above procedures involve soil variability which can not be ignored.

The specifications indicated in landfill design guidelines will be evaluated in the light of site specific details for clay liners as well as covers and waste characteristics. If they are not available, representative values will be used for evaluation. For rigorous analysis, software such as Pollute (from Canada) which is versatile software and considers the various mechanisms of contaminant movement such as advection and diffusion will be used. Hydrous 2D considers the use of unsaturated soil characteristics which are useful in the evaluation of desiccation behavior of clay covers and liners in landfills. HELP (Hydrologic Evaluation of Landfill Performance) software is useful to analyse the stability of covers based on site specific information about climate and rainfall in Bangalore or any other city in India. The present software version 5 needs to be upgraded to version 7 and is useful for stress deformation analysis as well as incorporation of variability using simulations based on random numbers. In addition, response surface methodology will be used in conjunction with numerical analysis results.

e) Performance assessment

Performance of the disposal modules need to be assessed regularly with the improved knowledge of assessment methodology or when there is any proposed change in the design concept of disposal modules. Post closure care and monitoring are required and need to continue for required period after final closure. In this regard, many long term reactions in leachate and other associated requirement need to be examined and monitored to ensure long term stability of disposal modules and performance assessment.. To ensure rational closure in the long term perspective, monitoring and analyzing the data are of paramount importance. Current landfill-cover design guidelines are not risk-based and do not consider long-term site-specific influences such as climate, vegetation, and soils. These design guidelines may not address important long-term features, events, and processes at the site that may contribute to the long-term risk of groundwater contamination and human exposure. In this regard, the risks can be assessed by employing the probabilistic methods. Probabilistic methods can act as reliable decision making tools by taking into account the long term site specific conditions and parameter variations.

The proposal seeks to examine the above issues and the following are the objectives: The objectives are listed as tasks and indicated in the work plan.

Objectives

1) Literature review in radioactive waste disposal in NSDF and design of disposal system
2) Collection of data pertaining to waste characteristics, waste disposal sites using field and laboratory testing, also collect data from literature on properties and variations
3) Analysis of data of laboratory/field test results.
4) Analysis of typical designs using various computational software such as Pollute, Hydrous 2D, HELP and FLAC.
5) Analysis of role of variability and uncertainties and formulation of limit state functions for different designs in landfills and reliability analysis.
6) Report preparation.

Methodology

The methodologies that will be followed for each of the activities are as follows.

1) Literature review in radioactive waste disposal in NSDF and design of disposal system

   Considerable information exist on this topic and the practice in different countries will be examined. The methodologies for design will be examined.

2) Collection of data pertaining to waste characteristics, waste disposal sites using field and laboratory testing, also collect data from literature on properties and variations

   Both laboratory and field tests and experiments will be conducted. Tests include field tests using SPT and SCPT tests, determination of physical properties of waste, engineering properties of waste using compressibility and shear testing equipment. In addition, a set up will be fabricated to observe settlements in the laboratory and the relationship between settlement and leachate will be examined.

3) Analysis of data of laboratory/field test results.

   Data collected from the field will be examined for assessment of engineering properties and the associated variability of the data. Representative data will also be collected if complete data is not available.

4) Analysis of typical designs using various computational software such as Pollute, Hydrous 2D, HELP and FLAC 2D.

   The specifications indicated in disposal modules design guidelines will be evaluated in the light of site specific details for clay liners as well as covers and waste characteristics. If they are not available, representative values will be used for evaluation. For rigorous analysis, software such as Pollute (from Canada) which is versatile software and considers the various mechanisms of contaminant movement such as advection and diffusion will be used. Hydrous 2D considers the use of unsaturated soil characteristics which are useful in the evaluation of desiccation behavior of clay covers and liners in landfills. HELP (Hydrologic Evaluation of Landfill Performance) software is useful to analyse the stability of covers based on site specific information about climate and rainfall in Bangalore or any other city in India. The present software version 5 needs to be upgraded to version 7 and is useful for stress deformation analysis as well as incorporation of variability using simulations based on random numbers. In addition, response surface methodology will be used in conjunction with numerical analysis results.

5) Analysis of role of variability and uncertainties and formulation of limit state functions for different designs in landfills and reliability analysis.

   Rigorous analysis considering property variations and formulations of limit state functions for clay liner, waste settlement, slope stability, clay cover stability will be made. Reliability analysis will be conducted for each of the limit state functions. This will enable understating the role of different design parameters in stability and performance of disposal system.

6) Report preparation.

   Based on the studied described above, a report will be prepared which will be a useful document in the design of landfills and waste impoundments.

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Work plan

Months wise different tasks

Task	Months					
Literature survey	6					
Collection and characterization of disposal site soil waste characteristics will be provided by BARC		18				
Laboratory and field testing			24			
Analysis of disposal modules design				28		
Variability and reliability analysis					33	
Report preparation						36