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Soil Void Ratio Correlation with Shear Wave Velocities and SPT N Values for Indo-Gangetic Basin

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ABSTRACT

In this study attempt has been made to understand in-situ void ratio in Indo-Gangetic basin (IGB) and to form empirical relations between void ratio and shear wave velocity (V_s) , N values considering subsoil investigation data. Multichannel analysis of surface wave (MASW) test and standard penetration test was carried out along with soil property measured at 25 locations. The general soil profile varied from silty sand to clay of low compressibility, ground water level fluctuated between 1-27 m, depth of borehole varied from 20-40 m. Regression analysis was conducted on 202 data sets of void ratio and shear wave velocity, 293 data sets of void ratio and SPT- N value, which resulted in inverse correlations between void ratio and V_s , SPT N value. The datas were segregated into fine, coarse grained data based on engineering classification and relations were developed separately. Until now, no studies have related in-situ void ratio to V_s and SPT N. These correlations will be useful to predict void ratio for sites having measured values of V_s and N value. These void ratios can be further used to assess liquefaction susceptibility.

INTRODUCTION

An idea of the permeability and the liquefaction evaluation of soil can be gained from quantified values of void ratio. These two engineering properties are predominantly controlled by the physical property of void ratio. Moreover, Yilmaz and Mollamahmutoglu (2009) highlighted that the strength and deformation characteristics of sand are controlled by the physical state and the nature of the sand either under static or dynamic loading. Researchers have related soil void ratio with liquefaction susceptibility and flow/slope failure (land slide) (Yilmaz and Mollamahmutoglu, 2009; Okura et al., 2002). Most of these works are limited with laboratory measurement and very few researchers have worked on in-situ void ratio and relating void ratio to engineering properties. Cunning et al. (1995) proposed correlations between normalized shear wave velocity and void ratio based on reconstituted, isotropically consolidated (K_0=1) sand and shear wave velocity measured using bender element tests. Ottawa sand, Alaska sand and Syncrude sand were studied. Variations in confining pressure and void ratio were found to have the greatest effect on V_s as per variable studies by Hardin and Richart (1963). Samples of Ottawa sand were studied and the shear wave velocity was found to vary linearly with void ratio and independent of relative density, gradation and relative grain size. Hardin and Richart (1963) also found that given two sands at similar void ratios, one with angular grains and another with rounded grains, V_s in the soil with angular grains is larger. Hardin and Drnevich (1972) conducted a resonant column and simple shear testing and concluded that strain amplitude, effective mean principal stress, and void ratio are very important parameters that affect the shear modulus of both clean sands and clays. Chang and Heymann (2005) conducted studies on the relation between shear wave velocity and void ratio of gold tailings. Triaxial apparatus was modified to accommodate bender elements and the shear wave velocity of gold tailings was determined at various void ratios and effective stresses. The shear wave velocity was normalized against effective stress and then related to void ratio. The authors stated that the knowledge of the relation would help in the evaluation of liquefaction susceptibility of gold tailings. The majority of the above mentioned studies were based on laboratory experiments and model study. It is clear that very limited studies have been carried out by relating in-situ measured shear wave velocity and SPT N values with void ratio. The present study is the first of its kind which aims at developing correlations between in-situ void ratio and shear wave velocity, SPT N value. In the present study, subsoil investigation carried out for Lucknow city was used to generate correlation between void ratios and shear wave velocities. The data available for Lucknow city has been combined with data from Barauni, Bhagalpur and Gurgaon to develop correlation of void ratio and SPT N value. A total of 202 data sets of shear wave velocity and void ratio, 293 data sets of SPT N value and void ratio were used in the process. The overall data were segregated into fine grained and coarse grained based on engineering classification and correlations were developed for all data, fine grained and coarse grained data separately. The prediction of void ratio from the measured value of shear wave velocity, SPT N will prove to be useful in the evaluation of liquefaction susceptibility of the site and in geotechnical engineering. It can be noted here that correlations serve as a quality assurance check on determined test results. The use of correlations are recommended when specific data are not available, a limited amount of data for the specific property of interest is available, the validity of certain data is in question (FHWA-IF-02-034, 2002). In addition, it must be borne in mind that, correlations cannot be used as a substitute for soil investigation. These types of correlations can be used as a guide to authenticate the values obtained from soil investigation.

STUDY AREA AND FIELD TESTING

In the present work, sub-soil investigation conducted in the city of Lucknow for seismic microzonation has been used. Lucknow is the capital of Uttar Pradesh, the most populous state of India and is situated on the northern Gangetic plains. The geographical location of Lucknow is between 26.50° north and 80.50° east. The study area is laid with thick alluvial sediments deposited due to river associated erosion in the Himalayas. Lucknow lies on the bank of river Gomati from Husainabad to Dilkusha garden. Regional soil deposits mainly comprise both older and younger alluvium of Ganga–Ghagra interfluves (GSI, 2001). The older alluvium spreads over the vast area between elevations 115 and 129 m, covering areas such as Chowk, Aminabad, Charbagh and Kakori. Sand mounds of height 4 – 5 m from ground level have been observed in the Malihabad and Gosainganj

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areas. Soil deposits studied here respresent Indo-Gangetic basin (IGB) deposit, which is located between 77° E and 88° E longitude and 24° N to 30° N latitude. The Ganga basin is home for more than 200 million people. They are prone to geotechnical hazards due to earthquake in the active Himalayan belt. Although a major part of the sediment is being transferred to the Ganga delta, considerable part of it settles in the basin. This continuous process resulted in a thick- fluvial deposit from a few meters to several kilometres at many locations in Ganga basin (Sinha et al., 2005). Anbazhagan et al. (2013) presented a detailed discussion on soil deposits and field experiments in the study area.

In this study, 22 shear wave velocity profiles and 84 borehole data with N-SPT values were identified and selected for developing correlations. Figure 1 shows location of boreholes and shear wave velocity measurement in the study area. Shear wave velocity was measured using MASW survey. MASW test was carried out using 24-channel geode seismograph in combination with 24 vertical geophones with a frequency of 4.5 Hz. An impulsive source of a 15-pound sledge hammer striking against a 30 cm x 30 cm steel plate generates the surface waves. A geophone interval of 1 m and varying shot distances of 5, 10, 15, 20, and 25 m with 10 stacks were used to reach a maximum depth of penetration. More discussion about MASW testing and results can be found in Anbazhagan et al. (2013). The shear wave velocity values recorded range from 100-650 m/s. Fig 2a-d shows shear wave velocity from MASW testing used in the study. Boreholes were drilled in the study area and N-SPT was measured and soil samples were also collected as per IS:2131 (1981). All boreholes were drilled with a diameter of 150 mm as per IS:1892 (1979), and N-SPT values were measured regularly at 1.5 m intervals as per IS:2131 (1981). Disturbed and undisturbed samples were collected at possible depths as per IS:2132 (1986). The physical properties were measured in the laboratory using disturbed soil samples as per IS:1498 (1970) and used for soil classification. N-SPT values and soil profiles were recorded in the field. The values of the SPT N value recorded ranged from 3 to 50. Plot of SPT N with depth for 23 boreholes from Lucknow, used in this study is shown in Fig 3a-d. Figure 4 shows a typical borelog up to depth 30 m with the SPT N values. More discussion about SPT N values and V_s values, comparison and correlation between SPT N and V_s can be found in Anbazhagan et al. (2013).

The general soil profile encountered varied from silty sand to clay of low plasticity. The overall data from each borehole was segregated into fine grained and coarse grained soils based on a standard classification system as per IS:1498 (1970) which is similar

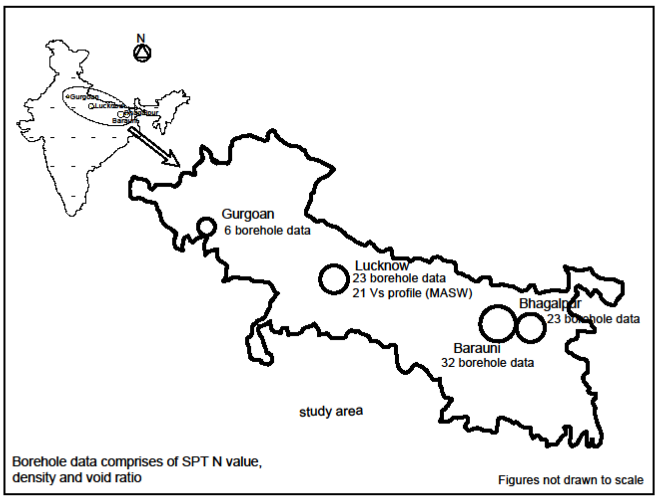

Fig.1. Location of borehole, shear wave velocity and void ratio data used in the study

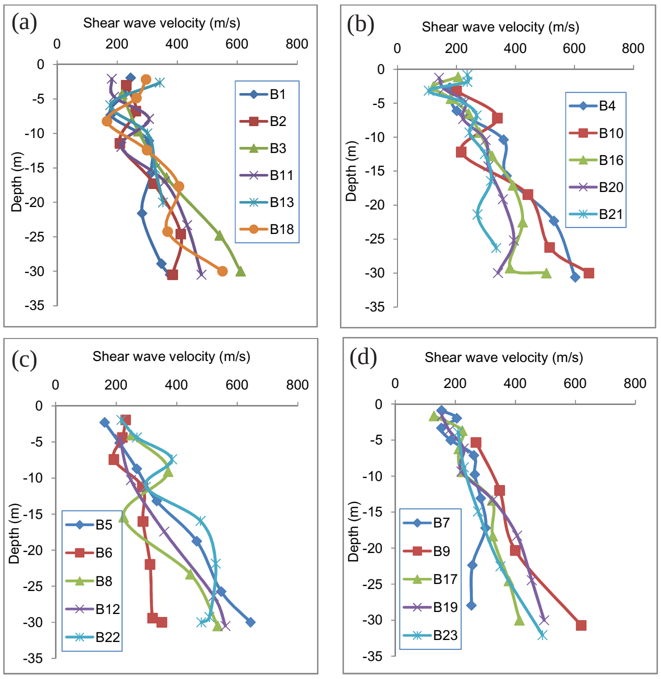

Fig.2a-d. Plot of shear wave velocity versus depth of data considered in the study

to ASTM D:2487 (2006). The classification of the soil present at the site was done based on the percentage weights passing through standard sieves and Atterberg limits. According to IS:1498 (1970), coarse grained soils are subdivided into gravel and sand based on the percentage of coarse fraction, whereas fine grained soils are sub-divided into three depending on the value of liquid limit. Inorganic clay of low plasticity (CL), inorganic silts of none to low plasticity (ML), inorganic clays of medium plasticity (CI), inorganic silts of medium plasticity (MI) and silty clay (CL-ML) have been grouped as fine grained and silty sands (SM), poorly graded sands (SP), poorly graded sand with silt (SM-SP) have been classified as coarse grained soils. Finally, these data were grouped as fine grained data, coarse grained data and all data (all soil types), which were further used to develop

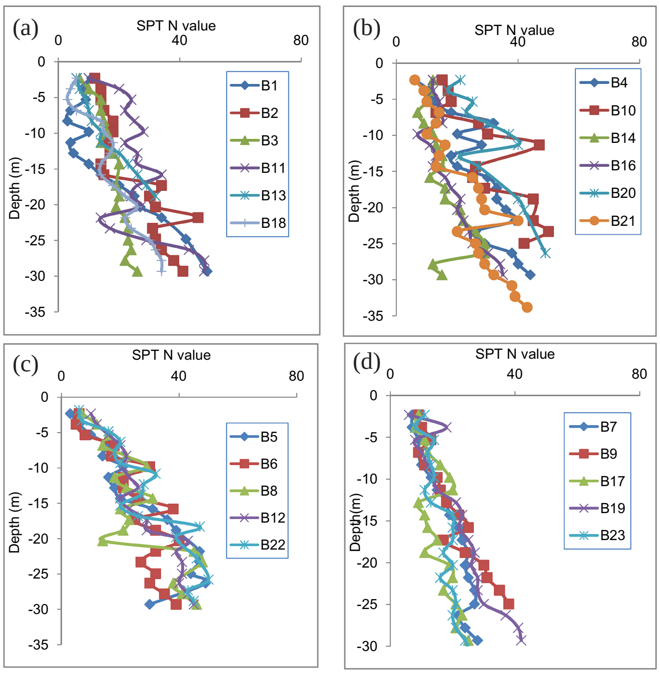

Fig.3a-d. Plot of standard penetration test (SPT) N values versus depth of data considered in the study.

Borehole No: BH 1
Water table: 24.8 m depth below Ground level

Depth below GL	Description	Thickness	Legend	Soil classification	Sample type	Depth	SPT N results
1 2 3 4	Silty clay	4.5		ML	UDS UDS SPT UDS SPT	 2.3 3.8	 7 7
5 6 7	Silty sand	3		SM-SP	UDS SPT UDS SPT	5.3 6.8	9 9
8 9 10 11 12	Silty sand	4		SP	UDS SPT UDS SPT UDS SPT	8.3 9.8 11.3	10 13 15
13	Silty sand	1		SM-SP	UDS SPT	12.8	18
14 15	Silty sand	1		SM	UDS SPT	14.3	19
16 17 18	Silty sand	2.5		SP	UDS SPT UDS SPT	15.8 17.3	22 23
19 20 21 22 23 24 25	Silty sand	6.5		SM-SP	UDS SPT UDS SPT UDS SPT UDS SPT UDS SPT	18.8 20.3 21.8 23.3 24.8	25 24 25 27 27
26 27 28 29 30	Silty clay	4.5		CL	UDS SPT UDS SPT UDS SPT	26.3 27.8 29.3	22 24 28

Fig.4. Sample borehole data of depth 30m showing the strata and SPT N values

correlation separately. Soil properties measured in laboratory for typical borehole is shown in Fig.5.

Void Ratio

During the drilling for SPT N value measurement, the undisturbed samples were obtained at regular intervals as per IS: 2132 (1986). The samples were collected by driving a thin walled casing and the hole was cleaned such that the sample remained undisturbed. The depth of casing below ground level and the depth of the water table were noted. The assembled sampling tube was inserted and the depth of the bottom of the borehole below ground level, amount of penetration of the sampling tube and water level in the borehole was recorded. The sampling tube was pushed in a continuous and rapid motion beyond the casing bottom. Samples were taken, by repeating the sampling procedures, at every change in the stratum or at intervals not more than 1.5 m, whichever was less. This procedure is similar to ASTM D:1587 (2012). The void ratio of in-situ soil was determined from specific gravity, which is determined as per IS:2720 (Part III) (2002). The soil samples were tested using a density bottle method to obtain the specific gravity. The complete density bottle was weighed to the nearest gram. About 1/3rd of density bottle was filled with sample and weighed. Sufficient air-free distilled water was then added such that the bottle was full and the weight was noted. The bottle was then filled with air-free water and the weight recorded. Using these weights, the specific gravity was measured. The void ratio was calculated from specific gravity using values of water content, and degree of saturation. The procedure adopted bears resemblance to ASTM D:854 (2014). The plot between void ratio and depth is shown in Fig. 6a-d. It is generally regarded that void ratio decreases with an increase in depth. This is not observed in some of the boreholes, which may be due to the variation in deposition process and age of the deposit. These void ratios are derived from in-situ undisturbed samples and represent in-situ conditions. Cubrinovski and Ishihara (1999) highlighted that the void ratios have advantages over direct physical soil properties, i.e. it provides a rational measure for quantifying the combined effects of grain size and grain size distribution. The void ratio range is an appropriate parameter to better characterization of sands (Yilmaz and Mollamahmutoglu, 2009). Most of the researchers used void ratio of laboratory soil samples and very limited study was done on in-situ void ratios.

PREDICTION OF VOID RATIO-CORRELATIONS

Empirical correlations are a part of geotechnical engineering and are widely used in many design applications. These correlations can

Sample No:	% material passing IS sieves				Atterberg limits			Wet bulk density (g/cc)	Dry bulk density (g/cc)	Void ratio	Cohesion (kg/cm^2)	Angle of internal friction (deg.)
	4.75 mm	2mm	0.425 mm	0.075 mm	LL (%)	PL (%)	PI (%)					
1	100	100	100	73	26	22	4	-	-	-	-	-
2	100	100	100	74	25	23	2	1.71	1.57	-	-	-
3	100	100	100	62	Non plastic			1.72	1.56	0.679	0	27
4	100	100	100	8	Non plastic			1.65	1.48	0.777	0	30
5	100	100	100	6	Non plastic			1.67	1.5	0.753	0	31
6	100	100	100	5	Non plastic			1.71	1.5	-	-	-
7	100	100	100	5	Non plastic			1.72	1.53	0.725	0	31
8	100	100	100	6	Non plastic			1.71	1.54	-	-	-
9	100	100	100	13	Non plastic			1.76	1.57	0.681	0	30
10	100	100	100	5	Non plastic			1.74	1.54	-	-	-
11	100	100	97	5	Non Plastic			-	-	-	-	-
12	100	100	98	8	Non Plastic			1.75	1.55	0.703	0	31
13	100	100	97	7	Non Plastic			1.79	1.55			
14	100	100	98	5	Non Plastic			1.79	1.52	0.707	0	32
15	100	100	98	8	Non Plastic			1.85	1.57			
16	100	100	99	9	Non Plastic			1.86	1.57	0.681	0	31
17	97	94	91	87	30	18	12	2	1.63	0.607	0.25	18
18	92	90	88	83	31	20	11	2.05	1.7	-	-	-
19	93	89	86	82	33	19	14	2.05	1.73	-	-	-
20	89	84	81	77	33	19	14	-	-	-	-	-

Fig.5. Typical laboratory results of a borehole

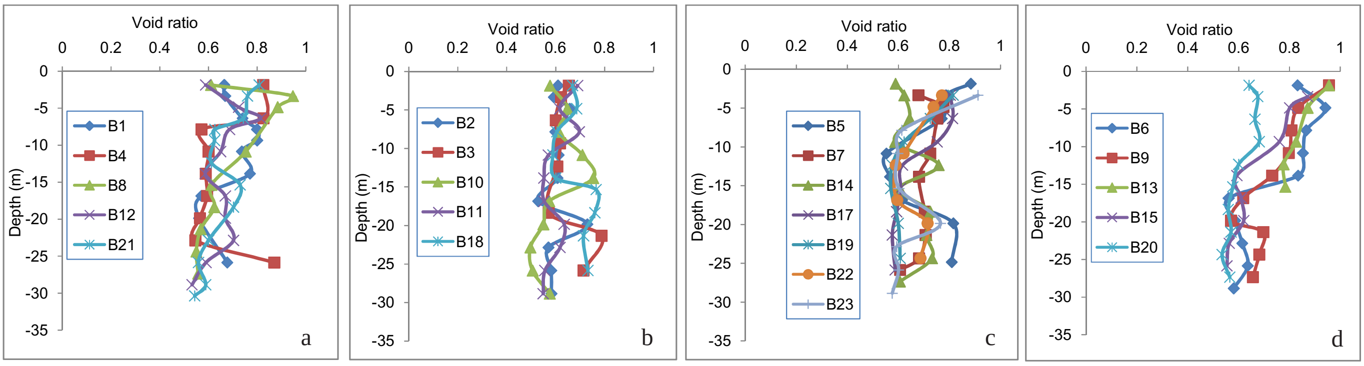

Fig. 6a-d. Variation of void ratio with depth in the boreholes

be classified in two groups: one derived from field and laboratory tests on undisturbed soils, and the other based on field-performance of soil deposit with known SPT N values (Cubrinovski and Ishihara, 1999). Several such empirical correlations are available in the literature. Most of the widely used geotechnical correlations were summarised by the estimating software by Novotech (2014). Very limited correlations are available for laboratory/field measured index properties with field measured engineering properties such as SPT N or V_s. In this study, measured data of in-situ void ratio (index property) has been correlated with engineering properties of shear wave velocity and SPT N values. General form of regression equation used for all the correlation is given below:

$$\underset{\text{(Void ratio)}}{\text{Independent variable}} = a \times \underset{\text{(SPT N or } V_s)^b}{\text{Dependent variable}} \quad (1)$$

where a, b are regression coefficients which vary inversely with each other.

It can be noted here that there few correlations like those of Cubrinovski and Ishihara, (1999) are available between relative density (D_r) or difference in minimum and maximum void ratio ($e_{max} - e_{min}$) and SPT N values and not for e value.

Void Ratio and Shear Wave Velocity

In the present study, void ratios from 23 boreholes corresponding to different depths were used to develop the correlation with shear wave velocity by least squares estimation. A statistical measurement of correlation was calculated using the least squares method to quantify the strength of the relationship between the two variables. The overall data comprised of 202 data sets of void ratio and V_s. These data are separated into fine grained and coarse grained soils as mentioned earlier leading to 128 fine grained and 74 coarse grained data points. The void ratio used in the study ranged from 0.45-0.95. The output of regression is the correlation coefficient or (r) and coefficient of determination (R^2), which ranges between -1 and 1. In least squares (LS) estimation, the unknown values of the parameters in the regression function were estimated by finding numerical values for the parameters that minimize the sum of the squared deviations between the observed responses and the functional portion of the model. Correlation coefficient which measures the strength of a relationship between two variables (for 'n' number of data points) was calculated as in Eqn 2. Coefficient of determination (R^2) gives the proportion of variance of one variable that is predictable from the other. It represents the percent of data that is closest to the line of best fit. It was calculated as equal to one minus the ratio of the sum of squared estimated errors (the deviation of the actual value of the dependent variable from the regression line) to the sum of squared deviations about the mean of the dependent variable.

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x)^2 - (\sum x)^2}\sqrt{n(\sum y)^2 - (\sum y)^2}} \quad (2)$$

Figs 7a-c shows the relation between void ratio and V_s for all soil types, fine grained and coarse grained soils. The regression equations between void ratio and V_s for all soil types, fine grained and coarse grained soils are shown in Eqs 3(a)-(c).

$$e = 6.745V_s^{-0.41} \quad (R^2 = 0.713) \text{ for all soil types} \quad (3a)$$

$$e = 2.737V_s^{-0.261} \quad (R^2 = 0.695) \text{ for fine grained soil} \quad (3b)$$

$$e = 6.887V_s^{-0.398} \quad (R^2 = 0.66) \text{ for coarse grained soil} \quad (3c)$$

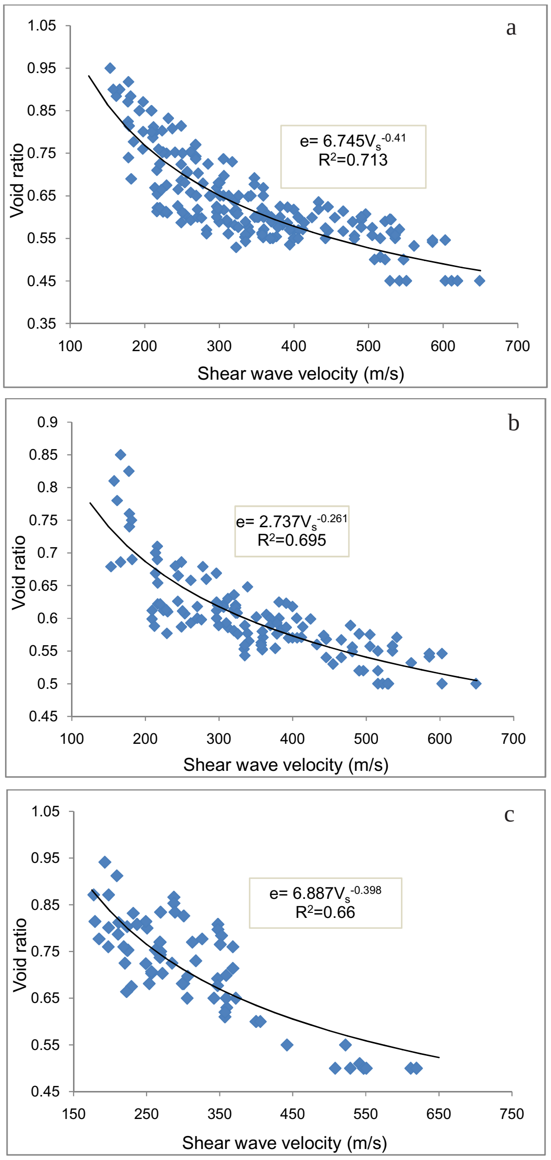

Fig.7. Relation between void ratio and shear wave velocity for **(a)** all soil types, **(b)** fine grained soil and **(c)** coarse grained soil.

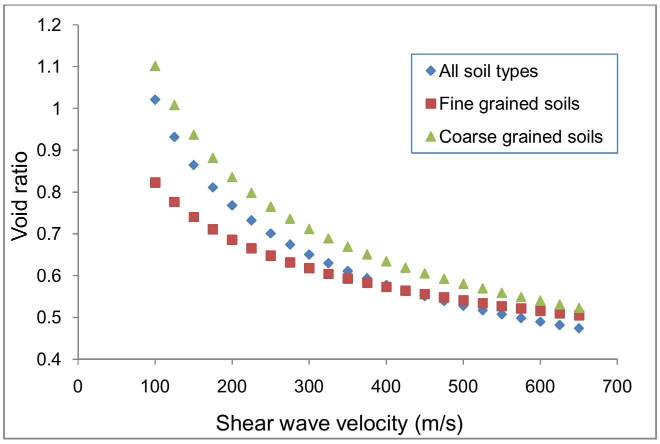

Fig.8. Comparison of relations developed between void ratio and shear wave velocity for all soil types, fine grained and coarse grained soils.

It can be observed from the above relations that correlation developed for all soil types has highest R^2 values when compared to other two relations. The relations developed for all soil types, fine grained and coarse grained soils have been compared in Fig 8. It can be noticed in Fig 8 that for higher velocity range all three equations predict similar void ratio.. In general, loose soil has lower shear wave velocity, which corresponds to higher void ratio and this trend was observed in the study. It can be also noted that cohesionless soil having lower shear wave velocity (<200 m/s) is susceptible to liquefaction and this soil must have higher in-situ void ratio, which can be also noticed in the above figures. Liquefaction susceptibility at a site can be assessed by using these simple parameters and detailed study may be carried out for susceptible sites.

Further, the predicted values of void ratio were compared with the measured values in Fig. 9 for all soil types. The plotted values are within the lines of slope 1:1.2 and 1:0.8 with the majority of the values lying on the line with 1:1 slope. This proves that the predicted values are close to the measured values and the relation is reliable. A similar observation was also noticed for fine and coarse grained soil correlations.

Void Ratio and SPT N Value

SPT based empirical correlations are being developed worldwide due to longtime and comprehensive data accumulations (Cubrinovski and Ishihara, 1999). These correlation are well related with index properties such as SPT N versus relative density (Gibbs and Holtz, 1957; Meyerhof, 1957; Cubrinovski and Ishihara, 1999) and SPT N versus difference in the void ratio ($e_{max} - e_{min}$). Relation between primary and index properties were investigated by MiuTa et al. (1997) and it was highlighted that maximum and minimum void ratio are significantly influenced by the grain size distribution and grain shape and also has linear realtionship between e_{max} and e_{min}. Several such correlations exist worldwide and very limited attempt has been made to understand IGB soil properties and relate the same with index properties. In this study, the borehole data were further used to develop relationships between void ratios and SPT N values. About 293 data points of void ratio and SPT N values were arrived from 84 borehole data. A total of 190 fine grained and 103 coarse grained data was founded after segregation based on engineering classification. The values for void ratio and SPT N value were analysed based on least squares method to arrive at the best-fit equation. Figs 10a-c show the relation between void ratio and SPT N for all soil types, fine grained and coarse grained soils and respective equations are given below.

$$e = 1.202N^{-0.217} \quad (R^2 = 0.736) \text{ for all soil types} \tag{4a}$$

$$e = 0.89N^{-0.12} \quad (R^2 = 0.71) \text{ for fine grained soil} \tag{4b}$$

$$e = 1.01N^{-0.105} \quad (R^2 = 0.729) \text{ for coarse grained soil} \tag{4c}$$

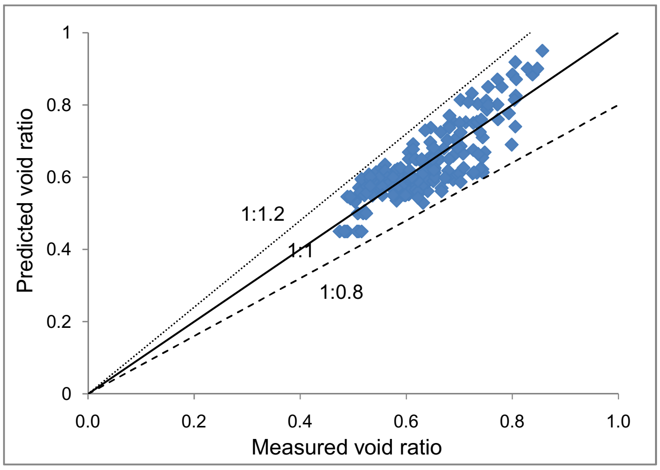

Fig.9. Plot between predicted void ratio and measured void ratio for all soil types considering shear wave velocity values

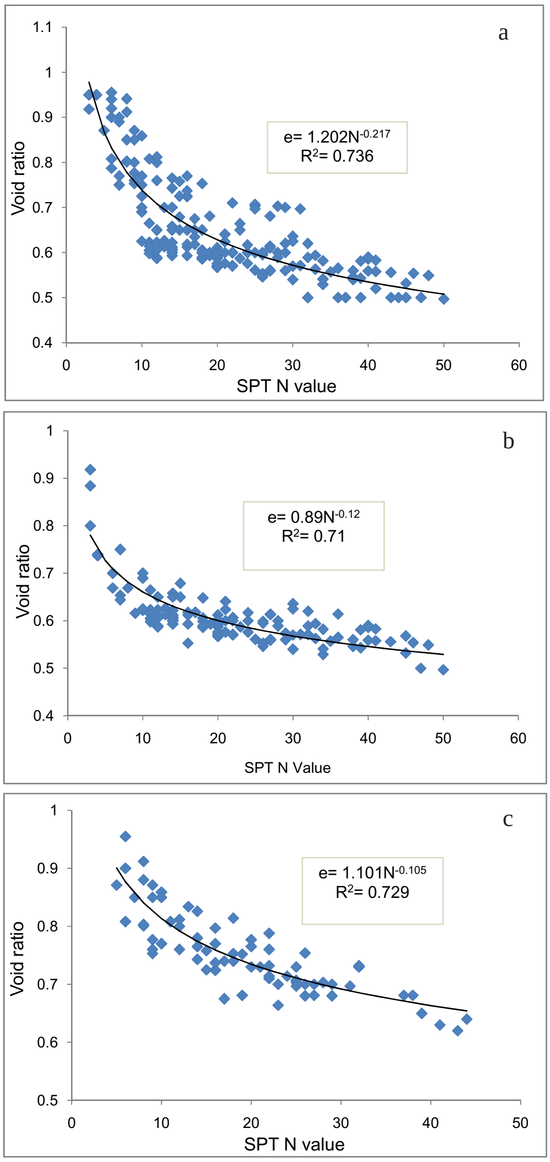

Fig.10. Relation between void ratio and SPT N value for **(a)** all soil types, **(b)** fine grained soil and **(c)** coarse grained soil.

The relations developed for all soil types, fine grained and coarse grained soils have been compared in Fig 11. The values predicted by the relation for all soil types and coarse grained soils coincide at lower values of SPT N. The relation for all soil types and fine grained soils give similar values of void ratio at SPT N value greater than 30. General trend of the correlation was found to match well with literature i.e loose soil with less SPT N values have higher void ratio, which is matching with lower SPT N values having higher range of void ratio as mentioned in previous studies. The predicted values of void ratio were compared with the measured values as shown in Fig 12. The plotted values are within lines of slope 1:1.2 and 1:0.8 with the majority of the values lying on the line with 1:1 slope. This proves that the predicted values are close to the measured values and the relation is reliable.

RESULTS AND DISCUSSION

In this work 84 borehole data with SPT N values and 22 shear wave velocity profiles were used to generate correlation between index property of void ratio and engineering properties of SPT N and shear wave velocity. Table 1 presents summary of correlations developed along with statistical parameters, which prove their credibility. The form of the equation along with the constants, standard error for 95 % probability, standard error of estimate, correlation coefficient and the coefficient of determination has been given in Table 1. Standard error of mean was calculated as the ratio of the standard deviation and square root of sample size. Standard error of estimate is given by the following Eqn.

$$S_{est} = \sqrt{\frac{\Sigma(Y-Y')^2}{N-2}} \tag{5}$$

where Y refers to individual data sets, Y' is the mean of data and N is the sample size.

The reliability and performance analysis has been established for all direct correlations given in Table 1 based on the normalized consistency ratio, C_d (Dikmen, 2009), determined as:

$$C_d = \frac{e_M - e_C}{V_s} \tag{6}$$

where e_M is the value of void ratio measured and e_C is the value of void ratio calculated from the correlations developed. Typical plot of the consistency ratio for void ratio versus shear wave velocity is given in Fig.13. Figure 13 shows that C_d values are close to zero for all shear wave velocities. Normalized consistency ratio curves were plotted for all the developed equations and it was found that the values of C_d lie close to zero, which meant that all the proposed equations have good prediction performance.

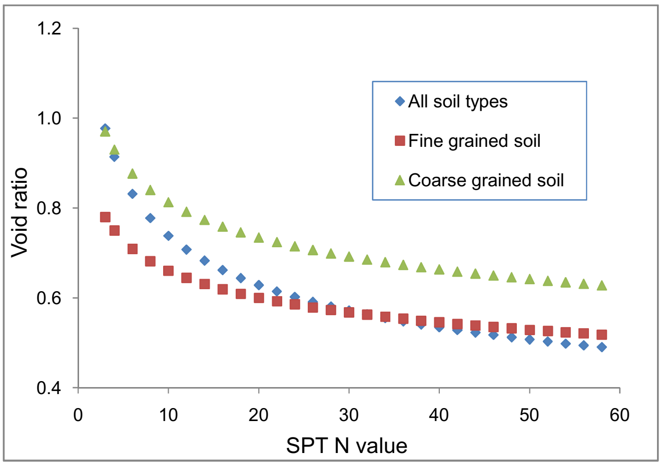

Fig.11. Comparison of the proposed correlations between void ratio and SPT N value for all soil types, fine grained and coarse grained soils

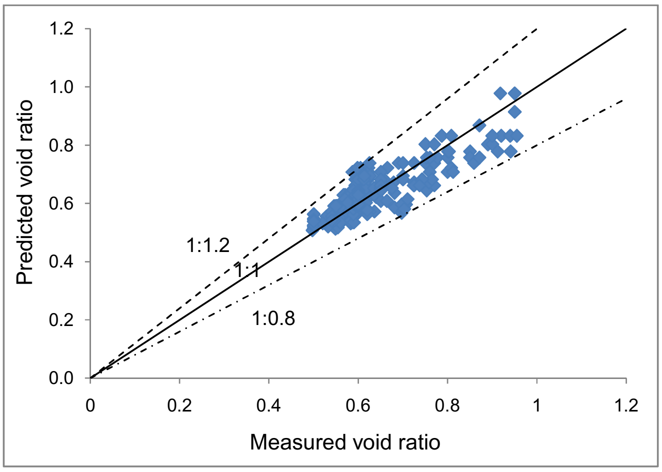

Fig.12. Plot between predicted void ratio and measured void ratio for all soil types considering SPT N values

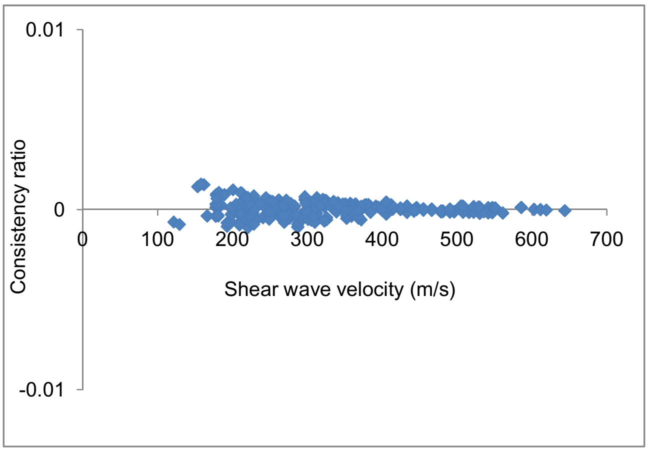

Fig.13. Typical plot of normalized consistency ratio of void ratio and V_s for all soil types

To estimate the capability of the new proposed relationship, scaled percent error E_r (Dikmen, 2009) was calculated. Scaled percent error is the ratio of residual to the measured value of shear velocity. A plot between scaled percent error and cumulative frequency of sample is considered to denote the quality of regression. The error values are specified to be within ±20% which represents the 95% probability prediction. Cumulative frequency has been calculated considering the percentage of total count of individual values in the sample. The graph between scaled error and cumulative frequency for the relations developed for void ratio for all soil types, fine grained and coarse grained soils is shown in Fig 14. From Fig 14, it is clear that using relation for all soil types, about 99% of the void ratio values were within a 20 % error margin. Using the equation for fine grained soil, it was observed that 95% of the void ratio values were predicted within 10% error. For coarse grained soils, almost 94% of the void ratio values were predicted within a 15% error margin. These results show that the proposed relationships for all soils, fine grained and coarse grained soils give a good estimation of void ratio. Fig 15 show scaled error and cumulative frequency for relation for void ratio from SPT N, developed in this study. It can be observed that the scaled errors of all the relations vary between ± 20%, indicating that all the proposed relations are able to predict values close to measured values with less

Table 1. Summary of the proposed regression equations of void ratio

Equation No. and Form	Soil type	No of data	Coefficients		Standard error		Standard error of estimate,	Correlation coefficient	Coefficient of determination
			a	b	a	b	s	r	R^2
(1) $e = aV_s^b$	All	202	6.745	-0.41	0.7	0.182	0.0556	0.844	0.713
	Fine grained	128	2.737	-0.261	0.239	0.015	0.0362	0.834	0.695
	Coarse grained	74	6.887	-0.398	1.388	0.0356	0.0656	0.81	0.660
(2) $e = aN^b$	All	293	1.202	-0.217	0.021	0.008	0.054	0.858	0.717
	Fine grained	190	0.89	-0.12	0.01	0.0045	0.021	0.843	0.71
	Coarse grained	103	1.01	-0.105	0.015	0.019	0.049	0.854	0.729

error. These relations can be used to estimate voids ratio using V_s and SPT N values for geotechnical engineering applications.

The proposed correlations considering shear wave velocity can be used in any region as V_s measurement by seismic surface wave methods may not differ from region to region, however correlation considering SPT N values cannot be used in other regions directly. SPT N values depend on hammer energy and other parameters, which are region specific and may vary from region to region. SPT N values depend on drilling methods, drill rods, borehole sizes and stabilization, sampler, blow count rate, hammer configuration, energy corrections, fine content and test procedure (Schmertmann and Palacios, 1979; Kovacs et al., 1983; Farrar et al., 1998; Sivrikaya and Togrol, 2006; Anbazhagan et al., 2012). These correlations can be used for other regions if proper correction factors are applied to normalize the SPT N values. The first and foremost correction factor is the hammer energy correction factor, which depends on the energy applied to count N values. SPT N values are measured in India as per IS:2131 (1981), which is similar to ASTM D:6066 (1996) procedure. Even though hammer energy measurement is mandatory to estimate normalized SPT N values according to ASTM D:1586 (1999), presently hammer energy is not measured during SPT in India. Recently an attempt was made by the first author and team to measure the hammer energy below anvil and above split spoon sampler by building a new indigenous SPT-Hammer energy measurement apparatus (SPT-HEMA). SPT-HEMA is capable of measuring force and velocity signals at different depth and energy transferred to drill rods and sampler. Preliminary field studies in selected sites of India showed that the typical energy ratio below the anvil is about 60% (Panneer Selvam et al., 2013). It was inferred that only 60% theoretical energy was transferred to the SPT rod in India. Regions with a similar energy transfer ratio can use the proposed correlations directly and regions with different energy transfer ratio need to apply necessary correction factor which is mentioned in Anbazhagan et al. (2012).

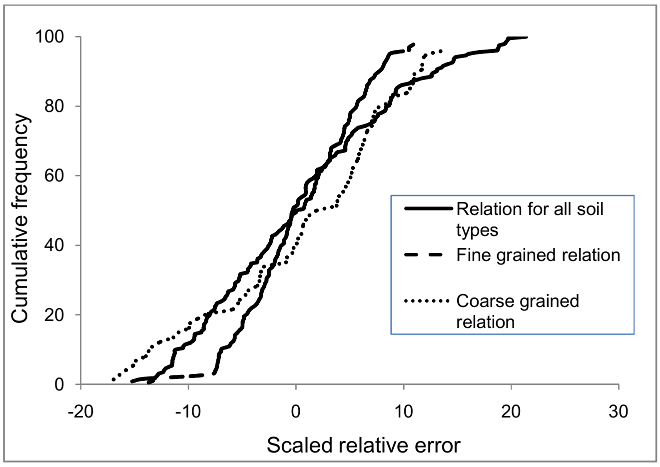

Fig.14. Scaled relative errors of void ratio predicted from V_s for all soil types, fine grained and coarse grained soils

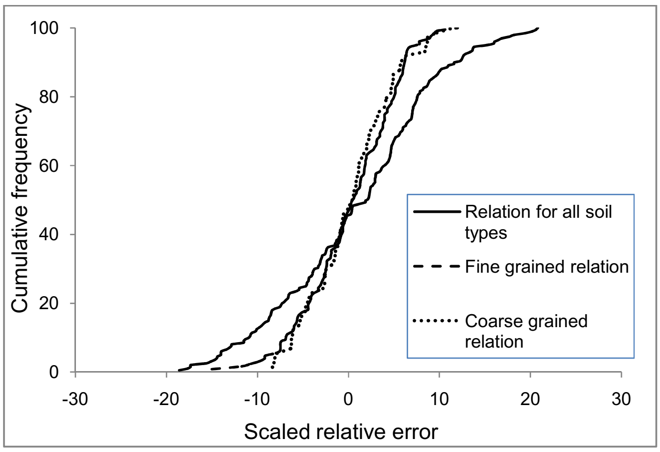

Fig.15. Scaled relative errors of void ratio predicted from SPT N for all soil types, fine grained and coarse grained soils

Liquefaction is a major geotechnical hazard in the IGB due to possibility of major damage by the occurrence of a strong earthquake in the Active Himalayan Belt and young river deposits. Estimation of liquefaction potential at a given site requires field testing, which is not always feasible for common buildings. Most of the liquefaction studies carried out in India adopt simplified procedure developed by Seed and Idriss (1971) and updated procedure by Youd et al., (2001) and Idriss and Boulanger (2005) with the assumption of SPT hammer energy (Anbazhagan et al., 2012). Some of researchers also follow the Chinese criteria by Wang (1979) for evaluating the liquefaction susceptibility of silts and clays. These criteria were studied and reviewed by Andrews and Martin (2000), Bray et al. (2004) and Boulanger and Idriss (2006). Assessment of liquefaction susceptibility requires major factors like liquid limit (LL) and Plasticity Index (PI), which require geotechnical skill and equipment to arrive at reliable values. In this study an attempt has been made to arrive at a preliminary estimate for the cut off void ratio for liquefaction susceptibility based on shear wave velocity and SPT N values. Representative corrected SPT N and shear wave velocity values are taken from Idriss and Boulanger (2008). Corrected SPT N values of 25 and shear wave velocity of 250 m/s are taken to arrive at cut off void ratio, so that a simple test below the foundation can be used to assess liquefaction susceptibility. The corrected SPT N values will be slightly different from measured SPT N values when N values are less than 30 (Anbazhagan et al., 2012). Hence SPT N value of 25 and V_s value of 250 m/s are taken as corrected values and plotted with in-situ void ratio in Figure 16. Based on SPT N values, soil having in-situ void ratio more than 0.6 is susceptible to liquefaction (Figure 16a) and based on V_s values, soil having in-situ void ratio more than 0.65 is susceptible to liquefaction (Figure 16b). A susceptible zone of liquefaction based on SPT N and V_s values is marked in Figure 16. In-situ void ratio plays a very crucial role in liquefaction susceptibility, but it was least studied when compared to other index properties. Okura

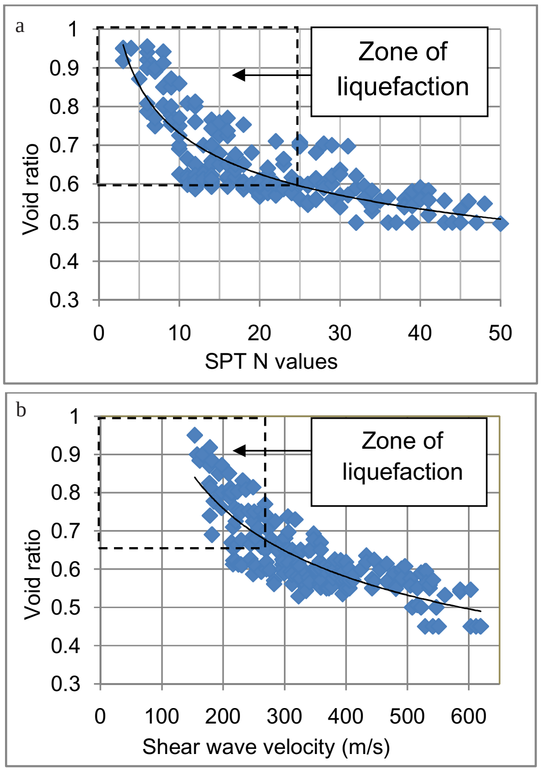

Fig.16. Zone of liquefaction based on the Void ratio considering SPT N and V_s values.

et al. (2002) reported that for a loose soil critical void ratio is about 0.67 which serves as the limit for liquefaction. The void ratio values arrived in this study is lower than Okura et al (2002) and hence can be taken as a safe value. Our findings also match with Yilmaz and Mollamahmutoglu (2009) results of soil having higher void ratio is more susceptible to liquefaction. Void ratio is also effective in evaluating the potential of compressibility and contractiveness of cohesionless soils (Cubrinovski and Ishihara, 2002). In-situ void ratio can be estimated below foundation up to the required depth by measuring simple parameters of moisture content, saturation values and specific gravity. If the in-situ void ratio values are less than 0.6, site is not susceptible to liquefaction and if it is more, then detailed testing can be carried out to assess liquefaction potential.

CONCLUSION

Twenty three drilled borehole with measurement of SPT N value at 25 locations, void ratio and shear wave velocities obtained at 22 locations using MASW was analysed in this study. In general, void ratio decreased with depth in most of boreholes. However, in some locations, increase in void ratio was also observed, which may be due to geological parameters which were not investigated. The results obtained from SPT, MASW, undisturbed samples and drilled boreholes were used in developing new correlations between void ratio and measured values of shear wave velocity, SPT N value. Different correlations were developed for all soil types, fine grained and coarse grained soils. About 95-100% of the predicted values were found to be within an error margin of 20% thus indicating good prediction capability. Further graphical comparison and statistical validation was carried out. The prediction of void ratio can be helpful in gaining knowledge about the subsoil profile and also in geotechnical earthquake engineering. The proposed correlations in this study can be useful for liquefaction susceptibility assessment. This study shows that sites in IGB may be susceptible to liquefaction if in-situ void ratio is more than 0.6 and required detailed analysis of liquefaction assessment. It should be noted that these empirical correlations depend on the data used in the process and the data should be calibrated for use in other soil conditions.

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