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One Dimensional Non-Linear Ground Response Analysis-A Site Specific Case Study of Peshawar District, Pakistan

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Abstract- This paper presents a one-dimensional non-linear ground response analysis conducted for a specific site at Peshawar District, Pakistan. The geotechnical properties and shear wave velocity from standard penetration test, confirmed the site as S_D according to the building code of Pakistan. The input ground motion used at the depth of bedrock are selected from strong motion database that are compatible to the seismic hazard of the site. The surface Fourier Amplification factor obtained from the ground response analysis showed amplification for all input motions near the site fundamental period. The higher amplification factor and spectral value is obtained in case of input motion that is stronger near the site fundamental period. The ground response analysis results show that, in case of same soil model, the variation of peak acceleration along the depth of soil profile depends on the acceleration response spectrum of input motion. The stronger the spectral acceleration value near the site fundamental period, the greater the amplification factor and thus higher peak ground acceleration is obtained.

Keywords- Non-linear ground response analysis; Shear wave velocity; Amplification factor; Ground response spectrum

I. INTRODUCTION

The earthquake hazard assessment and its mitigation play an important role in the sustainable development of earthquake prone countries like Pakistan, where the past devastating earthquake have shaken the entire nation in several ways. The collision of Eurasian and Indian plates during Eocene period has resulted in several seismogenic faults in the north and north western part of Pakistan [1]. The continuous subduction of Indian plate at a speed of 42 mm/year into the Eurasian plate along the Carsberg Ridge [2] still remains a continuous seismic hazard for the entire nation.

Peshawar district is located in the Khyber Pakhtunkhwa (KP) province in north western part of Pakistan. The seismic hazard in Peshawar is due to its vicinity to several active faults that have been resulted from the subduction of Indian and Eurasian plates. The study of [3] has identified about 21 seismogenic faults around Peshawar district as Shown in Fig. 1. In the building code of Pakistan (BCP-seismic provision) Peshawar has been placed in Zone-2B that has PGA value in the range of 0.16-0.24g. In the Modified Mercalli Intensity scale this corresponds to V-VI intensity.

Several seismic hazard studies such as [4] [5] and [6] are available that have either deterministically or probabilistically evaluated the seismic hazard for Peshawar. Most of these previous studies has calculated the peak ground acceleration value at bedrock based on the attenuation relationships developed for similar other regions in term of geological and seismic hazard. The different attenuation relationships used for the seismic hazard analysis take into account the site class based on the shear wave velocity. According to [7], although the seismic stress waves propagate through hundreds of kilometers in rock and probably less than 100 m in soil deposit. The soil deposit, however, plays an important role in the modification of seismic wave's pattern as it propagates through it. Therefore, the basic problem to be solved by a geotechnical engineer is to quantify the site-specific seismic hazard in layered soil deposit.

The effect of local site condition on the damaged pattern by earthquake loading has been confirmed from several historical case studies. According to [8], the buildings on rock site were slightly affected than those on soft ground in the 1819, cutch, India Earthquake. In similar, the intensity of seismic shaking according to [9] and [10] in San Francisco earth quake was related to the local site condition. The effect of local site condition on specific seismic ground motion has been well established in geotechnical engineering. Several studies are available on site specific seismic hazard analysis worldwide such as [11 – 18] and also in the neighborhood like [19 – 23] and others. In Pakistan, although there is considerable research available on seismic hazard assessment on regional basis such as [24 – 27], however, there is a complete scarcity of research work on site specific seismic hazard analysis and assessment. The site-specific seismic hazard analysis is needed on case-by-case basis in order to design earthquake resistant structures.

The present study uses one-dimensional non-linear ground response analysis for a specific site at Peshawar, District, Pakistan. The site has been characterized using Insitu and laboratory geotechnical tests for a 10 m deep borehole as most variation in soil strata is assumed upto this depth. The input ground motions have been selected from PEER strong motion database compatible to the seismic hazard of Peshawar. The analysis results are studied for different parameters such as amplification factor, peak acceleration and its variation along deposit profile, Fourier and spectral accelerogram for the propagating input ground motions.

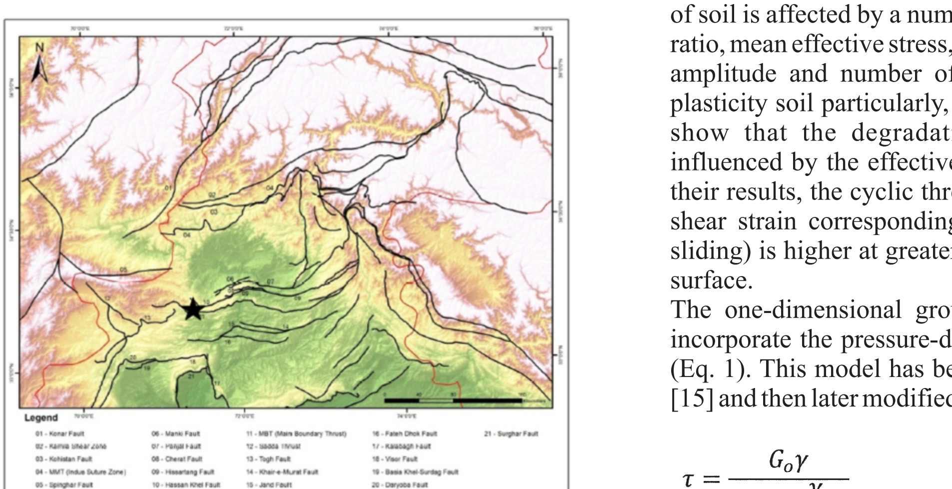

Fig. 1 Tectonic map showing the major regional faults of Northen Pakistan and NE Afghanistan (from [28]).

II. ONE DIMENSIONAL GROUND RESPONSE ANALYSIS

The ground response analysis is commonly used to evaluate or predict the response of ground deposit when subjected to seismic loading. The prediction of surface ground motion obtained from the ground response analysis is then further used in the development of design response spectra that can be used to evaluate seismic stresses in structures. The ideal condition for ground response analysis is to accurately model the rupture mechanism of source and to model the propagation of seismic waves to the bedrock beneath a particular site. The soil medium than acts as filter material and, the final stage of the ground analysis is to quantify its effect on the bedrock input motion. Although, the stress waves generated from seismic source may travel several hundred kilometers and less than 100 kM in soil, however, the soil layers play an important role in its modification.

The seismic stress waves as it travels through the layered soil deposit is reflected or refracted at different interfaces. According to Snell's law, the inclined stress waves are more reflected to a vertical direction when it strikes the horizontal ground layer. As these seismic stress waves propagate from bedrock into the soil medium, it induces shear stress and thus shear strain.

A. Equivalent Linear Analysis

Once the shear strain exceeds the linear threshold value, then, a unique non-linear behavior is developed between stress and strain. This non-linear behavior thus gives different value of shear modulus or damping. The shear modulus and damping of soil varies with the induced shear strain amplitude and is referred as shear modulus degradation and damping curves respectively. The laboratory test result shows that, the shear stiffness of soil is affected by a number of parameters i.e., (void ratio, mean effective stress, overburden ratio, plasticity, amplitude and number of loading cycles). For low plasticity soil particularly, the results of [29] and [30] show that the degradation of shear modulus is influenced by the effective overburden. According to their results, the cyclic threshold shear strain (i.e., the shear strain corresponding to the initiation of gross sliding) is higher at greater depth than that near to the surface.

The one-dimensional ground response analysis can incorporate the pressure-dependent hyperbolic model (Eq. 1). This model has been originally developed by [15] and then later modified by [31].

$$\tau = \frac{G_o \gamma}{1 + (\beta \frac{\gamma}{\gamma_\gamma})^s} \tag{1}$$

The model parameter, γ_γ depends on the effective vertical stress σ_{eff} and is given as follows [14].

$$\gamma_\gamma = Reference\ Strain \left(\frac{\sigma_{eff}}{Reference\ Stress}\right)^b \tag{2}$$

The modified pressure dependent hyperbolic model is linear and results in zero damping at small strain. The small strain damping is added separately in order to simulate soil actual behavior i.e., damping at small strains [32].

The layered soil deposit that behave as Kelvin-Voigt model that can reflect or transmit the seismic waves at the boundaries. The solution of wave equation to evaluate particle displacement, (*u*) at a depth *z* and time, *t* can be expressed as:

$$u(z,t) = Ae^{(i\omega t + k^* z)} + Be^{(i\omega t - k^* z)} \tag{3}$$

Eq. 3 shows the propagation of two stress waves with circular frequency ω in the upward -*z* and downward +*z* direction with amplitude B and A respectively. The amplitude of any one layer can be calculated from the amplitude of previous layer and is frequency depended. The applied shear stress τ, at a given layer and time is calculated with initial shear modulus *G* and damping ratio, ξ can be calculated as:

$$\tau(z,t) = G(1+2i\xi)\frac{\partial u}{\partial t} \tag{4}$$

B. Transfer Function

In layered soil deposit, the transfer function is commonly used to evaluate the parameter such as acceleration at the top of each layer. The non-linear analysis uses an iterative procedure with equivalent linear soil properties to calculate the transfer function. This transfer function as given in Eq. 5 depends on the circular frequency, (ω), of the input motion, height, H of soil layer, its damped shear wave velocity, v_s^* and impedance ratio of soil to rock α_z^*.

$$F(\omega) = \frac{1}{cos(\omega H/v_s^*) + i\alpha_z^* cos(\omega H/v_s^*)} \tag{5}$$

III. EXAMPLE PROBLEM

A. Site Characterization and Ground Model

The target site is located at Pushto Cultural Department in Peshawar Campus at Khyber Pakhtunkhwa, Pakistan. The site has been characterized using the standard penetration test results at various depth of a single borehole. The site characterization needs the shear wave velocity in order to calculate effect of ground motions in ground response analysis. In the absence of in situ dynamic field tests, several researchers have developed model to obtain shear wave velocity from SPT-N values. The present study uses the models developed by [33 – 36], and, that of, [37]. The variation of shear wave velocity using these models and that of average shear wave velocity along the depth at target site is shown in Fig. 2.

The average shear wave velocity for the layered soil deposit calculated is 204m/sec and is in the range of 175 to 350 and it confirms that the soil profile is S_D (Building code of Pakistan, 2007). The soil profile parameters used in the site-specific ground response analysis are shown in Table. 1 while Table. 2 shows parameters used for the pressure dependent hyperbolic model.

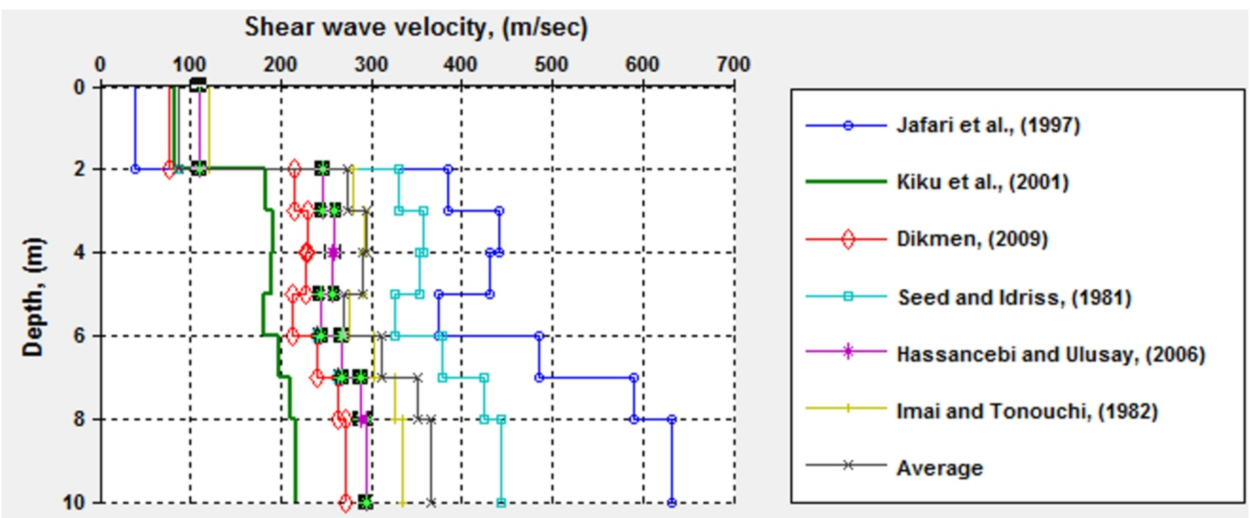

Fig. 2 Shear wave velocity versus depth at target site

Table. 1 Soil properties for one dimensional ground response analysis (Pushto Cultural Department)

Depth, (m)	Average Observed SPT N value	Shear Wave Velocity, Vs (m/sec)	Average Soil Plasticity Index, (PI)	Average Shear Wave Velocity, Vs (m/sec)	Soil Type as Per BCP 2007	Generic description
0 to 2	2	86	10	$v_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}}$ = 204	S_D	Stiff soil with $175\ m/sec \le V_s \ge 350\ m/sec$
2 to 3	29	273				
3 to 4	34	295				
4 to 5	33	291				
5 to 6	28	268				
6 to 7	38	311				
7 to 8	48	350				
8 to 10	52	368				

Table. 2 Parameters used in pressure dependent model

Damping ratio, ξ(%)	Ref. Strain, (%)	Beta, β
0.37	0.066	1.545

B. Input Ground Motion

Due to the absence of local seismogram network, the input ground motions are not widely available in Pakistan. In the present study, the input ground motions are those used from the Pacific Earthquake Engineering Research center (PEER) strong motion database. These motions are selected based on earthquake magnitude, site to fault distance, fault mechanism, average shear wave velocity of propagating medium. Furthermore, these motions can also be selected based on the target response spectrum. The input motions thus compatible to the seismic hazard of target area (Zone 2B) are thus applied in the form of accelerogram at the bedrock. The seven different accelerogram records used as input motions in this study are shown in Fig. 3.

Table. 3 shows the characteristics of earthquake records used as input motions in one dimensional ground response analysis. According to Table. 3, Input Motions (1, 5, 6 and 7) has higher peak acceleration (i.e., 0.20-0.22g) while Input Motions (2,3 and 4) has lower peak spectral acceleration value. The predominant period of Input Motions (5, 6 and 7) has the peak Fourier Amplitude at lower predominant period (i.e., at higher frequency) than Input Motions (1, and 2).

The acceleration response spectrum up to 1 sec natural time period for all input motions is shown in Fig. 4. It can be seen from Fig. 4 that Input Motion 5 has the highest spectral acceleration value at short time period. The spectral acceleration of Input Motion 4 has the lower peak spectral value; however, it is uniform between time period (0.02 sec to 0.4 sec).

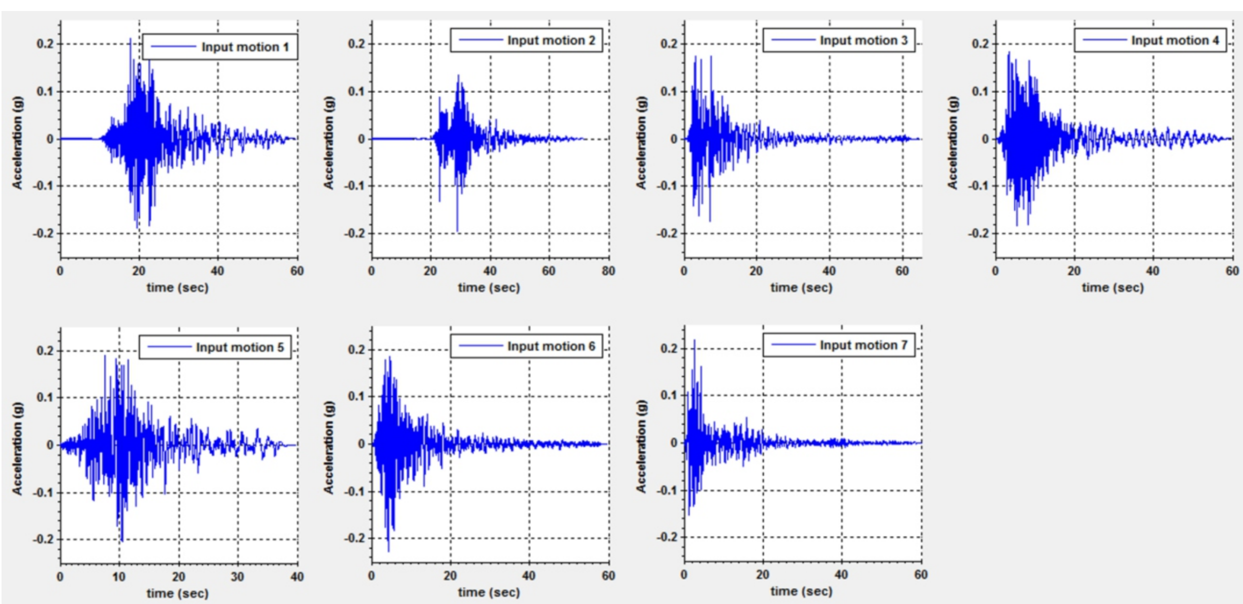

Fig. 3 Input ground motions used in site specific ground response analysis

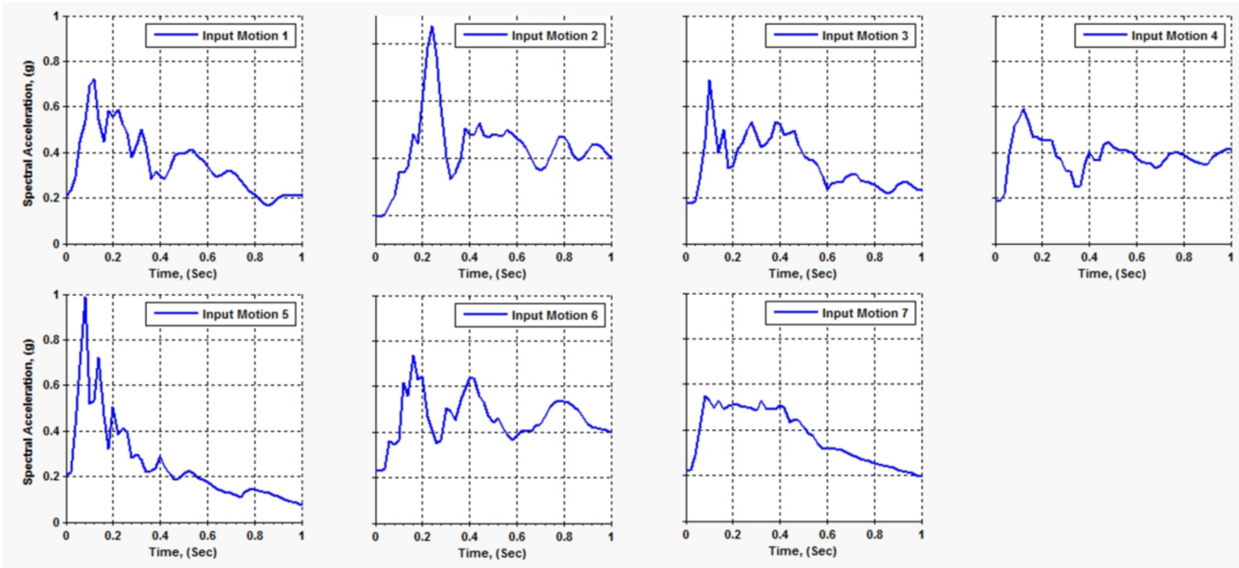

Fig. 4 Ground response spectra for input motions in ground response analysis

Table. 3 Characteristics of Input Motions used in ground response analysis

Input Motion Characteristics	Input Motions						
	1	2	3	4	5	6	7
Peak Acceleration, (g)	0.21	0.19	0.17	0.18	0.2	0.22	0.22
Predominant Period, (sec)	0.12	0.12	0.1	0.06	0.08	0.08	0.08
$\boldsymbol{2\pi\, v_{max}/a_{max}\,(sec)}$	0.31	0.50	0.75	0.70	0.31	0.50	0.44

According to Table 1, although the different Input Motions (1, 5, 6 and 7) has somewhat the same peak accelerations, however their peak spectral values occurs at different time period. The quantity $2\pi(v_{max}/a_{max})$ shows that the equivalent fundamental period of simple harmonic wave is lower for Input Motions 1 and 5 than that of other Input Motions.

IV. Results and Discussion

The fundamental period for the specific site is calculated as:

$$T_n = 4H/v_{s30} \tag{6}$$

Based on Eq. 6 the fundamental period of the site is 0.2 sec (i.e., frequency of 5 Hz).

The surface Fourier amplitude spectrum shows an ideal situation for the variation in amplitudes at different frequency of the input motions applied at the bedrock. Figure. 5 shows the surface Fourier Amplitude Spectrum of different input motions for the target site. It can be inferred from Fig. 5, that the amplitude up to time period of 0.4 sec (i.e., frequency 2.5 Hz) exceeds from the value of 1.2 to a highest value of 3 near the site fundamental period i.e., 0.2 sec. The Fourier amplification at fundamental period of site is 2.3 as shown in Fig. 3. This means that although the maximum amplification does not occur at the fundamental period of the site, however a resonant like condition may produce at some lower time period near to that of fundamental period.

With rule of thumb, the fundamental period of structure is calculated as (≈Number of stories/10) [7]. This corresponds to the time period ranging from a single to four stories building (i.e., with the fundamental period in the range of 0.1 sec to 0.4 sec). This means that, the input motion amplitude amplified by the soil deposit may be again amplified by the structure and a double resonance condition may thus occur. This condition may result in large deformations and thus damage these structures.

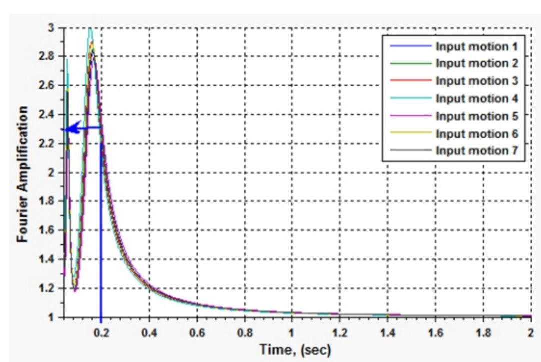

Fig. 5 Surface Fourier amplitude spectrum of input motions for target site

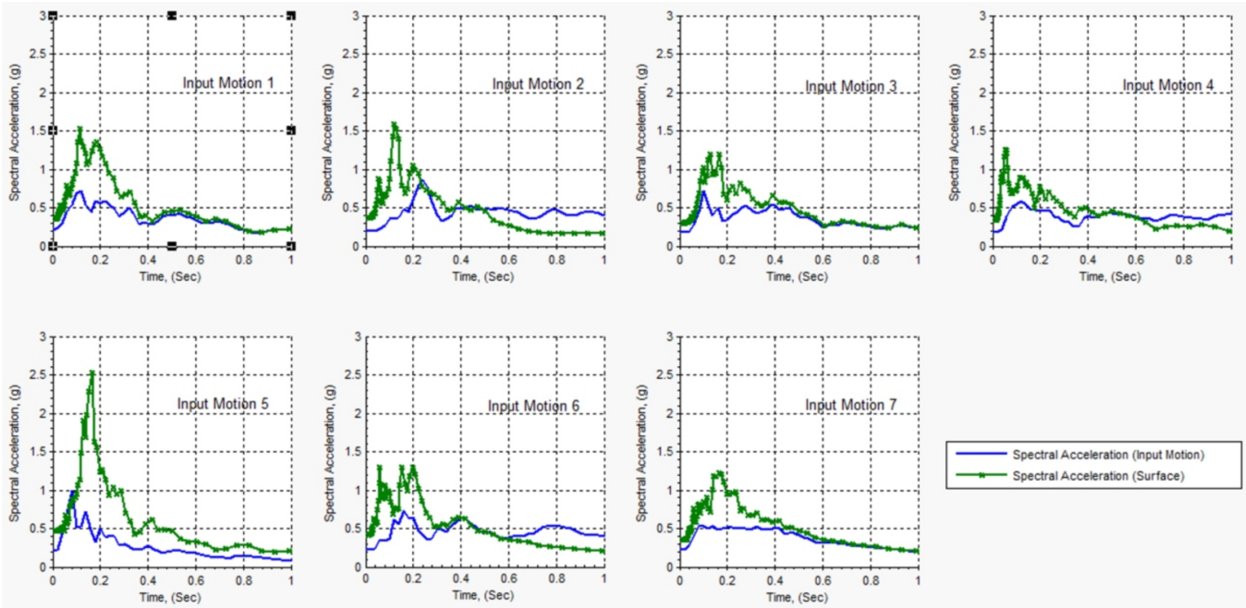

Fig. 5 Comparison of surface and input motion response spectra

Table. 4 Amplification factors for target site for different input motions

Input Motion 1	Input Motion 2	Input Motion 3	Input Motion 4	Input Motion 5	Input Motion 6	Input Motion 7
1.7	1.9	1.7	1.7	2.2	1.8	1.5

Fig. 6 shows the comparison of surface response spectrum to the input motions at the bedrock. The general trend of spectral acceleration shows amplification for all input motions up to 0.4 sec and beyond that it dampens out. Furthermore, it also shows that, the highest amplification occurs near to or below the fundamental site period i.e., (0.2 Sec). The amplification of spectral acceleration at fundamental period of the site is because of resonance condition as already discussed for Fig. 4. This amplification of surface spectra acceleration as shown (Fig. 5) depends on the spectral accelerogram values at the specified time period. The more the stronger the spectral values near to the site fundamental period, the higher surface spectral values are obtained. For example, Input Motion 5 has the highest spectral value near the fundamental period (0.2 Sec) followed by Input Motions 6, 2, 1, 7, 4 and at last 3.

The amplification factors for a particular site can be defined as:

$$\textit{Amplification factor} = (PGA_{Surface}/PGA_{Bedrock}) \qquad (7)$$

The amplification factors based on Eq. 4 for all input motions are given in Table. 4. It can be seen that for all input motions (amplification factor > 1) which implies that the surface PGA value resulted is greater than the PGA value at bedrock.

As already discussed in Eq. 6 the particle displacement at any depth depends on the amplitude of upward and downward waves that further depend on frequency of input motion, complex shear modulus and wave number and furthermore on the impedance ratio at different layers. Also, the transfer function as given in Eq. 5 depends on the frequency of the input motion, height, H of soil layer, its damped shear wave velocity, v_s^* and impedance ratio between soil layers α_z^*.

Thus, it is clear that for same soil profile the different input motions will result different numerical value for transfer function and also peak acceleration at different soil layer and interface. The peak acceleration along the soil profile depth for all input motions is further shown in Fig. 6. Peak acceleration is commonly used as a design parameter in civil engineering structures. According to Fig. 5 Input Motion 5 that is stronger near the site fundamental period and with highest amplification factor has resulted in continuous increase in peak acceleration toward surface.

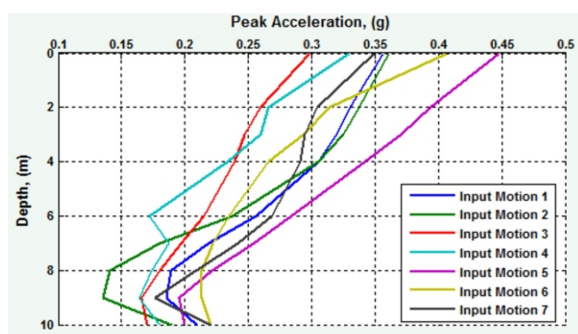

Fig. 6 Peak acceleration along the soil profile depth

V. CONCLUSION

The 1-dimensional ground response analysis were conducted for a selected location at Peshawar, Pakistan. The following conclusions have been drawn from this research work.

- The shear wave velocity values were determined to be in the range of 350-380 m/s. This shows that the site may be categorized as S_c as per the Building Code of Pakistan.
- Surface Fourier Amplification factor indicate amplification for Input Motions close to the fundamental period for the selected site (i.e., 0.2 sec). The amplification factor at the site fundamental period is about 2.3.
- The stronger input Motion close to the site fundamental period results in elevated spectral accelerogram value. The amplification factor obtained for all Input Motions obtained was greater than unity and the maximum value obtained was 2.2 in case of Input Motion 5.
- For a specific site, the amplitude of acceleration at the layer interface depends on the frequency of ground Input Motion. The stronger the accelerogram values in the vicinity of the site fundamental period will result in greater the amplification factor, this further results in higher peak acceleration.

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