Seismic Site Classifications and Site Amplifications for the Urban Centres in the Shallow Overburden Deposits

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ABSTRACT

This paper presents seismic site classification practices for urban centres in Australia, China, and India with special emphasis on their suitability for shallow soil sites. The geotechnical aspects of seismic site classifications play a critical role in the development of site response spectra, which is the basis for the seismic design of new structures and seismic assessment of existing structures. Seismic site classifications have used weighted average shear wave velocity of top 30 m soil layers, following the recommendations of National Earthquake Hazards Reduction Program (NEHRP) or International Building Code (IBC) site classification system. The site classification system is based on the studies carried out in the United States where soil layer may extend up to several hundred meters before reaching any distinct soil-bedrock interface. Most of the urban centers in Australia, China, and India are located on distinct bedrocks within few meter depth of soil deposits. For such shallow depth soil sites, NEHRP or IBC site classification system is not suitable. A new site classification based on average soil thickness, shear wave velocity up to engineering bedrock is proposed. The study shows that spectral value and amplification ratio estimated from site response study considering top 30 m soil layers are different from those determined considering soil thickness up to engineering bedrock.

Keywords: Amplification, Shear Wave Velocity, Site Classification, Site Response, Soil Depth

INTRODUCTION

There has been a growing demand for the expansion of cities in the Asia Pacific regions due to rapid increase in populations leading to unplanned constructions. The urban centres in the Australia, China and India are prone to significant hazard even in low to moderate magnitudes earthquake events. Earthquakes in and around India are as inevitable as the autumnal fall of fruit from a tree (Bilham & Hough, 2006). As the earthquakes are not precisely predictable, only way to reduce damages is to design or retrofit the structures against earthquake induced forces in urban centers, where risk level is more due to large population and

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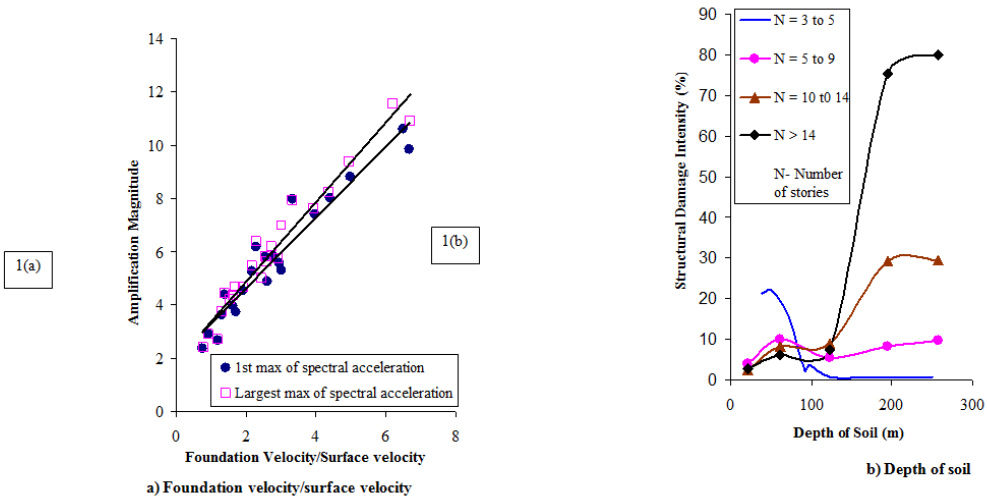
existing unplanned structures. Seismic codes are becoming popular over the last few years due to frequent earthquakes around the world. Site effects represent seismic ground response characteristics and are inevitably reflected in seismic code provisions. The selection of appropriate elastic response/design spectra according to soil categories and seismic intensity is the simplest way to account for site effects both for engineering projects and for general purposes like microzonation study (Pitilakis, 2004). Modern seismic codes in America and Europe (International Building Code, 2009; UBC 97, NEHRP and EC8) have produced valuable data and have incorporated the site effects based on important experimental and theoretical results. The accurate soil categorization is introduced based on a better description of soil profiles using standard geotechnical parameters like plasticity index (*PI*), undrained shear strength (S_u) and average shear wave velocity (Vs) values. Also, special attention has been given in the modern seismic design codes to incorporate site amplification factors to increase rock outcrop response spectral ordinates to properly account for the effect of soil sites reflecting field conditions. In general the important parameters describing site effects in seismic codes are expressed through: (a) site classification (b) spectral amplification factors and shapes of the response spectra. It is noted that seismic codes should always reflect the basic knowledge and technology of the present time. Code must be simple and realistic with an acceptable level of accuracy to adopt for the seismic design of the structures (Pitilakis, 2004).

Soil condition modifies ground motion and in many cases result in greater amplitude of motion together with change in frequency contents and duration of ground motion. Estimation of the earthquake response spectra with proper consideration of site effects is very important for the design of new structures and performance assessment of existing structures (Anbazhagan & Sitharam, 2008a, 2008b). The response at the surface of soil deposit is dependent on the frequency contents of bedrock motion, the geometry and material properties of the soil layers above the bedrock. These parameters are directly or indirectly quantified and represented by many researchers as part of the seismic microzonation study. Seismic site classification and empirical correlation between top 30 average shear wave velocities (Vs^{30}) are widely followed to quantify soil amplification or site effects. Although a number of methods are being recommended in design codes worldwide, most popular are those that consider borelogs with standard penetration test, (SPT)-N values, and shear wave velocity from Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW) (Anbazhagan, 2009). Most of the seismic site classification systems considers average of Vs or SPT-N values of top 30 m soil layers, because of the direct correlation with the proposal of National Earthquake Hazards Reduction Program (NEHRP) (BSSC, 2001) and International Building Code (2006). Site classification considering weighted average Vs of top 30 m soil layers has also been widely followed in seismic microzonation studies in many urban centers in Australia, China and India. These site classification schemes are then combined with probabilistic approach to estimate the surface level hazard accelerations (RaghuKanth & Iyengar, 2007; Anbazhagan et al., 2009). In spite of their wide use and well correlation with soil amplification factors, these site classification schemes (considering top 30 m soil layers) are still under research scrutiny (Marek et al., 2001; Anbazhagan et al., 2011b). In this study, for the assessment of site response, a suite of SPT-N and Vs data are collated from Australia, China and India. These soil sites are first analyzed based on top 30 m soil depths, according to seismic site classification recommended in National Earthquake Hazards Reduction Program (NEHRP) (BSSC, 2001) and International Building Code (International Building Code, 2006). Second, site classification scheme has been proposed considering soil layers up to engineering bedrock. Shear wave velocity of 700 m/s is considered as engineering rock (Anbazhagan & Sitharam, 2009a). Site response of the soil sites has further been

Figure 1. Stiffness and Depth directly related to the Damage of Structures (adapted from Seed et al., 1972; Shima, 1978). In (b) N represents building floor height.



carried out considering engineering bedrock condition and also site amplification of such soil sites have been evaluated. Site response analyses have further been carried out considering different bedrock rigidities. Site response study using recorded earthquake ground motions has also revealed the difference in spectral accelerations and amplification factors for the similar site class sites.

Site Effects and Geotechnical Data

The damaging effects of local site conditions have been evident in recent earthquakes around the world. Even an earthquake of moderate magnitude may cause severe damage to infrastructure incurring significant economic loss and even loss of lives if ground motion is amplified several times by local soil deposits. Newcastle earthquake (1989) in Australia is one of many examples where considerable damage were observed due to local site effects where the magnitude of the earthquake was only 5.6 (IEA, 1990). The correlation between site effects and building damages was studied by many researchers (Shima, 1978; Seed et al., 1972). Figure 1a shows the correlation between ratios of shear wave velocity of soil to rock and amplification magnitudes. Figure 1b shows the damage intensity versus depth of soil sites. Geotechnical properties of local soils play a major role in seismic site amplification. Many seismic microzonation studies are incorporating subsurface geotechnical modelling (Ansal, 2004; Sitharam & Anbazhagan, 2008a). Even though seismic microzonation study for major Australian cities were carried out, consideration of geotechnical subsurface model aspects for site response study has not been adequately taken into account.

Literature review revealed that seismic site classification for seismic microzonation studies are carried out based on NEHRP and IBC recommendations in Australia, China and India. In these regions many cities encountered distinct bedrock at depths from few meter to several meters from surface of the soil sites. Hence adopting 30 m-based site classification need to be verified by considering seismic design response spectrum of the site (Anbazhagan et al., 2011a). In order to highlight these aspects, in this study, site-specific geotechnical data (in the form of SPT-N or Vs) of depths up to engineering rock have been used for site classification and to estimate site amplification. Site-specific geotechnical data are collated from the published literature. These data contain drilled boreholes with SPT-N values and Vs profiles. Anbazhagan and Sitharam (2009a) studied different shear wave velocity profiles around the world corresponding to different materials and suggested Vs for weathered rock and engineering rock. Based on the study, they have also identified and mapped weathered and engineering rock depth. In this study, the Vs of 330±30 m/s and 760±60 m/s, and SPT N value of 50 or rebound and 100 for no penetration are considered, based on the recommendation of Anbazhagan and Sitharam (2009a), as weathered rock and engineering rock, respectively.

Seismic Site Classification

Local site conditions could play a dominant role in damage distribution as well as in the recorded strong ground motion (Roca et al., 2006). Geotechnical characteristics of soil deposits play an important role in the implication of seismic ground shaking termed as local site effects. Ground classification of individual sites based on soil boring or Vs is a more direct indicator of local site effects. Studies on site effects require knowledge of shear stiffness of the soil column, expressed in terms of Vs (Borcherdt, 1994). The site classes are defined in terms of Vs up to a depth of 30 m, denoted by Vs^{30}. Also the standard penetration resistance (N_{30}) and undrained shear strength (S_u^{30}) could be used (Borcherdt, 1994). Vs can be directly measured in field tests or can be estimated from existing correlations between SPT blow-counts (SPT-N) and Vs (Hasancebi & Ulusay, 2006). A number of correlations between SPT-N and Vs are available in the literature. Suitable correlation can be selected based on the type of soil.

Seismic ground response characteristics considering site effects are incorporated in modern seismic code provisions in many countries. However, the definitions of site classes in different codes are not consistent. Table 1 shows the summary of site classes adopted in National Earthquake Hazards Reduction Program (NEHRP) (BSSC, 2001), International Building Code (2006) or Uniform Building Code (UBC, 1997), Australian Standards Part 4: Earthquake Actions in Australia (AS 1170.4) (Standards Australia, 2007), China Code for Seismic Design of Building (GB 50011) (Code of China, 2001) and Indian Code (BIS 1893) (Bureau of Indian Standards, 2002). In order to avoid confusion of detailed specification, only key information is given in Table 1 for direct comparison. The soil types are mainly accounted by average Vs or SPT-N values. In this study, the site classification using SPT-N and Vs are considered. Undrained shear strength (S_u) is omitted as these are not available in all codes. The equivalent N_{30} and Vs^{30} values of soil based on SPT-N or Vs over 30 m depth can be calculated by

$$N_{30} \ or \ Vs^{30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \left(\frac{d_i}{N_i \ or \ Vs_i} \right)} \quad (1)$$

where $\sum_{i=1}^{n} d_i$ is the total depth, for 30 m average $\sum_{i=1}^{n} d_i = 30$ m, d_i and Vs_i or N_i denote the thickness (in meters) and corresponding shear wave velocity/standard penetration resistance (not to exceed 100 blows/0.3 m as directly measured in the field without corrections) of the i^{th} formation or layer respectively, in a total of n layers, existing in the top 30 m of soil layers. Table 1 shows the site classification according to 30 m Vs or SPT-N by NEHRP and IBC. It can be observed that site classification of IBC2006/UBC1997 and NEHRP are identical, in five different site classes have been considered, together with one special site class (Site Class F) for very loose soil for which site specific study is recommended. Australian Standard recommends five methods to classify a site; site class based on geotechnical details are placed higher order. General site classification of Australian Standard based on Vs and SPT N values are given in Table 1. A detailed site clas-

Table 1. Comparison of seismic site classification schemes in Australia, China and India with international standards

Site Class	Generalized soil Description	NEHRP (BSSC,2001)		IBC 2006/ UBC1997		Australian Standards AS 1170.4, 2007		Chinese seismic Code GB 50011(2001)		Indian Standards BIS 1893 (2002)	
		N_{30}	Vs^{30}	N_{30}	Vs^{30}	N_{30}	Vs^{30}	N	Vs^{20}	N	Vs^{30}
A	Hard rock	N/A	>1500	N/A	>1524	*	>1500	*	*	*	*
B	Rock	N/A	760-1500	N/A	762-1524	*	>360	*	>500	*	*
C	Very dense soil and soft Rock	> 50	360-760	> 50	366-762	*	≤0.6s (surface to rock)	*	250-500	>30	*
D	Dense to medium soils	15-50	180-360	15-50	183-366	Soil with SPT N values of<6 for depth of <10m	>0.6s (surface to rock)	*	140-250	All the soil 10 to 30 or Sand with little fines N>15	*
E	Medium to soft soil	< 15	< 180	< 15	< 183	Soil with SPT N values of<6 for depth of >10m	More than 10m depth of Soil with Vs ≤150 or less	*	<140	<10	*

N/A-Not applicable, * Not available, Vs^{30} and Vs^{20} are in m/s

sification procedure recommended in Chinese Code GB 50011 (Code of China, 2001) is described in Chapter 4, Section 4.1.6 of the code. It also includes provision for fault within the site and liquefiable soil. Site classifications are based on 20 m equivalent Vs of soil (Vs^{20}) and thickness of site overlying layers. Site classification according to the Chinese code based on the description of subsurface materials is given in Table 1. There is no separate section for site classification that considers geotechnical characteristics of sites in the Indian code BIS 1893 (Bureau of Indian Standards, 2002). But Section 6.3.5.2 of the code describes very general criteria for site conditions by specifying SPT-N values and type of foundation. Site classification in Indian code BIS 1893 (Bureau of Indian Standards, 2002) are based on SPT-N values and given in Table 1. In order to understand the differences between site classification schemes in IBC/NEHRP and other seismic codes in the Australia, China and India, site classification based on SPT-N and Vs data collected from the Australia, China and India has been presented.

Site Classification Using SPT Data

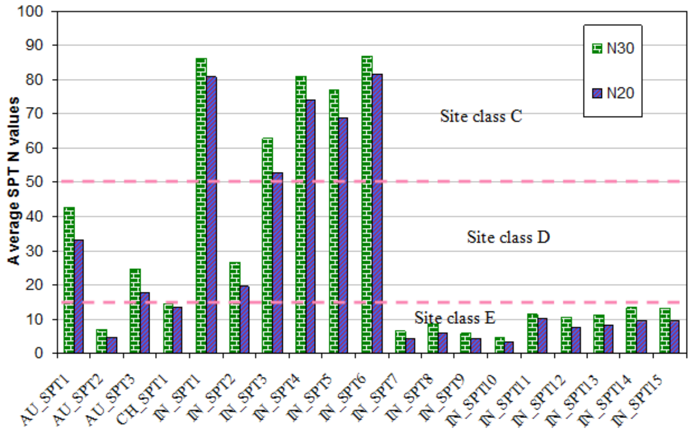
Boreholes with SPT-N values are one of the oldest, popular and common in-situ tests used for soil exploration in soil mechanics and foundation engineering. This is being popularly used worldwide in geotechnical projects, because of simplicity of the equipment and ease of test procedure. In particular standard penetration tests are widely used for seismic site characterization, site response and liquefaction studies towards seismic microzonation due to the availability of large data sets. However these SPT- N values may vary even for identical soil conditions because of their high sensitivity to operator techniques, equipment and poor boring practice. SPT-N values may be used for projects at preliminary stage or where there is a financial constraint (Anbazhagan & Sitharam, 2009b, 2010). SPT is carried out in a borehole, by driving a standard 'split spoon' sampler using repeated blows of a 63.5 kg hammer falling through 762 mm. The hammer is operated at the top of the borehole, and is connected to the split spoon sampler by rods. The split spoon sampler is lowered to the bottom of the hole, and is then driven a distance of 450 mm in three 150 mm intervals and the blows are counted for each 150 mm penetration. The penetration resistance (N) is the number of blows required to drive the split spoon for the last 300 mm of penetration. The penetration resistance during the first 150 mm of penetration is ignored, because the soil is considered to have been disturbed. In the present study, SPT-N values of the selected soil profiles have been collected from Australia, China and India (IEA, 1990; Pappin et al., 2008; Anbazhagan & Sitharam, 2009a; Anbazhagan, 2004). In total, nineteen boreholes data with SPT N values are used for the study.

Equivalent SPT N values for 30 m and 20 m depth were estimated using equation (1) and presented in Figure 2. SPT-N values have been used directly to classify the sites according to IBC/NEHRP. According to IBC2006/NEHRP, all N_{30} values above 50 are grouped in site class C. N_{30} based criterion was not given for site classes A and B. IBC2006/NEHRP does not have SPT-N based site classification for sites having N_{30} more than 50. Hence, for sites of average SPT-N values above 50 may be considered as site class C. Australian Standard recommends Vs for site class A and B, soil column period for site class C, SPT N or period for site class D and SPT N and Vs for site class F. Australian Standard recommendation of SPT N values for site classes D and E are much lower than IBC/NEHRP recommendation. General site classification of Australian Standard based on Vs and SPT N values are given in Table 1. Chinese Code recommends measuring Vs for site classification and no SPT-N value based site classification is recommended; however, for building categories C or D (and for buildings less than ten stories and not more than 30 m in height), appropriate Vs may be estimated using known geologic conditions. Indian Code suggests three site classes based on SPT-N values (not equivalent to the average SPT-N values of top 30 m). The site classification in Indian code may be considered very crude (compared to other contemporary codes) and may not be capable of providing accurate site amplification ratios.

Shear Wave Velocity

Shear wave velocity of subsurface is being used by many researchers for seismic site classifications, site response and microzonation study. A number of seismic methods have been proposed for near-surface characterization and measurement of Vs using a great variety of testing configurations, processing techniques, and inversion algorithms. The most widely used techniques are Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW). The MASW has been found to be a more efficient method for unravelling the shallow subsurface properties (Park et al., 1999; Xia et al., 1999; Zhang et al., 2004; Anbazhagan & Sitharam, 2008c). MASW is increasingly being applied to in earthquake geotechnical engineering for seismic microzonation and site response studies (Anbazhagan & Sitharam, 2008a, 2008b; Sitharam & Anbazhagan 2008b, 2009; Anbazhagan, Thingbaijam, Nath, Narendara Kumar, & Sitharam, 2010). In particular, MASW is used in geotechnical engineering for the measurement of Vs and other dynamic properties (Sitharam & Anbazhagan, 2008b), identification of subsurface material boundaries and spatial variations of Vs (Anbazhagan & Sitharam, 2009a). It can also be used for the geotechnical

Figure 2. Site classification of Australia, China and India profiles according to IBC2006/NEHRP

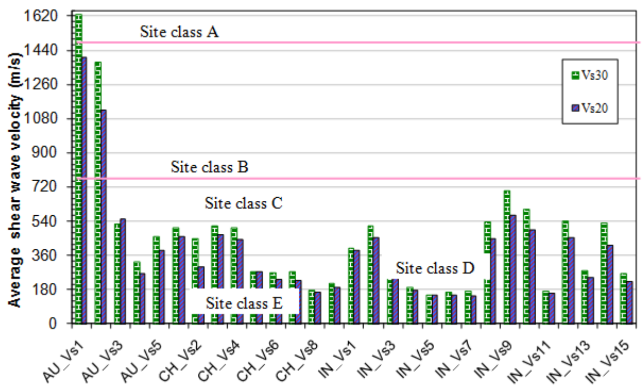


characterisation of near surface materials (Park et al., 1999; Miller et al., 1999; Kanli et al., 2006; Anbazhagan & Sitharam, 2008c). Recently this seismic surface wave method is being used in Australia at University of Wollongong to identify and measure the type and degree of fouling considering shear modulus variation (Anbazhagan, Indraratna, Rujikiatkamjorn, & Su, 2010). Until now, adequate surface wave studies have not been carried out in Australia to measure shear properties of subsurface layers except that reported in Collins et al. (2006). Authors highlighted the paucity of near-surface Vs data in Australia and the difficulties in estimating amplification effects. Recently, Geosciences Australia initiated Vs measurement using site-specific Spatial Autocorrelation (SPAC) surveys using microtremor (Asten & Roberts, 2005) and seismic cone penetrometer testing in two major cities in Australia (Newcastle and Perth). Vs profiles of Australia were compiled from Collins et al. (2006) and other sources. Similarly Vs profiles of China were collected from Song et al. (2007) and Hwang et al. (2004). Indian Vs profiles were measured by first author using MASW survey (Anbazhagan & Sitharam 2008a). Indian shear wave velocity profiles are collected from Boominathan (2004), Boominathan et al. (2008), Anbazhagan et al. (2009), and Uma Maheswari (2008a, 2008b).

Site Classification Using vs. Data

Weighted average Vs for depth of 30 m and 20 m were estimated using equation 1 and presented in Figure 3. Figure 3 shows that 76% of sites are classified as site class D, 5% are site class E. Australian sites 1 and 2 are classified as site classes A and B, respectively, according to IBC2006/NEHRP. Site classification definition in Australian Standard (AS 1170.4) is similar to IBC2006/NEHRP recommendation for site class A. However, for site class B, AS 1170.4 recommends Vs of greater than 360m/s, which corresponds to site class C in IBC/NEHRP. AS 1170.4 recommends low-amplitude natural site period as criteria for site classes C and D, that is not compatible with the recommendations of IBC/NEHRP. AS1170.4 recommends Vs less than 150 m/s for site class E, which is lower than IBC/NEHRP recommendation. Chinese code (GB 50011, 2001) classifies sites into four classes based on weighted average Vs of top 20 m soil layers. The range of values specified in Table 4.1.6 of GB 50011 is much lower than those in IBC/NEHRP. Indian Code (BIS 1893) (Bureau of Indian Standards, 2002) classifies sites into three site classes based on measured

Figure 3. Average Vs values of sites in Australia, China and India with site classification according to IBC2006/NEHRP



N values and Vs values are not recommended in BIS 1893 (Bureau of Indian Standards, 2002). It is apparent that site class according to Indian code is not well defined and hence may not provide similar site amplification effect compared to other codes.

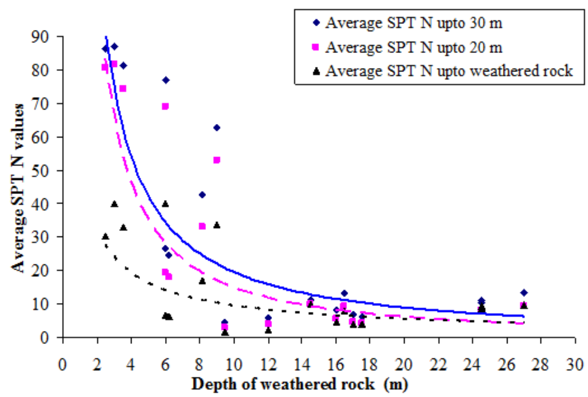
Proposal for Alternate Site Classification Scheme

Urban centres in the Australia, China and India have been severely affected by past earthquakes, but earthquake standards of these countries do not have adequate provision to account for site effects. Site classification studies for seismic microzonation in these countries are based on the top 30 m soil values similar to IBC2006 and NEHRP using SPT data or measured Vs. IBC2006 and NEHRP site classification are developed based on studies conducted in the United States, which may not be directly applicable in other parts of the world. IBC2006 and NEHRP classify all the sites having N_{30}>50 as site class C, which is also not applicable for all the sites (Anbazhagan, Sheikh, & Tsang, 2010). Anbazhagan, Sheikh, and Tsang (2010) considered for new site classification based on average SPT-N and Vs values up to depth of engineering rock. The authors highlighted that sites having engineering rock depth within top 30 m, classification based on soil average (up to engineering bed rock) provides different site classes and site amplification factor when compared to site class based on top 30 m. In this study, a new site classification scheme considering average Vs (or SPT-N) values up to hard stratum/weathered rock and engineering bedrock have been presented.

Site Classification Considering Weathered Rock Layer

Average SPT-N and shear wave velocity up to weathered rock depth has been estimated and used to classify the sites according to existing site class of NEHRP/IBC. Weathered rock depth can be identified in borelog data rather than SPT N values, because in most cases SPT-N values of above 50 represents the dense layer or weathered rock. Hence after studying borelogs carefully, weathered rock depth has been identified. Average SPT-N values up to weathered rock (NWR) depth have been estimated and which is shown in Figure 4. Figure 4 shows average SPT-N values up to 30 m and 20 m gives higher N values and stiffer site class when compared to NWR. When weathered rock depth within 10 m this site class variation is considerable,

Figure 4. Average SPT N values upto weathered rock and 30m and 20m average SPT N values with depth of weathered rock



however this need to be further confirmed using large number of data sets. Similarly weathered rock depth has been identified considering Vs of 330±30 m/s. Average shear wave velocity up to weathered rock (VsWR) has been estimated and shown in Figure 5. Figure 5 clearly shows that if weathered rock depth is within 15 m, VsWR are much less than 30 m and 20 m average Vs. Site classification based on 30 m and 20 m average Vs provides stiffer site class and lower spectral values for sites having soil thickness less than 15 m.

Site Classification Considering Engineering Rock Layer

Weathered rock is stiffer than overlaying soil layers, but many times it is difficult to differentiate dense soil and weathered rock layers based on SPT-N and Vs values, unless detailed borelog study is available. Site classification considering up to weathered rock layers may be subjected to significant criticism. Hence site classification considering average SPT-N and Vs values up to engineering bedrock has been attempted. Most of engineering structures are placed on rock where SPT-N values of 100 for no penetrations or Vs of 760±60 m/s (Anbazhagan & Sitharam, 2009a). This rock layer can be called as engineering bedrock (Anbazhagan & Sitharam, 2009a). Engineering bedrock layer has been identified from borelogs SPT-N data, considering layer corresponding to 700 m/s ± 10% in Vs data. Average SPT-N and Vs values have been calculated up to engineering bedrock layer. Figure 6 shows the average SPT-N values up to engineering bedrock (NER) versus depth of engineering bedrock along with NWR, N_{30} and N_{20}. The N_{30} and N_{20} give higher average SPT-N values for stiffer site class, compared to NER and NWR. The NWR gives slightly higher values when compared to NER for engineering rock depth up to 20 m and beyond this range they are quite similar. Figure 7 shows average Vs up to engineering bedrock versus depth of engineering bedrock along with VsWR, $Vs^{30}$and Vs^{20}. Average Vs up to engineering bedrock (VsER) is less than Vs^{30} if engineering rock depth is less than 25 m, and more than Vs^{30} if engineering rock depth is more than 35 m. It is noted that VsER are equal to $Vs^{30}$and Vs^{20} when the engineering rock depth is 30 m and 20 m, respectively. Site classification based average values up to 30 m gives stiffer site class if engineering bedrock is less than 25 m. This has been further verified using site specific response analysis considering typical Vs profile and synthetic and recorded ground motion data, which is discussed in next section.

Figure 5. Average Vs upto weathered rock and 30m and 20m average Vs with depth of weathered rock

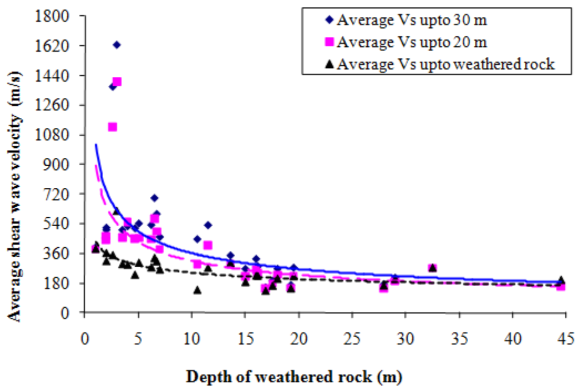
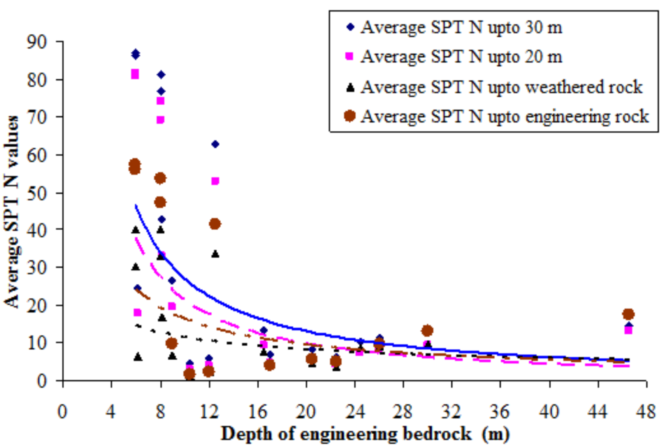


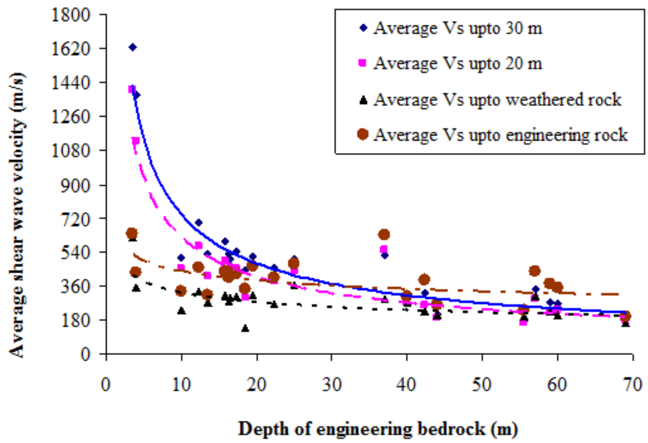
Figure 6. Average SPT N values upto engineering bedrock and 30m and 20m average SPT N values with depth of engineering bedrock



Site Response Parameters in the Shallow Engineering Bedrock Sites

Most of recorded site effect studies and amplification correlation with shear wave velocity are available for deep sites, where the engineering bedrock is more than 100 m. Hence the recorded data cannot be used directly to calculate or verify site effects in shallow engineering bedrock regions. Due to lack of recorded site response parameters from shallow engineering bedrock sites, site response analysis has been carried out using one dimensional site response analysis program SHAKE. The computer program SHAKE was written in 1970-71 by Schnabel et al. (1972). This has been, by far, the most widely used program for computing seismic response of horizontally layered soil deposits. SHAKE adopts equivalent linear approach to calculate the non-linear behaviour in which

Figure 7. Average Vs upto engineering bedrock and 30m and 20m average Vs with depth of engineering bedrock



ground motion of the object can be given in any one layer in the system and motions can be computed in any other layer. In equivalent linear approach, the non-linearity of the shear modulus and damping is accounted for the use of equivalent linear soil properties using an iterative procedure to obtain values for modulus and damping compatible with the effective strains in each layer. More discussion about SHAKE principal and options are discussed in Anbazhagan and Sitharam (2008b, 2009b). In this study, the degradation curves given by Seed and Idriss (1970) and Schnabel (1973) for sand average and rock has been used for soil and rock layers respectively.

Input Ground Motion

A large number of damaging earthquake with varying magnitudes have occurred in Asia particularly in India and China; however, only a limited number of recorded acceleration time histories are available for research to understand site effects behavior. For the area having limited or no seismic record, synthetic ground motion may be considered as a viable alternative (Sitharam & Anbazhagan, 2007). Modeling of strong motion helps to estimate future hazard of the region and study the local effects in local scale. Seismological model by Boore (1983, 2003) is used for the generation of synthetic acceleration-time response (Atkinson & Boore 1995; Hwang & Huo, 1997). In order to understand the site effects due to moderate earthquake, synthetic ground motion generated by Sitharam and Anbazhagan (2007) and Anbazhagan and Sitharam (2009c) has been used in this study. Figure 8 shows synthetic ground motion used as input earthquake ground motion in the site response analysis. This synthetic ground motion generated having peak acceleration of 0.155g for moment magnitude of 5.1 can be considered as representative of an intra-plate earthquake event. Typical inter-plate earthquake reported in Chamoli has been taken from Atlas of Indian Strong Motion Records (Shrikhande, 2001). The Chamoli earthquake occurred on 29 March 1999 at north of Chamoli in the Lesser Himalayas. This event has moment magnitude of 6.6 and peak ground acceleration of 0.19 g recorded at rock level. Figure 9 shows the acceleration time history of Chamoli earthquake.

Soil Profiles and Site Response Results

Site specific dynamic properties are very important in the site response analysis. Important

Figure 8. Input ground motion: synthetic ground motion for Mw of 5.1 -Intra plate earthquake

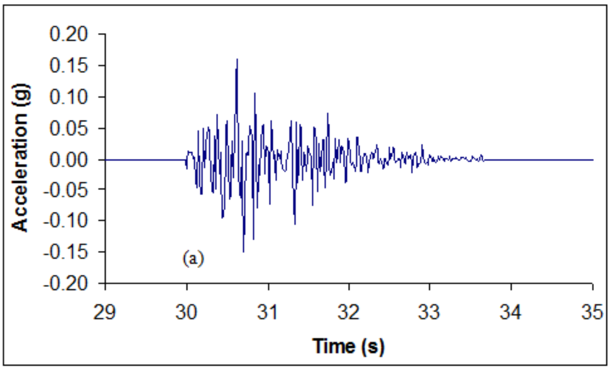
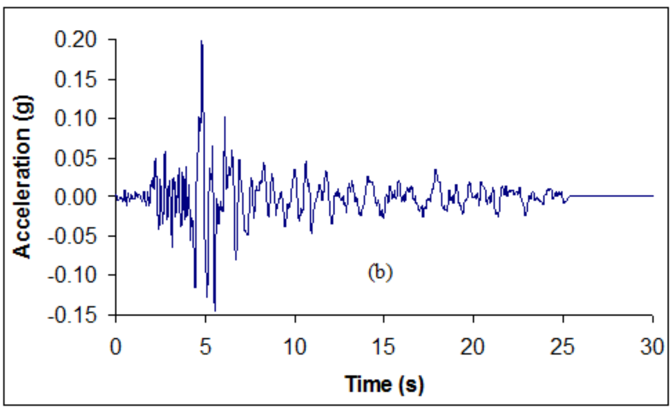


Figure 9. Input ground motion: recorded rock motion at Chamoli, Mw of 6.6 -Inter plate earthquake



parameter of shear modulus (G_{max}) is being estimated using empirical correlation between SPT N and G_{max} or shear wave velocity and density. The SPT-N and shear modulus correlations inbuilt in SHAKE software require modification and using of SPT N values with less knowledge of hammer energy may lead to erroneous result (Anbazhagan et al., 2011b). Hence SPT-N values are purposefully eliminated for site response analysis. Typical shear wave velocity profiles are selected with shallow engineering bedrock from data set. Two types of analyses have been performed: first, analysis based on modified shear wave velocity profile to represent soft to dense soil of same thickness above rock layers. These are representative of filled materials above rock i.e., filling of lakes. Second, analysis based on measured shear wave velocity for loose to dense soil profile having engineering rock depth at different level.

Modified shear wave velocity profiles are referred here after as MSWV. Figure 10 shows typical MSWV for loose, medium, dense, very dense and engineering rock layers above hard

Table 2. Summary of modified shear wave velocity profile used to estimate site response parameters

Parameters	Modified Shear wave velocity (MSWV) profile				
	1	2	3	4	5
Soil Type	Loose	Medium	Dense	Very Dense	Rock
Layer thickness-minimum (m)	1.4	1.4	1.4	1.4	4
Layer thickness-maximum (m)	2.6	2.6	2.6	2.6	4
Depth of weathered rock (m)	4	4	2.6	2.6	0
Depth of engineering rock (m)	4	4	4	4	0
Lowest SWV (m/s)	120	230	350	500	760
Vs^{30}	812.449	1129.39	1324.36	1466.367	1606.015
Vs^{20}	608.91	889.54	1076.84	1221.06	1369.84
Vs^{WR}	120.00	230.00	351.65	500.00	760.00
Vs^{ER}	170.15	304.26	433.09	568.01	760.00
Site class based on Vs^{30}	B	B	B	B	A
Site class based on Vs^{20}	B	B	B	B	B
Site class based on Vs^{WR}	E	D	D	D	D
Site class based on Vs^{ER}	E	D	D	D	D

rock. These repetitive materials have the thickness of 4 m and placed above hard rock having shear wave velocity of 1385 m/s. Summary of MSWV profiles are given in Table 2. Here it can be noticed that soil types are loose to very dense. MSWV of 1- 4 are called as stiffer site class B, when these are classified using 30 m average values as per NEHRP or IBC. Similarly MSWV 5 is also classified as site class A. These sites are also classified as similar class according to Australian Standard classification given in Table 1. These sites are classified as site class B according to Chinese seismic Code based on 20 m average values (Table 1). These sites can be classified as site class E (MSWV 1) and D (MSWV 2-5) while average soil Vs up to engineering bedrock is considered. This has been further investigated by carrying out site response analysis.

Site response analysis has been carried out using computer program SHAKE 2000 for recorded and synthetic earthquake records discussed earlier. Input motions are given at engineering bedrock. Response spectrum from the SHAKE 2000 for different soil layers stiffness (MSWV 1-5) having same thickness is shown in Figure 11. Synthetic ground motion correspond to moderate earthquake is the input motion at same rock level. Medium stiffness soil column spectral values (MSWV 2) are higher than other soil column up to period of 0.25 s. Lower stiffness soil columns spectral values (MSWV 1) are higher than other soil column from period 0.25 s to 4 s. Spectral values are same irrespective of soil column stiffness beyond the period of 4 s. Dense to very dense soil column (MSWV 3, 4 and 5) spectral values are slightly higher than rock values up to period of 0.25 s, beyond which soil spectral values are almost similar to rock values. Figure 12 shows response spectrum of MSWV profiles for recorded ground motion of Chamoli earthquake. Spectral values are higher when stiffness of soil column is low (MSWV 1) and decrease when stiffness of column increases up to period of 4 s. Beyond 4 s spectral values are the same irrespective of soil column.

For second analysis the measured shear wave velocity profiles (SWV) are selected with different engineering depth, which are shown

Figure 10. Modified shear wave velocity profile (MSWV) for different soil type above the hard rock

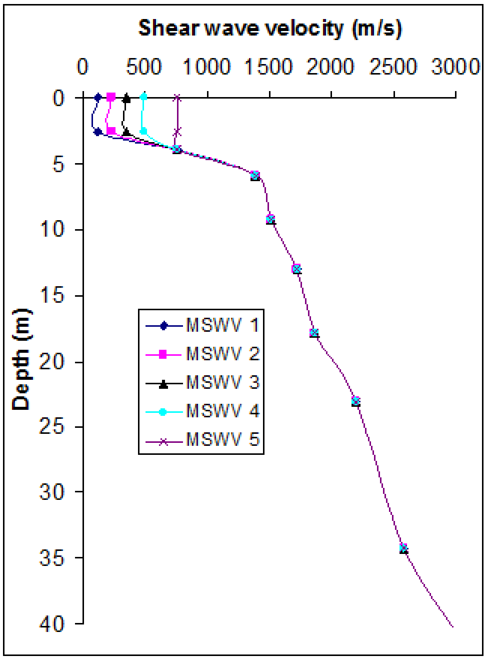
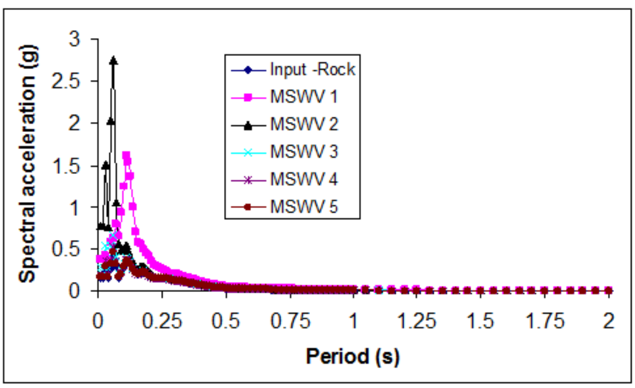


Figure 11. Response spectra of soil columns having similar soil thickness but different soil stiffness under synthetic ground motion at same rock level



in Figure 13. First profile (SWV1) represents loose to medium soil with lowest shear wave velocity of 140 m/s. Thickness of each layer varies from 0.3 m to 2 m and engineering bedrock is identified at a depth of 10 m. Second Vs profile (SWV2) represents dense to very dense soil. Shear wave velocity of layers varies from 337 m/s to 551 m/s above the engineering bedrock located at 12.85m. Thickness of each layer varies from 0.85 m to 2.6 m. Third Vs

Table 3. Summary of shear wave velocity profile used to estimate site response parameters

Parameters	Shear wave velocity (SWV) profile				
	1	2	3	4	5
Soil Type	Loose to medium	Dense - very dense	Medium	Dense	Medium
Layer thickness-minimum (m)	0.3	0.85	1.38	2.6	2.5
Layer thickness-maximum (m)	2	2.6	5.25	2.6	2.5
Depth of weathered rock (m)	4.67	4.92	5.25	2.6	32.5
Depth of engineering rock (m)	10	12.85	20.26	4	40
Lowest SWV (m/s)	140	337	184	350	272
Vs^{30}	513	802	492	1374	271.25
Vs^{20}	452	643	406	1127	271.84
Vs^{WR}	232	428	281	351	275.16
Vs^{ER}	333	540	413	434	305.63
Site class based on Vs^{30}	C	B	C	B	D
Site class based on Vs^{20}	C	B	C	B	C
Site class based on Vs^{WR}	D	C	D	D	D
Site class based on Vs^{ER}	D	D	D	D	D

Figure 12. Response spectra of soil columns having similar soil thickness but different site class under recorded earthquake ground motion at same rock level

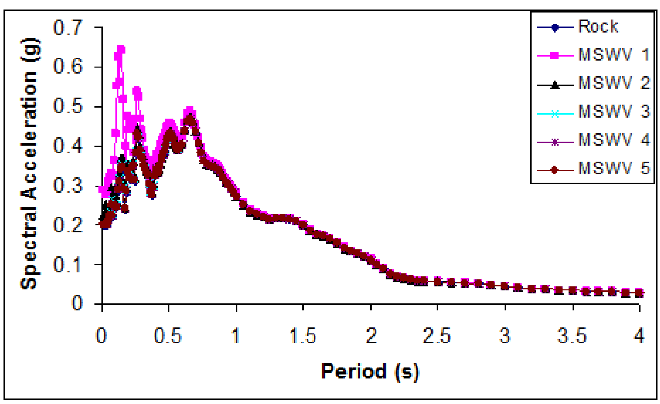


Figure 13. Measured shear wave velocity (SWV) with different rock depth used for site response analysis

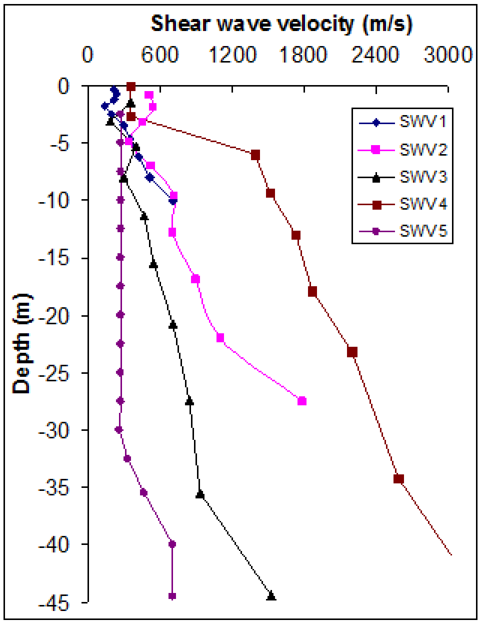
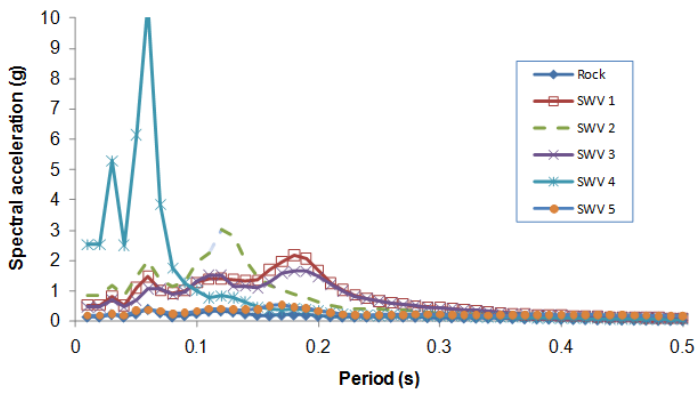


Figure 14. Response spectrum of different site class soil columns for synthetic ground motion at 30 m depth



profile (SWV3) represents medium soil with a lowest shear wave velocity of 184 m/s. Soil layer thickness varies from 1.38 m to 5.25 m and engineering bedrock located at 20.3 m. Fourth Vs (SWV4) profile represents dense soil having shear wave velocity of 350 and engineering bedrock at 4.0 m. Fifth profile (SWV5) consists of medium soil up to depth of 40 m with a average soil layer thickness of 2.5 m having Vs of 272 m/s. Summary of shear wave

Figure 15. Response spectrum of different site class soil column for recorded ground motion at 30 m depth

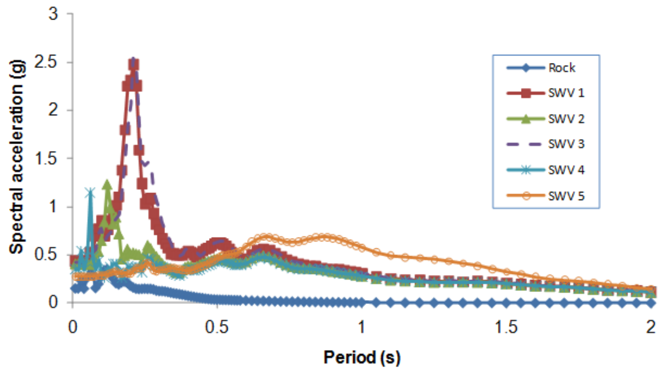
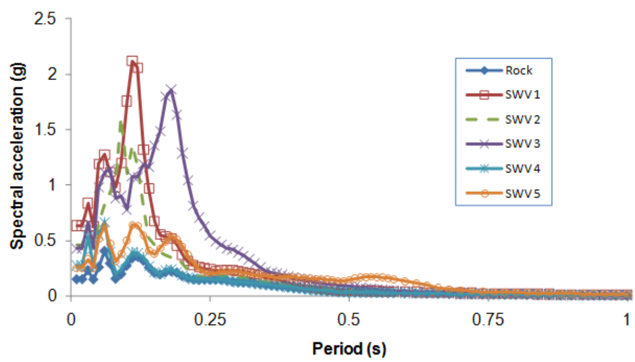


Figure 16. Response spectrum of different site class soil column for synthetic ground motion at engineering bedrock level



velocity profile with soil description, minimum and maximum layer thickness, depth of weathered and engineering rock, lowest Vs, average shear wave velocity up to 30 m, 20 m, weathered rock and engineering rock with site classification according NHERP and IBC are given in Table 3. SWV 1 and SWV3 can be classified as site class C according NHERP, which has Vs^{30} of about 500 and engineering rock at 10 m and 20 m (Table 1). Profiles SWV 2 and SWV4 can be classified as site class B; Vs^{30} of SWV 2 is 802 m/s and SWV 4 is 1374 m/s. SWV 2 has engineering rock depth at about 13 m and SWV 4 has at 4 m. Profile SWV 5 can be classified as site class D, where the engineering bedrock is at a depth of 40 m. Response spectrum and amplification ratio for these profiles are obtained using SHAKE using synthetic ground motion as input at a depth of 30 m and engineering rock level. Vs data for a profile SWV 1 and SWV 2 are less than 30m, these location last layer extend up to 30 m according to Boore (2004) for Vs^{30} calculation and site response analysis. Figure 14 shows response spectrum at rock and soil surface for five selected Vs profiles by giving synthetic

Figure 17. Response spectrum of different site class soil column for recorded ground motion at engineering bedrock level

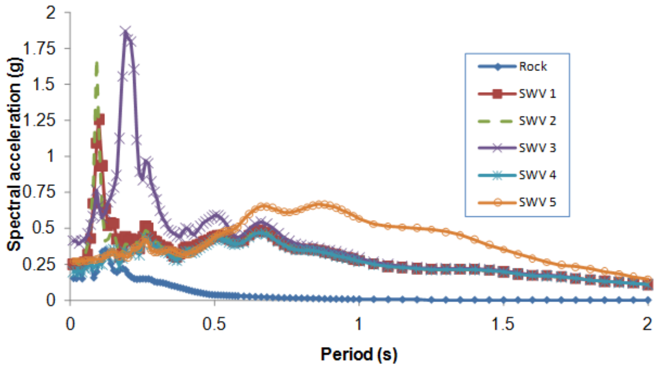
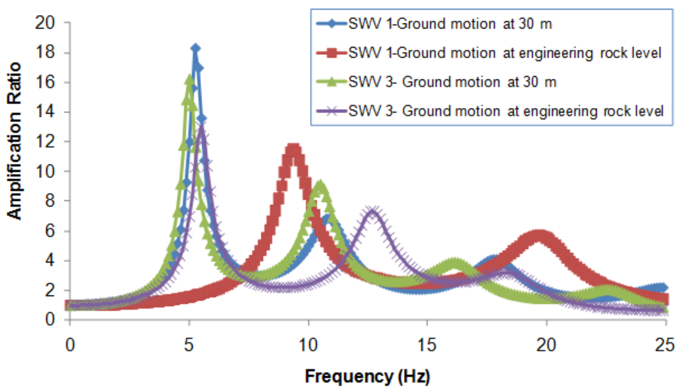
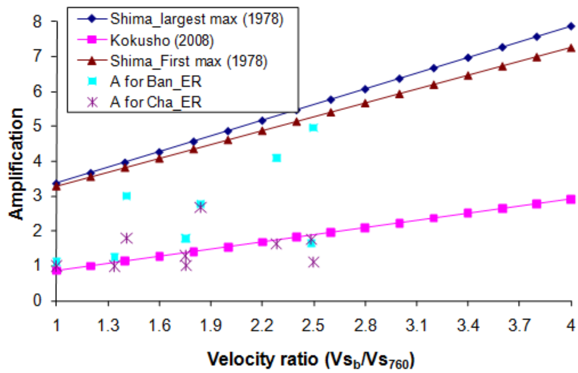


Figure 18. Amplification ratio for a same site class soil column for recorded ground motion at 30 m and engineering bedrock level



ground motion as input at 30 m. Site class C sites of SWV1 and SWV 2 have comparable spectrum up to period of 0.12 s and beyond 0.22 s, but spectral values are different from 0.12 s to 0.22 s. SWV 2and SWV 4 are classified as site class B with no amplification, but study shows that response spectrum is larger than site class C and D. Site class D profile SWV 5 response spectrum almost matches with rock, as per code it should have maximum spectral values. Figure 15 shows response spectrum at rock and soil surface for five selected Vs profiles for recorded ground motion as input at 30 m. Site class C sites of SWC 1 and SWV3 shows similar response spectrum and site class B sites of SWV 2 and SWV 4 shows different spectrum. Figures 16 and 17 show response spectrum at soil surface with input spectrum by giving synthetic and recorded ground motion as input at engineering bed rock. Similar mismatching site class and spectral values are observed between spectrum obtained from the study and site class spectrum. Typical amplification ratio for site class C

Figure 19. Amplification from this study compared to empirical correlations proposed in Shima (1978) and Kokusho and Sato (2008)



profiles of SWV1 and SWV3 is shown in Figure 18. Amplification ratios of same site class sites are considerably different with respect amplification ratio and frequency at first peak. Site response study shows that spectral values, amplification ratio and frequency correspond to peak amplification ratio are different for 30 m and soil depth. These parameters are dependent on soil stiffness and thickness and hence following 30 m or 20 m and grouping them is not representative, particularly when the rock depth is less than 30 m.

Amplification Values

The main aim of the site classification scheme is to estimate amplification of seismic waves for particular site considering geotechnical aspects. Amplification ratios based on empirical correlation considering average soil properties are widely used for seismic microzonation of urban centers. Amplifications are used to represent site effects of particular soil column. Many empirical correlations are available to estimate amplification of seismic waves. These correlations are based on the ratio of shear wave velocity of foundation/rock to soil velocity or 30 m equivalent shear wave velocity (Vs^{30}) and are developed considering deep soil data. Summary of these correlation and applicability for shallow soil sites in India are presented by Anbazhagan et al. (2011a). This study examines applicability of available amplification relations in the literature for shallow soil profiles considered in this study. Amplifications for an earthquake waves are estimated for these sites using empirical relations and compared with site response analyses results. Site effect studies and amplification correlations with shear wave velocity are available for deep soil sites where the engineering bedrock is not noticed or more than 100 m. In contrast, limited recorded ground motions at rock and surface with shear wave velocity profiles are available for shallow rock sites. The correlations developed for deep soil sites are used directly to represent site effects in the seismic microzonation irrespective of engineering bedrock depth in the region. These practices are widely followed by many researchers because it is given in manual for zonation on seismic geotechnical hazards published by Technical Committee for Earthquake Geotechnical Engineering (TCEGE, 1999). It is obvious to verify the suitability of these correlations by measured amplification data from shallow engineering bedrock regions. Site response analysis has been carried out for input ground motions at engineering bedrock level where Vs is more than 760±60 m/s and at 30 m depth. To focus amplification calculation only PGA has been considered here. Figure 19 shows amplification ratio calculated from shake analysis and of the correlation given by Shima (1978), Kokusho (2008), and Kokusho and Sato (2008). Few amplification values matches with Kokusho and Sato (2008) and trend of values differ from Shima (1978) and Kokusho and Sato (2008). Existing amplification correlations may not be directly applicable to shallow soil sites in urban area of Asian pacific region. Also, existing site classification system and amplification correlations may not be suitable for microzonation of urban centers. However, many site classification and amplification studies are being published for seismic microzonation map of urban centers in these countries without properly accounting for soil depth and stiffness. The authors recommend for region specific scheme for site classification and site amplification for future seismic microzonation studies.

CONCLUSION

This study shows that site classification based on soil profiles of top 30 m or 20 m may not be representative of expected site amplification in Australia, China and India. Site classification considering top 30 m soil profile was developed originally in the USA and has been followed to develop site amplification in many design codes. Also, site classification considering top 20 m soil profile is widely used in China. The 30 m and 20 m approaches calculate similar site class when rock depth is close to 30 m and 20 m. When engineering rock depth is shallow, these approaches calculate larger average SPT-N and Vs values resulting in stiffer site classes. Site response study using two earthquake data (recorded and simulated) for selected soil profiles shows that amplification ratio and response spectrums are considerably different. Hence, direct adoption of IBC2006 and NEHRP classifications for sites having shallow engineering rock in Australia, China and India may result in stiffer site class. Considering equivalent SPT-N or Vs up to engineering rock provides better representation of site effects. However, the proposed approach of site classification considering engineering bedrock needs to be extensively investigated before its adoption in the next generation seismic design codes.

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