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Research Article

Ground Response Analysis and Seismic Behavior Assessment Using SPTN Values

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Abstract – In the city of Islamabad, a thorough examination into one-dimensional equivalent linear ground response was methodically performed. This thorough investigation was carried out with special attention to the city's distinctive geological features using the DEEPSOIL software in a methodical manner. Notably, the analysis avoided the influence of the groundwater table in Favor of the more general seismic factors that control ground response dynamics. Subsoil data for input were acquired from a combination of laboratory and field research and were chosen based on site-specific conditions. The investigations were carried out at a bedrock site 13 meters below ground level. Following evaluations with the USCS, the soil at the location was classified as silty clay to lean clay. This classification is the result of extensive field and laboratory research. In the study, a set of eight unique accelerograms were carefully chosen and used at the bedrock layer, perfectly coinciding with the seismic characteristics unique to the target geographic location. Surprisingly the study of surface response spectra revealed a significant amplification phenomenon that was present across all seven possible accelerograms and deviated just slightly from the fundamental period inherent to the site. The study's conclusions indicated that the computed spectral acceleration values, which notably fell within the range of 0.16g to 0.24g, surpassed the requirements established by the Pakistan Building Code.

Keywords – Ground Response Analysis, Seismic Risk Assessment, Site Amplification, Standard Penetration Test, Soil-Structure Interaction,

I. INTRODUCTION

On October 8, 2005, at approximately 8:50 AM local time (03:50 AM UTC), a seismic event with a magnitude of 7.6 occurred in the Lesser Himalayas of northern Pakistan and India. The epicentre of the earthquake was situated at coordinates 34°29′35″N and 73°37′44″E, at a depth of 26 kilometres. This epicentre was located 10 kilometres northeast of Muzaffarabad, within the provincial boundaries of Azad Kashmir.[1]. The fault was predicted to be located between N27E and N30E. The breach spanned roughly 75 kilometres. The fault plane dips around 29 degrees, and the mechanism is primarily thrust. The average slip was between 2 and 5 meters[2]. The landslides caused by the Kashmir earthquake devastated an area of approximately 7500 km2 and killed 1000 people directly and many more indirectly[3], [4].

Pakistan is a geological manifestation of the Eurasian and Indian Plates[5]. The country was devastated by several destructive earthquakes, including the Makran earthquake (Mw = 8.0), Mach earthquake (Mw=7.3), and the 2005 Muzaffarabad Kashmir earthquake (Mw =7.6)[6]. This catastrophic seismic event killed approximately 80,000 people, according to government statistics. If there are seismically active faults in the northern and southern regions, seismic risk will exist. As a result, the anticipated earthquake risk, associated hazards, and mitigation is critical for Pakistan's long-term prosperity as a seismically active country.

Islamabad, Pakistan's capital city, is located at 33.43^{o}N and 73.04^{o}E and is surrounded by seismically active, major tectonic features such as the Main boundary thrust (MBT), Riwat Fault, Jhelum Fault, Kalabagh Fault, Mansehara Fault, and the Kotli Thrust. Islamabad is located on the eastern Potwar Plateau, between the Main Boundary Thrust (MBT) and the Suleman Range Thrust (SRT)[7]. Islamabad is in Zone-2B, where the Peak Ground Acceleration (PGA) varies from 0.16 to 0.24g at the rock surface, according to the Pakistan Seismic Provision of 2007 (BCP-SP, 2007)[8]. According to historical seismicity data, Islamabad has been subjected to earthquakes with intensities ranging from VII to VIII on the Modified Mercalli Intensity (MMI) scale. It's crucial to consider how the soil medium affects stress waves above the bedrock in ground response analysis. This issue arises because stress waves are restricted to a range of around 100 meters while moving through soil but can travel over several kilometres through bedrock. This highlights how important the soil medium is for controlling ground motion at the foundation level[9]. Past seismic activities such as in 1989 Loma Prieta, 1994 Northridge, 1995 Hyogoken-Nanbu, and 1999 ChiChi provided solid evidence of how regional soil features have a considerable impact on seismic activity at the foundation level. As a result, carrying out ground response research at specific locations research is crucial for producing design response spectra. These spectra are essential for seismic resistant design of constructed slopes and externally stabilized soil systems, as well as for determining liquefaction susceptibility.

For determining site-specific seismic hazard response, one-dimensional ground response modelling is often used. Vertical SH wave propagation through horizontally stacked soil from the bedrock is widely considered in analyses utilizing software like as SHAKE and DEEPSOIL[10]. Several research, including Seed and Idriss[11], Grasso and Maugeri[12], Phillips and Hashash[13], Bonaccorso et al.[14], Monaco et al.[15] have taken site-specific soil attributes into account.

Fig. 1 Location Map of Target Site

II. Local Geological Profile

The convergence of the Pakistan-India and Eurasian Plate tectonic plates is the main factor influencing the region's geology. Three structural zones can be identified in the region; Jurassic through Eocene limestone and shale are folded in a complicated manner in the Northern Margalla Hills[16]. The uplifts have generated significant topographic obstacles. The Rawalpindi group sandstone and shale underpin the south-sloping piedmont lying south of the Himalayas. At its southernmost point, the Soan River follows the axis of the Soan syncline.

Weathered and deformed sandstone and claystone dominate the bedrock, which is partially covered by successive strata of silt, sand, gravel, and occasionally hardened limestone. Deposits of strongly bonded limestone conglomerate, loose silt, and gravel with thicknesses of up to 90 meters exist in locations not directly exposed to bedrock and are often covered by layers of silt. All the building materials are of low durability. The groundwater table is located between 6 and 65 feet below the earth surface.[17].

According to the discussion above and the authors' understanding, Pakistan has very little research on site-specific ground reaction analyses. As a result, in the context of research, a one-dimensional non-linear subsurface behaviour assessment was carried out for Islamabad, Pakistan, by Utilizing geotechnical information obtained from field and laboratory investigations carried out by a borehole at the site. The choice of bedrock input motion was also carefully chosen to consider the unique earthquake risk factors of the targeted region, namely Islamabad.

III. PARAMETERS FOR SUBTERRANEAN PROFILE IN COMPUTATIONAL MODELLING

The subterranean profile used in the analysis was developed using the geotechnical investigation data collected through field and laboratory tests on samples taken from the area around PIMS Hospital in the Islamabad region. Table 1 provides specifics on the underground profile's physical properties. The subsurface soil was classified as silty and clayey by systems for classifying soil, such as AASHTO and USCS. SPT results revealed that the soil beneath the ground level was extremely stiff to hard. The unit weight of the subterranean profile varied from layer to layer and ranged from 17.1 to 18.4 kN/m3. Bedrock stratum was identified at varied depths at indicated areas. However, to keep the current study simple, the substratum was set at a depth of 13 m. Calculations are based on drilling depth in Islamabad due to the varying depth of the bedrock, assuming a shear wave velocity of 700 m/s, a damping coefficient of 1.5%, and unit weight of 23 kN/m3. The damping and deterioration curves for shear modulus are based on Vucetic and Dobry's (1991) plasticity index (PI) with a damping value of 5%.

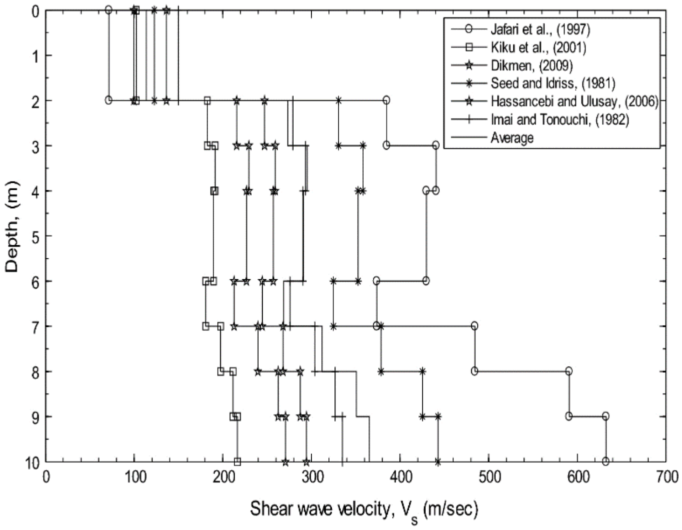


Fig. 2 Velocity profile of shear waves as a function of depth within the borehole

Shear wave velocity is commonly calculated using the results of a standard penetration test (SPT-N value). Seed and Idriss[11], Imai and Tonouchi[18], Jafari et al.[19], Kiku et al.[20], Hasancebi and Ulusay[21], and Dikmen[22] are among the researchers who have constructed shear wave velocity and SPT-N value connections for various types of soils. The fluctuation of shear wave velocity with depth based on these researchers' relationships, as well as the average shear velocity employed in one-dimensional ground response.

Table 1 Subsurface soil profile characteristics utilized in one-dimensional ground response analysis at the Cancer Screening Centre, PIMS, Islamabad

Depth (m)	**SPT-N VALUES**	**V_S (m/s)**	**Unit weight (kN/m^3)**	**Mean shear wave velocity (m/s)**	**Soil classification according to BCP (2007)**
0.76	9	169	17.12	211.7	Stiff soil, S_D (average shear wave velocity 175 to 350 m/s)
1.52	9	169	17.12		
2.28	10	178.3	17.12		
3.04	10	178.3	17.12		
3.80	14	206.8	17.44		
4.56	14	206.8	17.44		

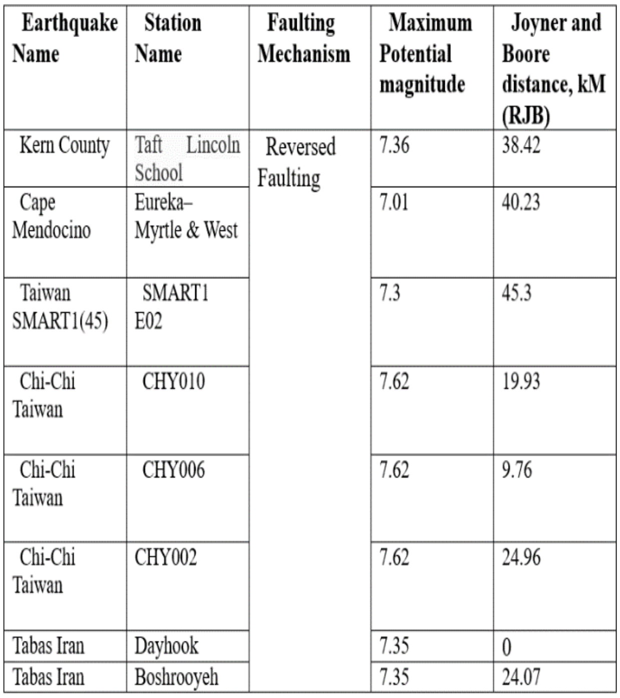
6.84	11	185.6	17.28		
7.60	11	185.6	17.28		
8.36	12	192.5	17.44		
9.12	12	192.5	17.44		
9.88	9	169.7	17.12		
10.64	9	169.7	17.12		
11.4	50	376.4	18.44		
12.1	50	376.4	18.44		

IV. INPUT GROUND MOTION

The key variable of interest in this study is ground motion, which is an important consideration when building civil engineering constructions. The availability of detailed records appropriate for dynamic analysis in Pakistan is restricted. As a result, using recorded acceleration time histories to conduct site response evaluations appears to be a more practical strategy.

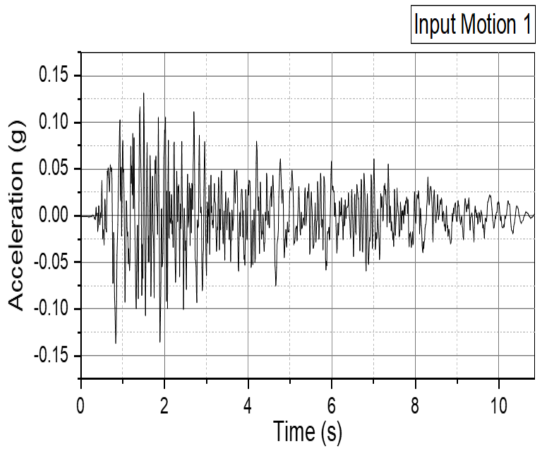
Pacific Earthquake Engineering Research (PEER) Centre’s strong motion database was utilized in this research. This database is heavily reliant on Modified Mercalli Intensity (MMI) values. Eight unique Accelerograms methodically selected from this vast database. These Accelerograms were chosen to align with a magnitude range of Mw 7-8, the closest vicinity to the source, and varying Peak Ground Acceleration (PGA) values. Table 2 shows the seismic input data for your convenience.

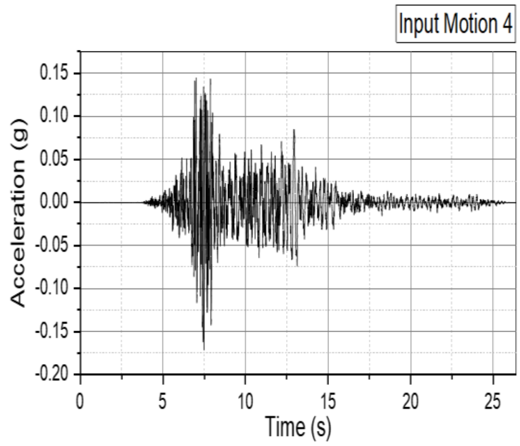
Table 2 Input Ground motion parameters

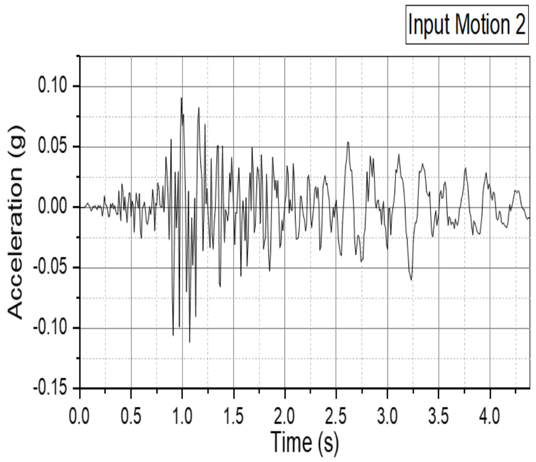


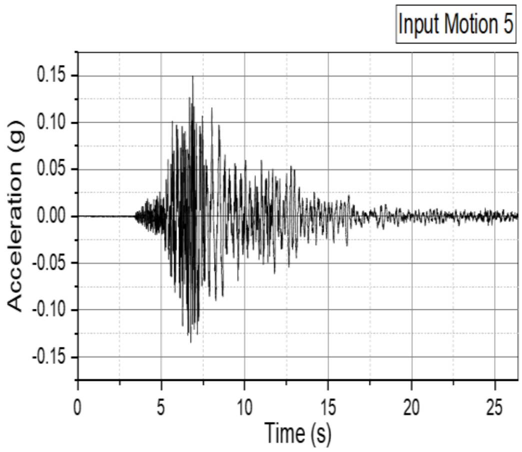
Earthquake Name	Station Name	Faulting Mechanism	Maximum Potential magnitude	Joyner and Boore distance, kM (RJB)
Kern County	Taft Lincoln School	Reversed Faulting	7.36	38.42
Cape Mendocino	Eureka–Myrtle & West		7.01	40.23
Taiwan SMART1(45)	SMART1 E02		7.3	45.3
Chi-Chi Taiwan	CHY010		7.62	19.93
Chi-Chi Taiwan	CHY006		7.62	9.76
Chi-Chi Taiwan	CHY002		7.62	24.96
Tabas Iran	Dayhook		7.35	0
Tabas Iran	Boshrooyeh		7.35	24.07

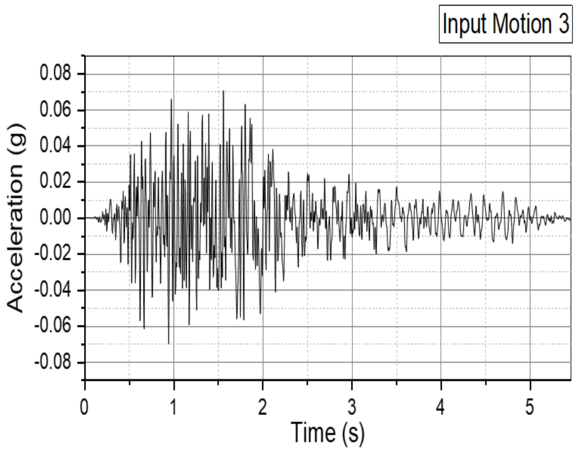
A crucial point in our research in the area of seismic ground response analysis is the change from initial input motion parameters to the dynamic viewing of bedrock accelerograms. Although informative and theoretical, the first parameters offer the crucial framework for seismic evaluation. The heart of our research, however, is found in the following stage, when eight carefully chosen bedrock accelerograms from various geographical regions give these theoretical constructs real-world application. These accelerograms are displayed in complete time sequence using DEEPSOIL software, providing a dynamic representation of the intricate interplay of the earth's crust during seismic occurrences.

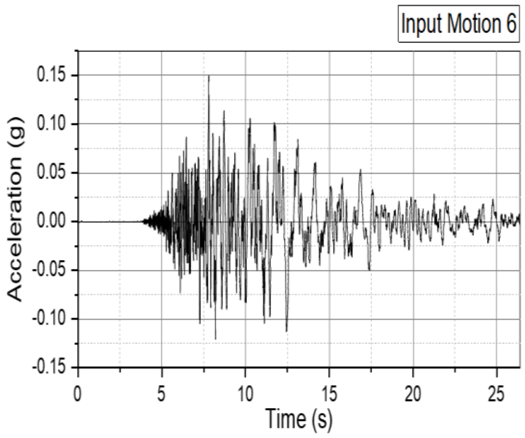

Input Motion 1
Acceleration (g)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
0
2
4
6
8
10
Time (s)

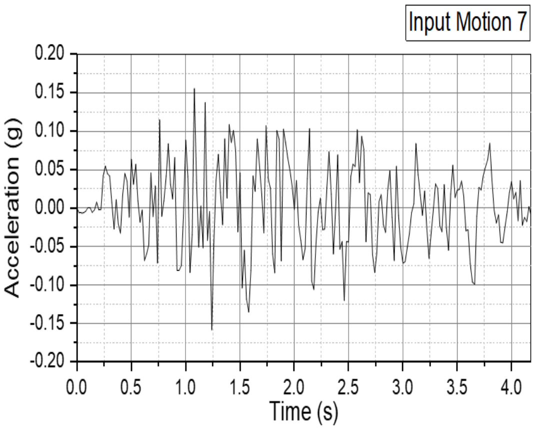

Input Motion 4
Acceleration (g)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
0
5
10
15
20
25
Time (s)


Input Motion 2
Acceleration (g)
0.10
0.05
0.00
-0.05
-0.10
-0.15
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (s)


Input Motion 5
Acceleration (g)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
0
5
10
15
20
25
Time (s)


Input Motion 3
Acceleration (g)
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
0
1
2
3
4
5
Time (s)


Input Motion 6
Acceleration (g)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
0
5
10
15
20
25
Time (s)


Input Motion 7
Acceleration (g)
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (s)

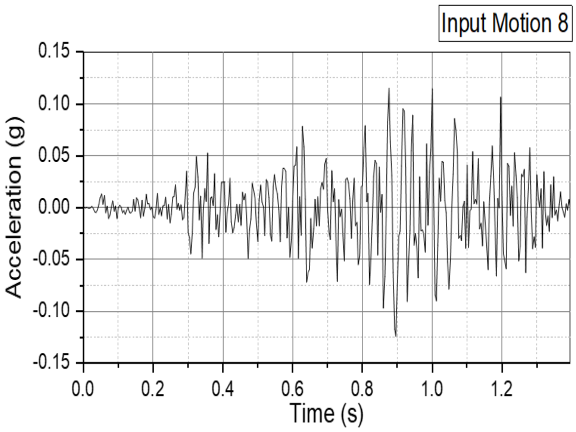


Fig.3 Accelerogram used as bedrock input motions

V. One-Dimensional Soil Analysis Assessment

Local soil features, influenced by numerous underlying theories, play a crucial role in regulating ground surface motion. Soil density and shear wave velocity are often lower at the surface of geotechnical sites than at greater depths. If we exclude material dampening effects, this property difference implies the presence of an energy transfer from deeper soil layers toward the ground surface. As a result, as one approaches the surface, soil particle velocity ('u') increases, corresponding to a decrease in density and shear wave velocity ('vs'). As a result, site-specific location characteristics have a direct impact on metrics such as Peak Ground Acceleration (PGA) and spectral acceleration values, which can diverge from bedrock values.

A useful approach for resolving the difficulties of seismic stress wave propagation inside multilayer soil layers is one-dimensional ground response analysis. The DEEPSOIL software is being applied in this work to accurately classify soil deposits. Incorporating viscous damping, this software uses a Kelvin-Voigt model to describe the continuous elastic characteristics of soil shear moduli. It's vital to note that DEEPSOIL includes both equivalent linear (EL) and nonlinear (NL) studies, which are two different categories of ground response research.

The pressure-dependent hyperbolic model is applied in this research to analyse EL site response. Matasovic[23] devised this model, which is based on Kondner's hyperbolic model. When subjected to minor strains, the model used here demonstrates 0% hysteresis damping. However, damping is integrated into the model even under light loads to appropriately describe nonlinear soil behaviour. Vucetic and Dobry (1991) offered complete soil deterioration and damping curves in this area, notably addressing a 5% damping threshold.

VI. Analysis of Test Results And Discussions

The fundamental natural period Tn of a location with homogenous soil deposit over lying substratum with continuous shear wave velocity can be stated as:

$$f(Hz) = \frac{Vs}{4H}$$

Where H represents the height and Vs represents the continuous shear wave velocity. The fundamental period of a Layered soil stratum, which consists of multiple strata with distinctly varied soil qualities, is generally calculated using the deposit's equivalent shear wave velocity Vs. If the ith layer's uniform thickness is hi and its shear wave velocity is (Vs)i, then the corresponding shear wave velocity of m layers is as follows:

$$Ts(\text{sec}) = \frac{1}{f(Hz)} = \frac{4H}{Vs}$$

The primary natural period of the profile was derived by substituting Equations. The reciprocal of the fundamental natural period was then used to calculate the fundamental natural frequency. According to the description, the site's fundamental natural period and frequency are 0.229 and 4.352, respectively.

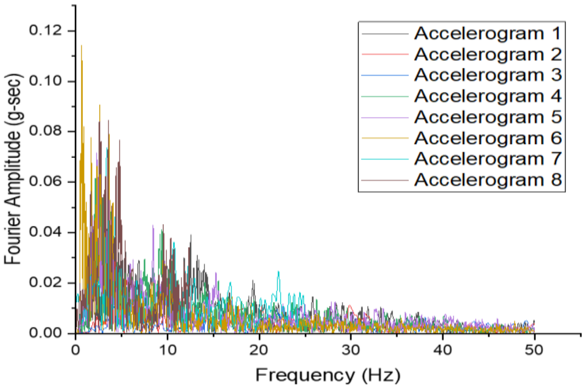


Fig.4 Fourier amplitude spectrum of bedrock seismic inputs

Ground Motion Amplification at the premises is one of the primary measures used to assess ground response[24]. The ratio of surface peak acceleration to bedrock acceleration determines this factor. Standing waves are observed on the Earth at various natural frequencies. Soil displacement is synchronized across all depths in the fundamental mode, with movements happening in tandem. At frequencies greater than the fundamental frequency however, a portion of the soil stratum may travel in one orientation while the rest flows in the other orientation [25]. The amplification factors for different accelerograms were determined at the surface, where all accelerograms exhibit an increase in proximity to the fundamental frequency.

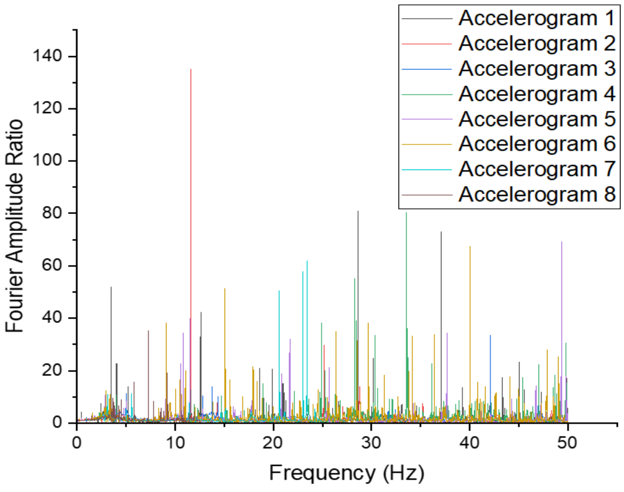


Fig.5 Fourier amplitude ratio for different accelerograms.

In earthquake geotechnical analysis, the study of the relationship between depth and PGA is very technical. This investigation is based on the complex fluctuations in ground motion intensity related to the stratified soil composition below the surface. As seismic waves move across various geological strata, they dynamically change, causing a change in PGA. For developing resilient structures and putting effective seismic risk reduction measures into practice, this understanding is essential. A key component of earthquake geotechnical analysis is the interaction between depth and the Shear Stress Ratio (Shear/Eff. Vert.). This relationship reveals how soil layers respond dynamically when seismic forces move through the ground. We can learn about the amplification or mitigation of seismic forces inside particular soil strata by looking at the variation in the shear stress ratio with depth. It is crucial to comprehend this depth-dependent behaviour to evaluate seismic risk and improve foundation design.

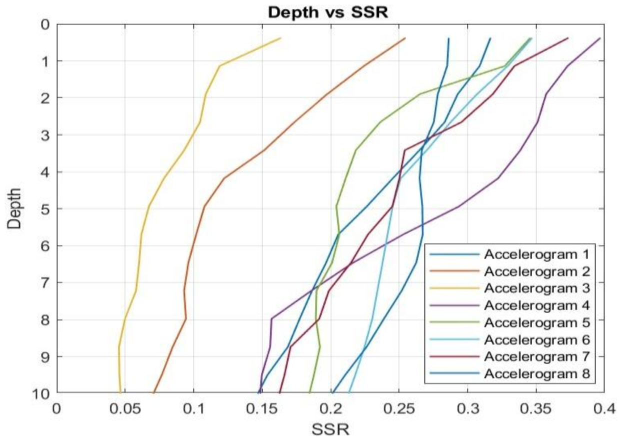


Fig. 7 Shear Stress Ratio (SSR) throughout the soil profile's depth.

Seismic input signals provided at the bedrock level causes shear strain and associated deterioration in the soil strata by producing shear stresses at various layers throughout its transmission to the surface. As a result, the EL analyses employ diverse methods to estimate soil dynamic behaviour during input motion waves throughout soil layers. Consequently, the resultant shear strain along the vertical extent of the soil profile for the EL investigations may differ for a range of input motions. Fig. 7 depicts the shear strain caused by a range of input motions down the soil horizon depth.

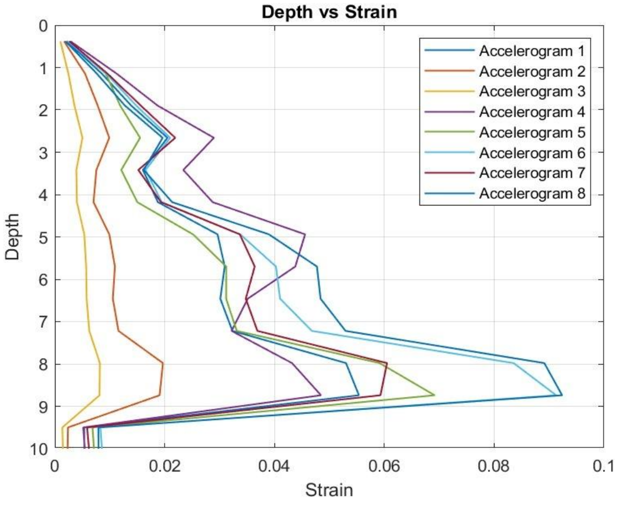


Fig. 8 Strain distribution along the soil profile's depth.

In earthquake geotechnical study, it is crucial to look at how soil layers and shear strength relate to one another. This connection reveals the stratified makeup of subterranean soils and their wide range of shear force resistance capabilities during seismic activity. Critical insights into the intricate behaviour of soils under seismic loading are provided by the subtle variations in shear strength with various depths.

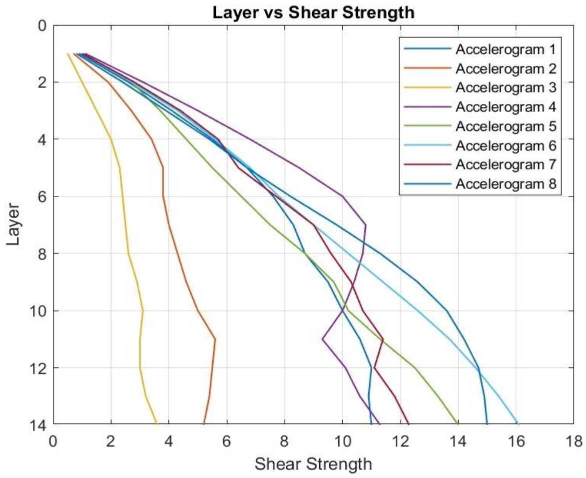


Fig. 9 Shear resistance variation through the soil profile's depth.

The seismic spectrum is a commonly utilized resource in the engineering of structures capable of withstanding seismic events. The frequency components of ground motion are represented in this spectrum, which is described as spectral acceleration at the surface. It is an important measure for determining ground response during seismic occurrences.

The standard way to quantify ground reaction is a one-dimensional linear ground response analysis, typically by applying the tools like SHAKE or DEEPSOIL. While linear response analysis is extensively employed, it is fundamentally conservative since it approximates nonlinear behaviours within the limits of a linear framework. One significant disadvantage of comparable linear response analysis is its reliance on constant linear shear modulus and damping under idealized strain data throughout the investigation.

VII. CONCLUSIONS

In Islamabad, Pakistan, one-dimensional Equivalent Linear (EL) ground response assessments were conducted, providing the following key findings:

- The soil stratum at the chosen sites was predominantly composed of silty and clayey elements, according to geotechnical laboratory and field investigations.
- Using several proven methodologies, the EL analytical methods were used to compute shear deterioration and shear strain inside the subterranean soil layers.
- The results showed that a transfer function may efficiently connect Peak Ground Acceleration (PGA) values across different levels of a soil deposit. Impact of shear degradation on shear strength generation and the subsequent strain was attributed to this correlation, which led to various outcomes and measurements along the depth of the subterranean soil layers.

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