Effect of Bedrock Depth on Site Classification

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SUMMARY:
One of the most important steps in seismic microzonation is site characterization. Average Shear Wave Velocity up to 30 metres [$\overline{V_s}(30)$] is a common parameter for classifying sites. But often problems are encountered in obtaining $\overline{V_s}(30)$ from models of shallow shear wave velocity [where the soil column doesn't extend up to 30m] and in that case, extrapolation is done. But none of those extrapolation methods considers the bed rock shear wave velocity. This article attempts to study the effect of bed-rock shear wave velocity, impedance contrast of bedrock and superficial soil layers, and depth of bed-rock, on site amplification and classification. Five sites in Delhi, India are chosen for which the shear wave velocity profiles and bed rock depths are known. Software SHAKE2000 is used for estimating site amplification. These sites are classified according to NEHRP site classification scheme (BSSC, 2003) and Eurocode-8 (2003) adopting three methods: *extrapolation assuming constant velocity*; *extrapolation using the correlation between* $\overline{V_s}(30)$ & $\overline{V_s}(d)$; and the proposed method. Better site class is obtained adopting the proposed method.

Keywords: Site class, Average shear wave velocity up to 30 metres, Bedrock shear wave velocity, Amplification ratio, Natural frequency.

1. INTRODUCTION

From the early hours of civilization, mankind has been challenged by various natural calamities. The greatest hazard it has faced is probably the earthquakes which can neither be predicted nor be prevented. However, the severity of the damages can be minimized by proper infrastructure planning based on microzonation studies and by following appropriate construction procedures adopting codal provisions. Seismic microzonation studies are considered as one of the most important parametres in mitigating seismic hazards as it provides the expected level of shaking in a region and associated seismic risks such as liquefaction, lateral spreading, landslides, tsunamis, etc.

India has experienced most disastrous earthquakes i.e. Assam 1897 (M=8.7), Kangra 1905 (M=8.6), Bihar-Nepal 1934 (M=8.4), Assam-Tibet 1950 (M=8.7), Uttarkashi 1991 (M=6.5), Latur 1993 (M=6.4), Jabalpur 1997 (M=6.0), Chamoli 1999 (M = 6.8), Bhuj 2001 (M= 7.6) and Kashmir 2005 (M=7.4). The devastating Bhuj Earthquake has created greater awareness among the engineering fraternity of India and various schemes have been implemented to avoid losses from future earthquakes. As a result of this, seismic microzonation of various urban areas, like Delhi, Chennai, Bangalore, Lucknow, Ahmedabad, Guwahati etc. are being carried out. Boominathan (2004) has given the criteria for seismic site characterization for nuclear power plants and structures. However, problem lies with the fact that there are no standard procedures and/or guidelines available for seismic microzonation, and hence these studies are considerably different from each other, particularly in site characterization studies. Also the availability of different geotechnical and geophysical studies for dynamic site characterization often leads to confusion in adopting a particular test or methodology.

In conventional methods of site classification, Average Shear Wave Velocity up to 30 metres[$\overline{V_s}(30)$] is a widely used parameter for classifying sites to predict their potential to amply seismic shaking (Dobry et. al, 2000). However, in many cases models of shallow shear wave velocities do not extend up to 30 metres. For this purpose some methods of extrapolation are devised (Boore, 2004). Extrapolation is also done for the sites with lack of information about the subsurface geology or where shear wave velocity cannot be obtained up to 30 metres due to various practical problems. But in none of these methods, the effect of bed rock has been considered. The article aims to study the effect of bed-rock shear wave velocity, impedance contrast of bedrock and superficial soil layers, and depth of bed-rock on site classification and amplification of seismic waves. Two conventional methods as commonly used i.e. *Extrapolation Assuming Constant Velocity* (Boore 2004) and *Extrapolation using the Correlation between* $\overline{V_s}(30)\ \&\ \overline{V_s}(d)$ (Boore 2004) are also employed to perform a comparative study. Five sites in the Delhi region i.e. Janakpuri, Dilshad Garden, Rohini, Pushpa Vihar and J.N.U. Campus are chosen for which the shear wave velocities and bed rock depths are known (Rao and Neelima, 2004). These sites are classified according to National Earthquake Hazard Reduction Program- NEHRP (BSSC, 2003) site classification scheme and Eurocode-8 (2003).

To understand the effect of local site conditions, theoretical one dimensional ground response analysis is performed using the software SHAKE2000. Several researchers have already carried out ground response analysis for many cities in India: e.g. Govindraju et. al. (2004) for Gujrat; Rajiv Ranjan (2005) for Dehradun; Boominathan et. al. (2007) for Chennai; Mohanty (2007) for Delhi; Raghukanth (2008) for Guwahati; & Choudhuri and Shukla (2011, a, b) again for Gujrat.Kowk and Stewart (2006) showed that 1-D ground response analysis can be useful in predicting the average effects of sediment nonlinearity.In this articleBhuj earthquake (2001) is considered as the input motion. The acceleration-time history at the surface, response spectra for 2, 5, 10 & 20% damping and amplification ratio are obtained from this analysis.

2. SITE CHARACTERIZATION METHODS

Recently most of codes like Eurocode-8 (2003), NEHRP (BSSC, 2003), International Building Code (IBC, 2009) etc. specify the site classification based on the average shear wave velocity values in the top 30 m [$\overline{V_s}(30)$]. The density and the shear wave velocity of the overlying soil layer play major role in the amplification of shear waves. However due to comparatively lesser variation in the density of soil, the amplification depends heavily on the shear wave velocity near the earth surface. $\overline{V_s}(30)$ is calculated using the equation

$$V_s^{30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{d_i}{v_i}\right)} \qquad (2.1)$$

Where d_i - thickness of the i^{th} soil layer in metres; v_i - shear wave velocity for the i^{th} layer in m/s and N – no. of layers in the top 30 m soil strata which will be considered in evaluating V_s^{30} values.

In many locations the rock depth will be shallow (less than 30 m) and hence the evaluation of $\overline{V_s}(30)$ value will not be possible. In those cases, extrapolation of available V_s values has to be done to evaluate $\overline{V_s}(30)$. The method proposed by Boore (2004) can be used for this purpose. He has suggested different models to extrapolate the shear wave velocities, for depths less than 30 m, to get the $\overline{V_s}(30)$ value. The first method is extrapolation based on constant velocity. In this model it is assumed that the shear wave velocity remains constant from the deepest velocity measurement to the 30 m.

$$\overline{V_s}(30) = \frac{30}{tt(d) + (30 - d)/V_{eff}} \text{ (Boore, 2004)} \quad (2.2)$$

Where $tt(d)$ is the travel time to depth d and $V_{eff} = V_s(d)$, $V_s(d)$ is the timed average velocity to a depth of d.

Even though this method is simple, it gives under estimated $\overline{V_s}(30)$ values, since the shear wave velocity increases with depth in most of the soils. Another relation proposed by Boore (2004) was based on a power law relation, the V_s^{30} value can be estimated as:

$$\log \overline{V_S}(30) = a + b \log \overline{V_s}(d) \text{ (Boore, 2004)} \quad (2.3)$$

Where $\overline{V_S}(d)$ is the velocity at a depth of d m (10 < d < 30). The values of the regression coefficients a and $b$are given for depths ranging from 10m to 30m.To incorporate the effect of bed rock shear wave velocity on seismic site characterization a method is proposed in this article. It is calculated using the equation:

$$\overline{V_s}(30) = \frac{30}{\sum_{i=1}^{N} \frac{d_i}{v_i} + \frac{(30 - d)}{v_r}} \quad (2.4)$$

Where d is the depth of soil layer (1 <d< 30), d_i and v_i are depth and shear wave velocity of the i^{th} layer respectively, N is the number of layers up to depth d and v_r is the shear wave velocity of the bed rock.

A comparative study is performed among the methods described by the equations (2.2), (2.3) and (2.4).

A site classification scheme based on V_s^{30} values was proposed by Burckhardt (1994) and a similar scheme was adopted by the National Earthquake Hazard Reduction Program (NEHRP) also. Eurocode-8 (2003) has also classified the site based on V_s^{30}, standard penetration test (SPT) and cone penetration test (CPT) values. Here site classification is done in accordance with both the codes.

3. GROUND RESPONSE ANALYSIS:

The effect of bed rock depth on site characterization is particularly of importance for sites like Delhi where the bedrock topography is undulating in nature with several humps and depression (Rao and Neelema, 2004). In their study, they have calculated $\overline{V_s}(30)$ for 118 sites in Delhi using MASW testing. Five sites in Delhi i.e. Janakpuri, Dilshad Garden, Rohini, Pushpa Bihar and J.N.U. campus are chosen for which bed rock depth and shear wave velocity are known (Rao and Neelima, 2004). Table 3.1 shows a comparison for the two extrapolation techniques as described by equations (2.2) and (2.3) and the proposed method as given by equation (2.4).

Table 3.1. Comparison of Three Methods

Site	Bed Rock Depth from surface (m)	V_s^{30} (m/s)	Site class		Remarks
			NEHRP	EUROCODE 8	
Janakpuri	>30	286	D	C	Since soil column extends up to 30m, no extrapolation is done.
Dilshad Garden	24	a. 277	D	C	Higher value of V_s^{30} considering bed rock shear wave velocity.
		b. 280	D	C	
		c. 303	D	C	
Rohini	20	a. 366	C	B	-------
		b. 403	C	B	
		c. 435	C	B	
Pushpa Vihar	16	a. 338	D	C	Better site Class is obtained considering bed rock shear wave velocity.
		b. 355	D	C	
		c. 425	C	B	
J.N.U. Campus	8	a. 439	C	B	--------
		b. 541	C	B	
		c. 615	C	B	

a. Extrapolation assuming constant velocity (Boore, 2004).
b. Extrapolation using the correlation between $V_s(30)$ and $V_s(d)$ (Boore, 2004).
c. Proposed Method considering the shear wave velocity of bed rock.

To understand the effect of bed rock depth a hypothetical case study is presented. 4 cases are considered with bed rock depth linearly reducing from 25 metres to 10 metres at 5 metres interval. Figure 3.1 shows the comparison of the extrapolation techniques and the proposed method for four sites where bed rock lies at 10m, 15m, 20m and 25m respectively.

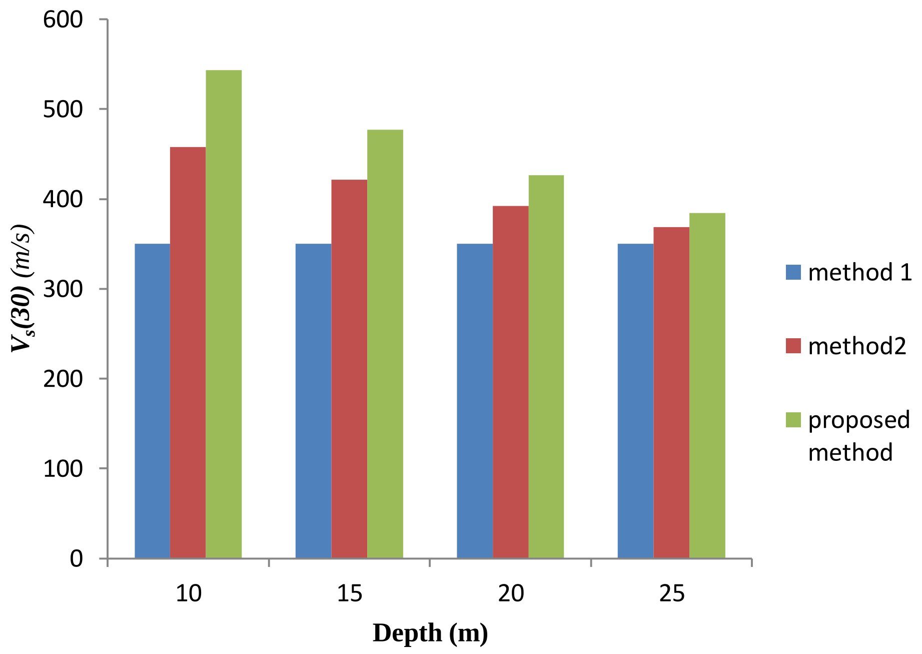

Figure 3.1. Comparison of Three Methods

Table 3.2 gives the difference of estimated $\overline{V_s}(30)$ values using the proposed method and method given by equation (2.3).

Table 3.2. Percentage Difference Of Estimated V_s^{30} Values

Depth of Bed Rock from G.S (m)	V_s^{30} (m/s)		Difference (%)
	Extrapolation using the correlation between $V_s(30)$ and $V_s(d)$ (Boore, 2004).	Proposed Method	
10	457.5	543.1	15.5
15	421.7	477.3	12
20	392.4	426.7	8
25	370.2	383.8	3.5

One dimensional ground response analysis is performed for all these sites using SHAKE2000. The modulus reduction curves and damping ratio curves are chosen from the database.

For a typical case study the following parametres are chosen:

Depth of bed rock = 15 m from the ground surface.
Type of soil = sand.
Shear wave velocity of sand = 350 m/s
Shear wave velocity of bed rock = 750 m/s
Depth of W.T. = 12 m from the ground surface.

The results can be interpreted through the figures 3.2, 3.3 and 3.4 as shown below:

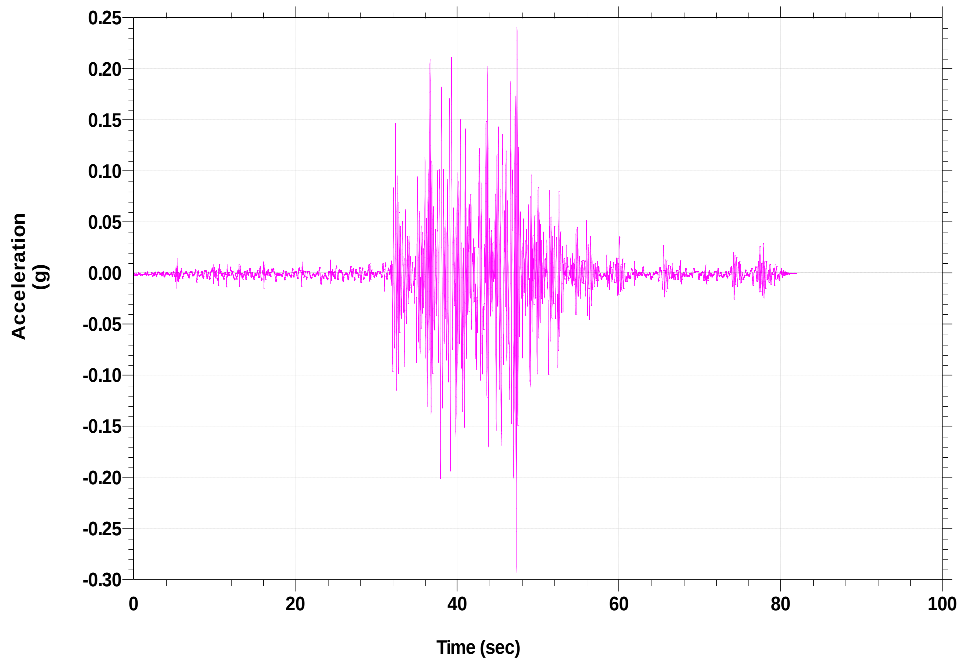

Figure 3.2. Acceleration Time History at the Surface

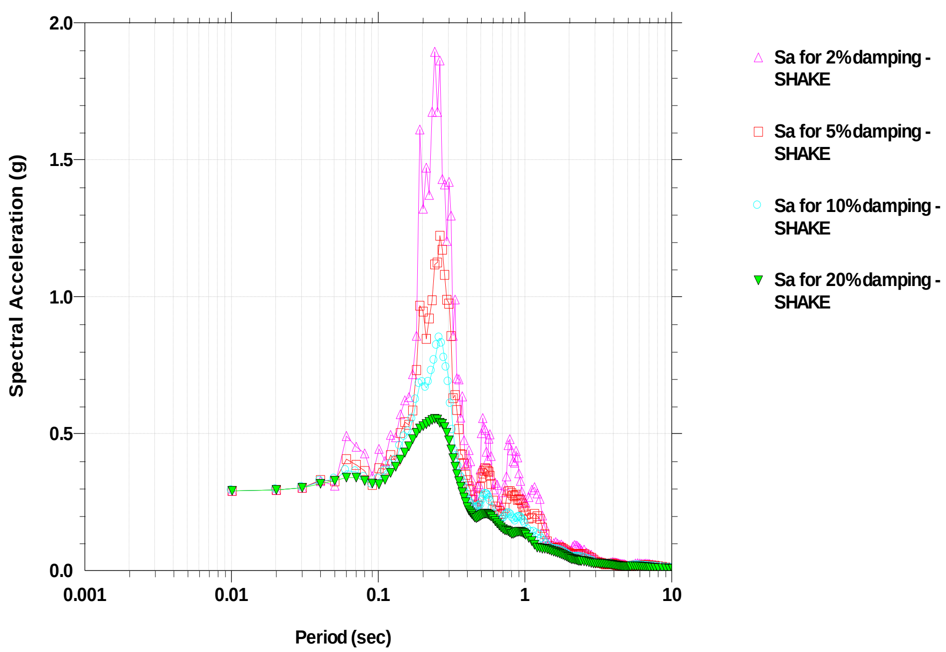

Figure 3.3. Response Spectra at 2, 5, 10 & 20%damping

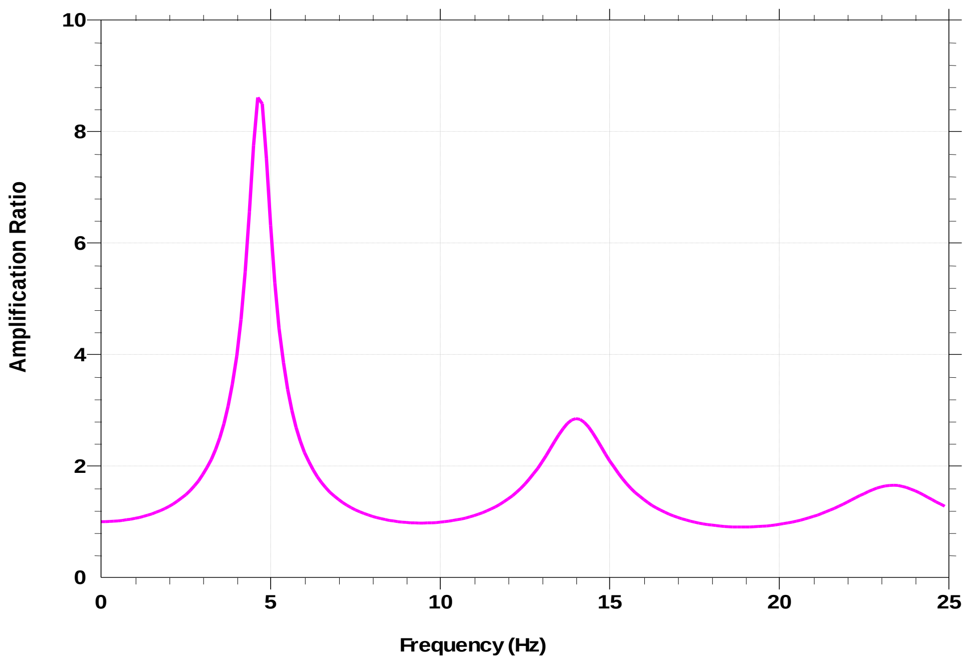

Figure 3.4. Amplification Spectrum

The presence of soil modifies each and every component of the strong ground motion and it can be seen from fig. 3.5in which natural frequency for all the cases are graphically represented.

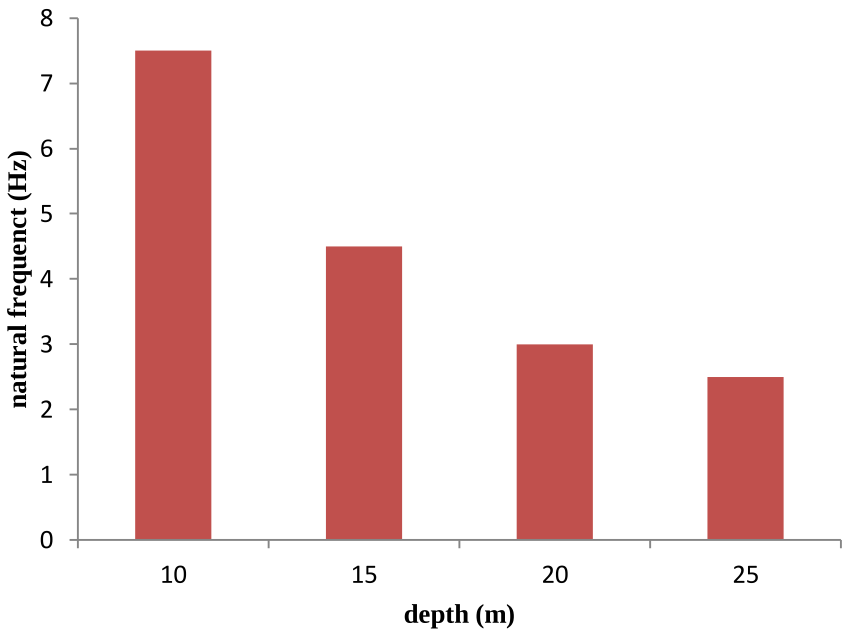

Figure 3.5. Natural Frequency for Four Cases

Table 3.3 gives the amplification ratio for different cases at different frequencies. [up to 5Hz considered]

Table 3.3. Amplification Ratio For Different Depths At Different Frequencies

Depth of Bed Rock from G.S (m)	Amplification Ratio at Frequencies		
	0-1 Hz	1-2 Hz	2-5 Hz
10	0.4	0.4	0.8
15	0.9	0.6	0.8
20	1.0	1.6	0.9
25	1.0	2.4	1.0

4. DISCUSSION AND CONCLUSIONS:

The main limitation of the conventional approaches of classifying sites where the shear wave velocity model do not extend up to 30 metres, is that it gives underestimated site class. If actual shear wave velocity of the bed rock is considered $\overline{V_s}(30)$ value improves and consequently better site class is obtained. It is also observed that the difference of estimated values of V_s^{30} using the extrapolation techniques and the proposed method decreases as the depth of soil layer increases. For shallower depths extrapolation techniques are relatively less reliable. Bed rock depth also influences the amplification of the strong ground motion. Natural frequency shifts towards right i.e. increases with decrease in the depth of soil column over bed rock. Amplification ratio increases as the depth of soil layer increases for lower frequencies. Whereas at higher frequencies, the opposite patterns has been followed. So from these above observations it can be concluded that depth of bed rock influences seismic amplification for different depths at different frequencies i.e. for shallow thickness of soil deposit above bed rock amplification occurs at higher frequencies and for high depth of bed rock amplification occurs at lower frequencies. Also the decrease of amplification ratio (at lower frequencies) for the shallower depth of bed rock indicates the better response of the site towards seismic excitation (i.e. better site class). Hence it is recommended to use the actual shear wave velocity of the bed rock in site classification.

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