Estimation of Linear Site Amplification by a Ground Motion Prediction Equation Using Results from a Site Survey.

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Abstract

One of the ground motion prediction equations (GMPEs), which have recently been developed in the Next Generation Attenuation (NGA) project, is employed in this article to estimate site response in terms of amplification factor of the seismic waves in soft superficial sedimentary layer. This study also presents briefly the existing information dealing with the methods for estimating subsurface shear wave velocities. The discussion about three geophysical methods, one invasive and two noninvasive namely SPSVL, SPAC and HVSR respectively, presents a better identification of their actual possibilities and limitations. The results obtained from a field survey from these three methods are utilized in this article to evaluate linear site amplification. This study can be considered as one of the instances where the limitation, to apply GMPEs in diversified geological conditions, was encountered. Some amendments in the fixed parameters were considered necessary in the original NGA GMPE to get realistic results. The variation in amplifications, obtained in this way, from SPSVL and SPAC method is negligible and their average is 1.33 for a spectral period of 1.1 sec. Some recommendations are furnished to utilize other NGA relations and craft adaptation in them according to the local geologic conditions, if required, to evaluate ground motions for seismic hazard analysis.

Key words: SPSVL, SPAC, HVSR, next generation attenuation, ground motion prediction equation, site response, amplification.

Introduction

The growth rate of the big cities and development of metropolises all over the world has tremendously increased since the last quarter of a century. The same trend is expected for the impending quarter of this century. Most of the big cities of the world, including Islamabad, are located on the soft sediments. Such a local site condition is undesirable because it may give rise to the amplification of seismic waves during earthquakes. Thus, for an efficient mitigation of seismic risk, site-specific studies are of uttermost importance. The estimation of site responses, namely the resonance frequencies of the sedimentary layers and the amplification factor for these soft deposits, has been a matter of concern for geoscientists and engineers.

The present study deals with the estimation of linear site amplification and is an expansion of a previous study (Babar, 2010) based on a field survey conducted in Jyoso city, Ibaraki prefecture, Japan in June, 2010.

The ground-motion prediction equations (GMPEs) are used for the characterization of earthquake ground motions. Previously developed GMPEs could only be applied in specific geographic regions due to their relative sophistication. Notable examples are Ambrasey et al. (2005) and Akkar and Bommer (2007) whose work focused on Europe and Middle East. In the project namely Next Generation Attenuation (NGA) various GMPEs were developed in such a way that these could be applied to geographically diverse regions. In the present study, the amplification factor is calculated using a GMPE developed by Boore and Atkinson (2008), in the NGA project. Slight modifications are made in the relationship taking into account the geological conditions of the aforementioned site in Japan.

Methods

Numerous methods for geophysical exploration exist, which include borehole measures, passive and active seismic methods. The primarily focus of all these methods is estimation of subsurface S-wave

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velocity (or slowness represented by p, a reciprocal of velocity). As seen from an easy on the pocket viewpoint, the noninvasive methods based on passive source(s), mainly ambient noise, are more widely used.

Mainly the geophysical techniques are grouped into three main categories. The first category is based on classical geophysical and geotechnical techniques such as seismic refraction, seismic reflection, boreholes, penetrometers, etc. which provide reliable estimates of the parameters like thickness of sedimentary layers, S and P wave velocities and density of various layers. The back draws of these techniques are prohibitively expensiveness and their environmental impact as sometimes explosives like TNT or Vibroseis are used and boreholes are drilled. The second category is based on direct measurement of the site response using earthquake records. However, this technique suffers a lot of delay in those areas which are positioned in low seismicity zones due to the delayed accumulation of a significant number of recordings with satisfactory signal to noise ratio.

The third category is based on the ambient (background seismic) noise recordings. The significance of this technique is its cost effectiveness, environment friendliness, no reliance on seismicity of a region and convenience during site survey. Because of these features, the ambient noise measurement techniques are more useful in urbanized areas. The ambient noise is dispersive and forms a continuous low amplitude wave field which constitutes of body and surface waves. Its origin in space and time is from a wide variety of sources, and propagates over a wide frequency band. The ambient noise wave field is a generic terminology further classified by the researchers into two categories depending on their origin i.e., microtremor and microseism. Microtremor are high frequency waves generated due to cultural activities of human beings such as movement of pedestrians, cars, trains and working of machinery in factories. Mostly, the frequency of microtremor is considered to be higher than 1.0 Hz. Microseisms consist of low frequency waves, generated because of natural phenomena such as rain, wind, variation of atmospheric pressure, oceanic tides and waves. By and large, it is believed that their frequency is lower than 1.0 Hz. Notable example of methods reliant on the ambient noise is SPAC and HVSR.

Three geophysical techniques have been discussed in this section with brief details. The first one is invasive in nature while the other two are noninvasive and reliant on passive source.

Suspension P and S wave Velocity Logger (SPSVL)

Traditional approaches to shallow seismic testing involve the use of “active source” methods such as seismic reflection and refraction. In geotechnical applications in particular, seismic refraction with surface seismic sources has gained widespread acceptance as a viable investigation tool. The effectiveness of this approach, especially in urban situations, is limited in order to achieve the required depth penetration. It is believed that invasive methods are the most reliable to obtain both P- and S-wave velocity data. Suspension P- and S-wave velocity logging (or simply PS logging) is a method used for measuring seismic wave velocity profiles and is originally developed by researchers at OYO Corporation, Japan.

With the help of this technique shear-wave velocity can be measured in deep and uncased boreholes to characterize earthquake site response. A probe 7.0 m long is used which contains a source for generating pressure waves and two receivers spaced 1.0 m apart. This setup is suspended into the borehole by a cable. The pressure waves are transformed into the P and S waves and are received at the receivers which finally send an analog signal to a logger at the surface. The difference of time in arrivals of various P and S phases is utilized to estimate a shear wave velocity profile.

This method can be applied to dam safety investigations, seismic site response studies for bridge abutments, buildings foundation studies, measurement of soil/ rock properties (i.e. shear modulus, bulk modulus, compressibility, and Poisson’s ratio), characterization of strong motion sites and velocity control for seismic reflection surveys. As mentioned before that invasive methods are the most reliable to obtain both P and S wave velocity data. This method too brings out a velocity profile in single hole with very high level of confidence at depths greater than 70 m to 700 m. It offers very high resolution of the order of 1.0 m which helps resolving thin subsurface layers that can have a remarkable effect on response of ground motion (Geovision, 2010).

SPAC: 2D Receiver Array, Microtremor Method

Array techniques, originally developed to detect and localize nuclear explosions, were adapted by seismologists to derive the surface wave dispersion curve from the ambient noise array measurements, in view of inverting shear wave velocity profiles. The receivers are arranged in typical geometries e.g., circles, triangles, L-shaped arrays, etc. The preference for selecting array layout generally depends on the predestined processing technique.

Aki (1957; 1965) proposed a theory based on the relationship between temporal and spatial spectra of seismic waves to obtain phase-velocity dispersion curve. Based on this theory, he developed an array technique called Spatial Auto Correlation (SPAC) microtremor method to determine the underlying subsurface velocity structure of S waves and phase velocity of Rayleigh waves using short period microtremor with frequency more than 1.0 Hz. Initially, only circular shaped arrays were used in SPAC method, but now triangular, 'L' shaped and irregular shaped arrays of various shapes and sizes arrays are also used. One of the limitations of this method regarding a maximum explorable depth is that it is comparable with the lateral extent of the 2D array (Hayashi, 2010).

HVSR: Single Station, Microtremor Method

The 0D array involves actually a single station recording applied to ambient noise wave fields known as the Horizontal to Vertical Spectral Ratios (HVSR). For ambient noise recording for HVSR method, the conventional way is to use a long period seismometer with a sampling rate of 100 Hz. The recording may continue for 30 minutes to one hour.

The HVSR method was empirically found by Nakamura (1989). Since then it has been serving well for getting reliable information related to site response. The technique sometimes gives comparable results in terms of accuracy with those yielded from any other method. According to Nakamura (1989), the HVSR reflects S-wave resonance on soft surface layer. However, Yamanaka et al. (1994) argue that there is a relationship between the ellipticity of Rayleigh waves of fundamental mode and HVSR curves.

The following relationship between power spectra of three components of ground motion defines the spectral ratio:

$$HVSR = \sqrt{\frac{P_{NS} + P_{EW}}{P_{UD}}}, \qquad (1)$$

Where, P_{NS}, P_{EW} and P_{UD} are the power spectra for north-south, east-west and up-down components, respectively. It is noteworthy to take into account that P_{NS} and P_{EW} are merely used for reference. These may not essentially represent the absolute directions as mentioned in Equation (1).

Results and Interpretation

The estimation of amplification in the present study is based on results of previously conducted field surveys. The site for these field surveys was located near the Toyota Community Baseball Ground, Jyoso City, Ibaraki Prefecture, Japan. The site can be located in map shown in Figure 1. Two noninvasive geophysical exploration methods reliant on passive source, namely SPAC and HVSR were employed. The SPAC microtremor method was used to estimate a velocity model for the shear waves. An invasive method called SPSVL was applied at the same site a few years ago and the results from that method were considered in order to check the reliability of those obtained from SPAC method. The resonant frequency

(f_r) for a 520 m thick soft sedimentary layer was estimated using HVSR microtremor method, in that study. The value of f_r was validated with the help of an analysis performed on an earthquake record.

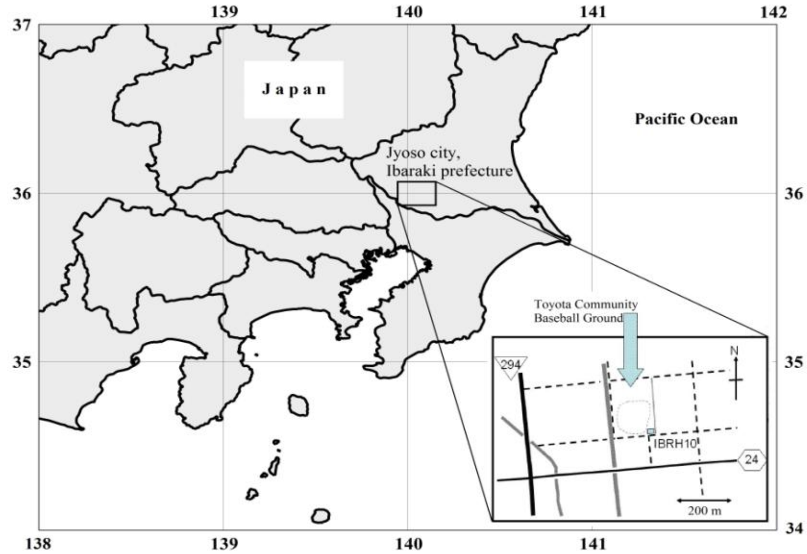

Figure 1: Map of central part of Japan, focusing on the Jyoso city in the inset (modified from: Yokoi and Hayash, 2010).

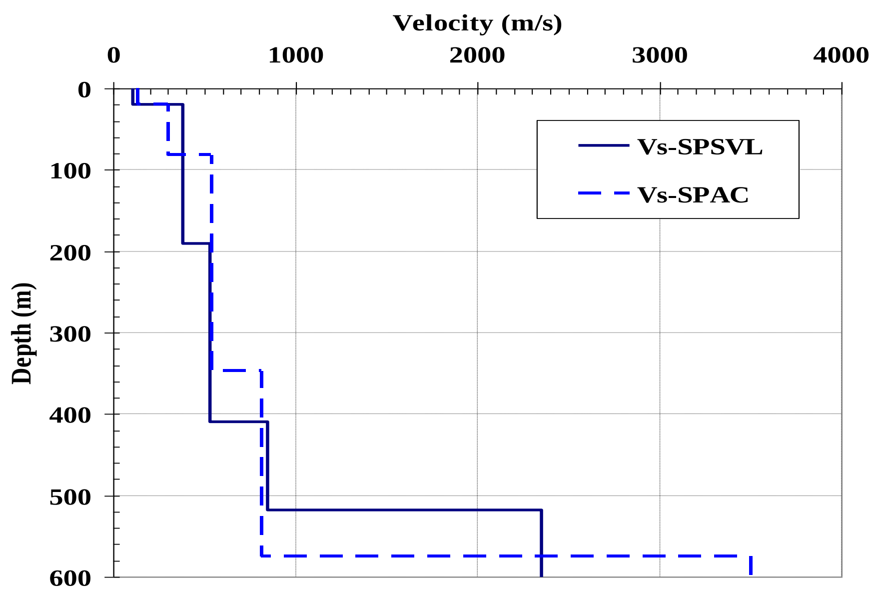

Figure 2: The comparison of velocity model for the field survey data.

Field survey for SPAC method was performed from March 5 to 7, 2009 and that for both SPAC and HVSR methods was conducted from June 15 to 17, 2010. In order to check the reliability of results obtained from SPAC method, SPSVL data (Yokoi and Hayashi, 2010) was obtained. The comparison is shown in Figure 2. The velocity models from SPSVL and SPAC methods and the spectral ratio between horizontal and vertical components of ground motion are described in the following sections.

Velocity Models (SPSVL and SPAC Methods)

The shear wave velocity at 30 m depth represented by $V_s(30)$ is considered to be an important parameter in the field of earthquake engineering. Four layers could be resolved with a very minute velocity differences. The big difference can be observed at depth more than 500 m because of an underlying hard granitic layer below the soft sediments. On the whole it can be established that Figure 2 is an illustration of a nice agreement between V_s obtained from SPAC and SPSVL methods from the surface of the ground up to the depth of about 580 m. The lateral extent of 2D array used for SPAC method was a limitation for this depth range. While applying a geophysical exploration technique, especially using an array method, it is believed that the deepest possible (or more precisely: reliable) depth explored is of order of size of the array.

Dominant Period (HVSR Method)

Figure 3 shows power spectral density of one vertical and two horizontal components of dataset obtained from the field survey, whereas Figure 4 shows HVSR for the same. The curves of power spectra for two horizontal channels can be seen very close to each other but for the vertical component the curve is slightly different from the other two. However, overall behavior of the curves for two horizontal channels and that for a vertical channel is almost same within the frequency band under consideration.

The power spectral density has higher values at a frequency band between 0.8 Hz to 4.0 Hz (0.25 sec to 1.25 sec). Therefore, the best reliable values of HVSR obtained computed mainly using equation (1), shown in Figure 4 are lying within this frequency band. The dominant peak of HVSR from microtremor data can be seen near 1.1 sec the inverse of which is regarded as the resonant frequency fr of sedimentary layer. There is another peak seen in Figure 4 at 4.5 sec. This peak cannot be pronounced as the one representing dominant (spectral) period because it lies outside the frequency band of interest conceived from the power spectral density diagram (Figure 3).

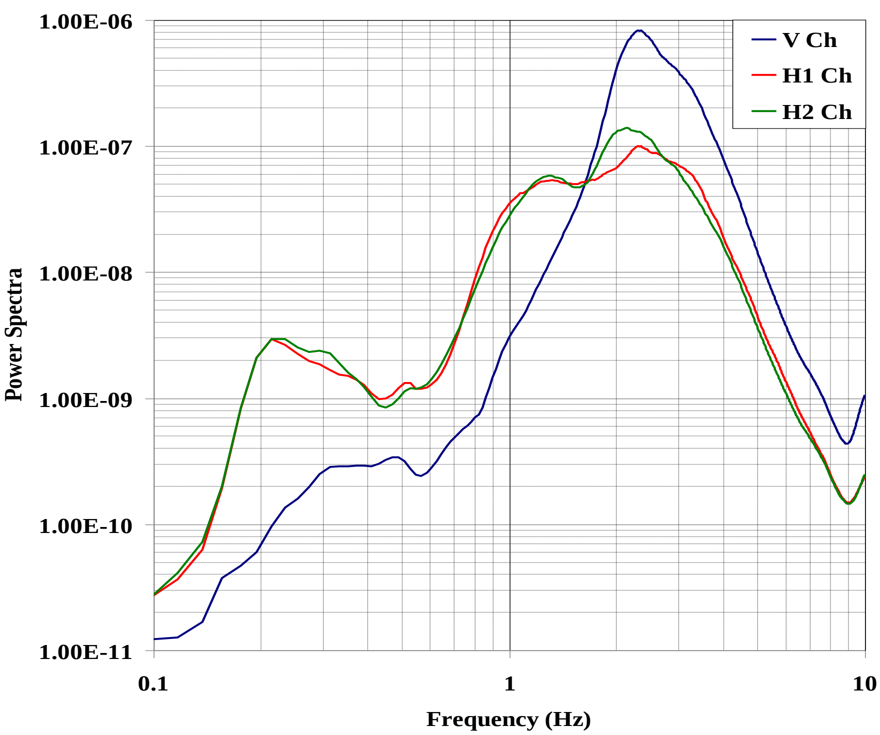

Figure 3: Power spectrum of HVSR obtained after analyzing the field survey data.

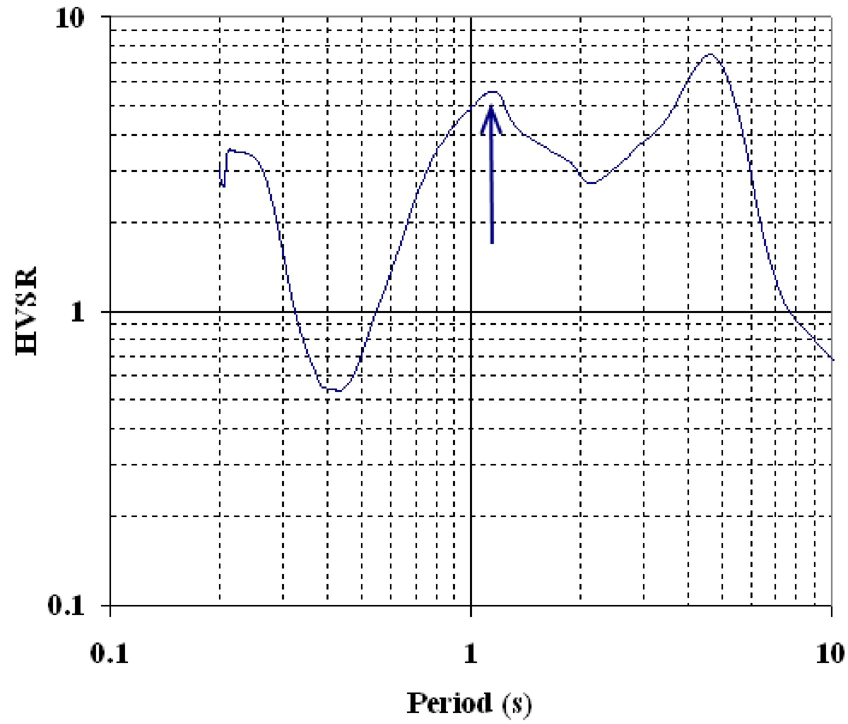

Figure 4: Curve showing HVSR. The arrow indicates the dominant (spectral) period.

Linear Site Amplification

The estimation of the linear site amplification is based on ground motion parameter like resonance frequency and shear wave velocity. The linear site amplification A, defined by Boore and Atkinson (2008), is mathematically given as:

$$A = b_{lin} \ln \left| \frac{V_s(30)}{V_{ref}} \right| , \qquad (2)$$

Where b_{lin} is site-amplification coefficient, V_{ref} is the specified reference velocity and $V_s(30)$ is the shear wave velocity for upper 30 m depth. Various values of b_{lin} corresponding to dominant spectral periods (or resonant frequencies) are given in Table 1.

Table 1: The site amplification coefficient b_{lin}
(modified from Boore and Atkinson, 2008).

Dominant periods	site-amplification coefficients (b_{lin})
PGV	-0.60
PGA	-0.36
0.01	-0.36
0.02	-0.34
0.03	-0.33
0.05	-0.29
0.10	-0.25
0.15	-0.28
0.20	-0.31
0.25	-0.39
0.30	-0.44
0.40	-0.50

0.50	-0.60
1.0	-0.70
1.5	-0.72
2.0	-0.73
3.0	-0.74
4.0	-0.75
5.0	-0.75
10.0	-0.65

From Table 1, the value of b_{lin} corresponding to the dominant spectral period of 1.1 sec is found approximately equal to –0.7. According to Boore and Atkinson (2008) the value of V_{ref} should be fixed equal to 760 m/s. This value of reference shear wave velocity corresponds to National Earthquake Hazard Reduction Program (NEHRP) B/C boundary site conditions based on the recommendations of Building Seismic Safety Council (BSSC, 2004). Further details are shown in Table 2. The Unified Building Code (UBC) and International Building Code (IBC) permit a similar approach regarding $V_s(30)$.

Table 2: Definition of NEHRP site classes (BSSC, 1994).
Rock type from Martin and Diehl (2004).

Site Class	Rock Type	Range of $V_s(30)$
A	Hard rock	Greater than 1500 m/s
B	Rock	760 m/s to 1500 m/s
C	Very dense soil and soft rock	360 m/s to 760 m/s
D	Stiff soil	180 m/s to 360 m/s
E	Soft soil	Less than 180 m/s
F	Soils requiring site-specific evaluation	Estimation required

In order to apply the NGA relationship proposed by Boore and Atkinson (2008) (hereafter BA08) for calculation of amplification, three approaches for a period of 1.1 sec were taken into account:

Approach–I

The shear wave velocity at 30 m depth, $V_s(30)$, is 380 m/s in case of SPSVL and 298 m/s in SPAC method case. The value of V_{ref} is fixed at 760 m/s, as recommended by Boore and Atkinson (2008). The amplifications so obtained are not realistic. In continuing the endeavors to get a realistic amplification, following Boore et al. (2011), the average of V_s up to 30 m depth was also incorporated which as well yielded unacceptable results.

Approach–II

A slight modification was made in the BA08 following Kanno et al. (2006), that instead of $V_s(30)$ the value of $V_s(20)$, shear wave velocity at 20 m depth, was incorporated. This approach was taken into consideration because a velocity discontinuity was revealed at the site of field survey at a depth of 20 m in velocity models yielded from both methods. Furthermore, a similar approach has been advocated by Boore et al. (2011) to use $V_s(z)$ in stead of $V_s(30)$ where z is less than 30 m. The shear wave velocity from SPSVL was 110 m/s and that from SPAC was 130 m/s (Figure 2). The amplifications so obtained were 1.35 and 1.24 for PS logging and SPAC method, respectively.

Approach–III

According to Yokoi and Hayashi (2010) the superficial soft sedimentary layer of unconsolidated soil and sand particles at the site of field survey has a thickness of 520 m. Below this thick layer lies a hard granitic layer where shear wave velocity approaches to 2350 m/s. Another approach to estimate amplification by using BA08 was to adapt the relationship by using V_{ref} equal to 2350 m/s instead of 760 m/s and considering actual values of $V_s(30)$ for both velocity models obtained from PS logging and SPAC methods, i.e., 380 m/s and 298 m/s, respectively. The amplifications so obtained were 1.28 and 1.45 for SPSVL and SPAC method, respectively. This approach is also realistic because the amplification on surface is computed with respect to the hard granitic layer having shear wave velocity 2350 m/s.

Table 3: Comparison of various amplification factors from three different approaches.

Method	Approach – I		Approach – II		Approach – III		Amplification		
	$V_s(30)$ [m/s]	V_{ref} [m/s]	$V_s(20)$ [m/s]	V_{ref} [m/s]	$V_s(30)$ [m/s]	V_{ref} [m/s]	I	II	III
SPAC	298	760	130	760	298	2350	0.66	1.24	1.45
SPSVL	380	760	110	760	380	2350	0.49	1.35	1.28

Discussion

Despite their wide applicability to geographically diverse regions, one of the NGA GMPE proposed by Boore and Atkinison (2008), could not be applied on 'as it is' basis. The parameter $V_s(30)$ is fairly easy to estimate as compared to other detailed site characteristics associated with site amplification. However, according to Boore et al. (2011) shear wave velocity at only 30 m of depth is not capable to "capture all of the physics controlling site amplification". As seen in first approach during estimation of amplification, the values so obtained could not be explained on the basis of rules governing the site characterization, known so far. Therefore, $V_s(20)$ was used as an alternative of $V_s(30)$. The value 760 m/s corresponds to a boundary between site classes B and C (Table 2) as defined by the UBC and IBC. The essence for fixation of V_{ref} at 760 m/s recommended by Boore and Atkinson (2008) and BSSC (2004) was to estimate amplification of seismic waves on surface with respect to a hard underlying rock layer below the soft sediments. If the boundary between site classes B and C corresponds to some other value of shear wave velocity, as in the current scenario, value of V_{ref} can be altered accordingly.

Three approaches were followed to get to the value of linear site amplification. Approach-II (where $V_s(20)$ was interchanged with $V_s(30)$ and Approach-III (where V_{ref} was fixed equal to 2350 m/s instead of 760 m/s) seem more realistic in the scenario under consideration. Amplification for the SPAC method was lower than SPSVL with Approach-II while it was a reversal with Approach-III (Table 3). This is merely because of incorporation of augmented values of parameters, like $V_s(20)$, $V_s(30)$ and V_{ref} in Equation (2). However, the estimated amplification from Approach-II and Approach-III (Table 3) is very close to each other with an insignificant difference for both geophysical methods, taken as a whole.

The shallower depths are practically resolved precisely by SPAC method. However, at the depths comparable with lateral extent of 2D array for SPAC method, the results so obtained become insignificant (or more precisely: not reliable). As depicted from velocity model under consideration, SPAC method revealed the hard granitic layer at a depth of 570 m with an abrupt increase in V_s from 812 m/s to 3497 m/s. The lateral extent of array was 600 m (Babar, 2010). It implies in this scenario that the depth at which this interface between layers is revealed and the value for shear wave velocity are both not precise. The same granitic layer is unmasked by SPSVL method at a depth of 520 m with a rapid variation of V_s from 850 m/s to 2350 m/s. Taking into account the preciseness of an invasive method over a noninvasive method and the limitations of SPAC method regarding possible explorable depths, the value of V_{ref} is fixed at 2350 m/s from SPSVL method. The linear site amplification of seismic waves has been calculated with reference to a hard granitic layer 520 m below the surface where V_s approaches to 2350 m/s, while considering actual values of $V_s(30)$ for a particular site at 1.1 sec.

Conclusions

The already validated velocity models and dominant spectral period of sedimentary layer for a particular site in Japan were used in this study. The two velocity models had a slight variation, however, an overall agreement was found such that the amplifications calculated on the basis of both of them, in the present study, are quite close to each other. The amplification was calculated with a slight modification of the relationship (BA08). Taken as a whole the variation in amplifications calculated from an invasive and a noninvasive method is 0.07 and 0.31, respectively, for a spectral period of 1.1 sec. The average value is 1.33 for all amplifications.

Recommendations

It would be advantageous to apply other NGA GMPEs in future studies with or without certain adaptations, if required, for site response estimation at various places of interest in Pakistan, especially Islamabad. Such studies, based on field surveys, will prove to be fruitful to evaluate expected ground motions and seismic hazard analysis in the country.

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