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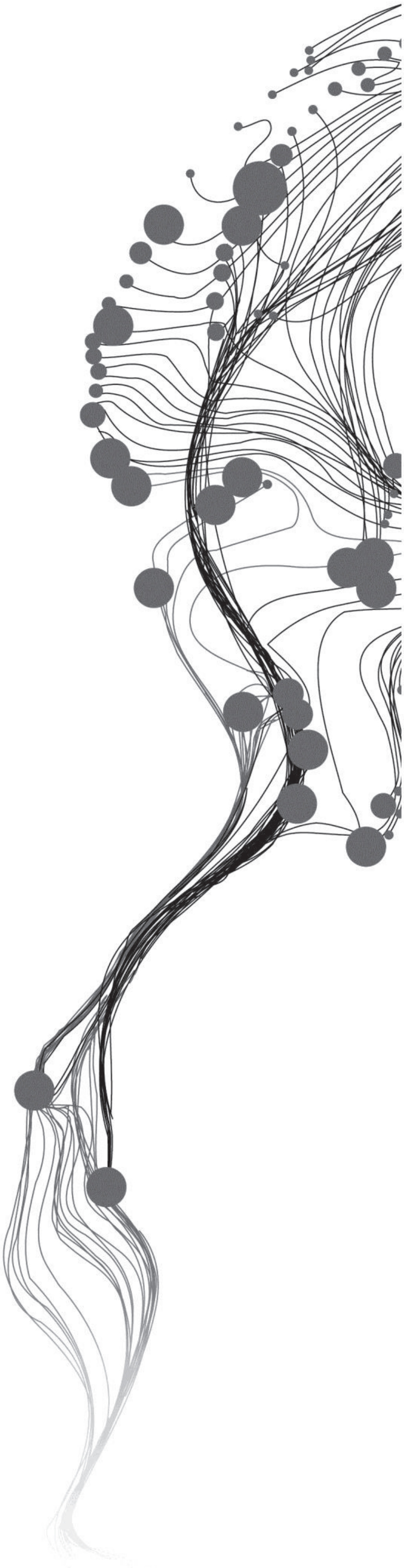

NUMERICAL ANALYSIS OF SEISMIC AMPLIFICATION BASED ON SOIL THICKNESS VARIATION

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ABSTRACT

The influence of soil on the response of the ground during an earthquake event remains unclear. The seismic amplification is the term applied to describe the increased ground motion on the soft grounds as the seismic shear waves are slowed down from the bedrock. However, the influence of the soil thickness variation in site amplification phenomenon has been generalized in many studies. Soils are capable of changing the character of a seismic motion by amplifying or de-amplifying it depending on the soil conditions which results to varied damage pattern observed after an earthquake event. This study evaluates the amplification effect in different geotechnical soil types which included the Soil type E, Soil type D and Soil type C based on NEHRP classification of soils. The key parameter used to define the soils is the shear wave velocity (Vs). Equivalent linear analysis approach is applied in analysing seismic shear wave propagation in one-dimensional path in Edushake program. The ground surface motion parameters which are associated with the level of damage during an earthquake are computed. These parameters involve the amplification factor, spectral acceleration, the PGA and PGV in the three different soils of interest in this study. The study uses the soil thickness data derived from the model by Shafique et. al 2011b for the case of Balakot-Muzaffarabad cities in Kashmir region, Pakistan. The predicted amplification model of the soil type E shows that the estimated amplification is 3 times that of the soil type C in the thin layers <10m and about 1.5 times in the thick layers >20m. The models are also correlated with the level of damage that was observed in the Muzaffarabad city after the Kashmir earthquake in 8^{th} October, 2005. The relation between earthquake damage and the amplification factor of the soil type E was $R^2=0.38$, $R^2=0.36$ in the soil type D and $R^2=0.35$ in the soil type C. The soil type E shows similar correlation as that of the regolith thickness with the level of damage in the same area. The study predicts that severe damage is likely to be observed in the soil type E since the amplification is higher than in the other soil types. This study suggests that the areas covered with Soil type E in Balakot-Muzaffarabad region are likely to have experienced severe damage since a close match in the damage map is observed.

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1. INTRODUCTION

Substantial investigation on the influence of the physical characteristics of the ground such as the topography (Anggraeni, 2010; Assimaki & Gazetas, 2004), soil stiffness and layer thickness (Suetomi et al., 2004; Tezcan, 2002) on the ground response in seismic motion has been done. From the past observations, buildings located on top of hills and ridges as well as on the depositional basins have suffered intensive damage from destructive seismic events: Anggraeni (2010), Assimaki et. al. (2004), Shafique et. al. (2011) and Govindaraju & Bhattacharya (2012). Due to insufficient documentation of evidence on topographic amplification and the complexity in the geometry of the soil depositional basin, soil layer thickness variation over a given area and lack of field data, the influence of soil layer thickness as a contributing variable in ground seismic response, has not been incorporated in several microzonation studies. Assuming the variation in soil layer thickness for example, when evaluating the topographical impact on the amplification of seismic ground motion has led to neglecting the key factor of the soil that influences the seismic response.

Even though it has been a challenge to conduct analysis on both the impact of soil and topography in a single model, there is the need first, to understanding the effect of the soil layer thickness variation in ground response during an earthquake. This has been evidence with discrepancies in the evaluation of the influence of topography on site amplification whereby, the amplification of the seismic motion on soil basin as well as on the hill tops are equally high. This implies that each of these parameters; topography and soils thickness would only explain part of the amplification. To avoid this confusion, this study focused on the application of numerical computations in simulating seismic ground motion in 1D and in 3D to evaluate the amplification factor at varied soil thickness to explain the spatial distribution of the seismic response. From this investigation, the relationship between the spatial variation in soil thickness and seismic response was established. The record on earthquake damage which was observed after the Kashmir earthquake (8th October, 2005) in Pakistan in the Muzaffarabad city area was applied as a case study to evaluate the correlation between the amplification factor on varied soil thickness and the spatial distribution of the damage.

1.1. General Information

Earthquakes are renowned as being amongst the most destructive natural hazards which cause huge devastation in a single event and trigger of other related disasters such as fire, landslides, soil liquefaction, rock-falls, flooding and slope instability. The experience of earthquake disaster across the world has led to property damage, loss of lives and economical losses. In only the top ten most destructive earthquake events since 1900 to 2013, the International Emergency Disaster Database (EMDAT) shows that these events have caused more than 1,490,000 people killed, more than 100,600,000 affected and property damage worth more than US$ 553,800,000. This implies that any property damage, loss of lives and any intangible loses such as economic losses due to earthquake cannot be neglected. We therefore need proper measures prior to any possible future events especially in the earthquake prone areas so that such damages and loses can be minimized.

In an effort to mitigate the earthquake disaster, a wide range of investigations have been carried out on vulnerability in different localities and spatial variation in the ground characteristics that influence ground shaking during an earthquake. However, the suggestion for the mitigation measures cannot be precise without understanding the parameters that influence spatial variation in intensity and duration of the ground shaking due to earthquake. Some of these parameters involve: the source effects such as the magnitude of the seismic wave, seismic frequency, amplitude, source mechanism, depth of the hypocenter and epicentral distance (Flores-Estrella et al., 2007). The characteristics of the medium of propagation such as the softness, shear velocity, shear strength, Soil type Dness, thickness and density of the soil profile also influence ground motion during an earthquake (Robinson et al., 2006; Shafique et al., 2011a). The knowledge of these fundamental parameters is the basis for this study to evaluate the impact of soil thickness variation on seismic ground response.

1.2. Research statement

Continued investigations on the ground properties and their influence on seismic ground motions have been of great significance in hydrogeological, environmental and engineering practices. From the past experiences, recorded earthquake events have shown that amplification and de-amplification of ground shaking and the associated damages to structures are related to the local site ground conditions. Understanding these ground conditions is an essential task in earthquake hazard analysis. Several researchers have incorporated seismological records to develop regional and local models to explain the causes of the spatial distribution of seismic amplification. This study focuses on the evaluation of seismic amplification in a city area.

It is from the past evidence, that seismic amplification has been strongly associated with parameters such as the geology, soil thickness, topography and other local site ground conditions. Some studies on these parameters have been performed to evaluate their influence on determination of ground shaking intensity. However, exploration into the key role of soil layer thickness and spatial variations that is essential in the variation of seismic damage distribution has not been extensively addressed. In this study, the simulation of a seismic motion was performed to examine the mean amplification factor of at varied soil thickness considering site conditions such as the shear wave velocity, shear modulus, unit weight of the material and plasticity index value. Evaluations on the influence of the soil thickness variation on seismic amplification factor was performed in 1D model. The amplification maps were used to determine relation between site amplification and the damage distribution patterns. This investigation was done using the the Muzaffarabad city area in Pakistan as the case study.

1.3. Objective of the study

To evaluate the impact of soil thickness variation in seismic amplification in 1D model

1.3.1. Specific objectives

i) To examine the influence of the soil thickness, density and shear velocity on the earthquake induced ground motions

ii) To evaluate the impact different soil types in the amplification of seismic motion

iii) To compare the influence of the bedrock stiffness on site amplification

iv) To establish the relationship between the site amplification and damage distribution pattern

This research answers the following questions;

1.4. Research Questions

i) What is the impact of varied soil thickness in site amplification?

ii) What is the contribution of the soil density in determining its response to seismic motion?
iii) What is the contribution of the shear wave velocity of the soil in determining its response to seismic motion?
iv) What is the impact different soil types in the amplification of seismic motion?
v) What is the influence of the stiffness of the bedrock on site amplification?
vi) Is there any relations between site amplification and damage distribution pattern with respect to the soil thickness?

1.5. Previous Works

Ground response analyses are important in predicting the occurrence of future possible damage by relating with specific magnitude of ground shaking. Ground response assessments have been improving from time to time. The assessment on the behavior of the ground during earthquake events for example, have been improved due to the establishment of newer techniques in the analysis, advanced methods in subsurface investigation and physical understanding of seismic events. In addition, since 1980's, computer technology and development of geo-science computational techniques in numerical modeling have played a great role in ensuring efficient studies on seismic response analysis. Seismic response analyses have been improving due to the application of modeling techniques in 1D and 2D and most recent introduction of the 3D and 4D models. The advancement through these stages have enabled seismologist to relate earthquake parameters such as the variation in intensity of ground shaking with the associated ground conditions from one place to another. In this regard, investigations into the influence of different conditions of the ground have been carried out and documented in the past literature on regional and local variation in seismic induced ground shaking, for example Assimaki and Gazetas (2004); (Anggraeni, 2010); Shafique et al. (2011a); Shafique et al. (2011b); and Ito and Towhata (2012).

Seismic amplification describes the increased response of the ground surface relative to the bedrock motion during an earthquake event. Several studies have shown that seismic amplification is highly influenced by the difference in some geophysical attributes of the ground such as the seismic wave velocity, density contrast, decrease in velocity of the incident seismic wave propagated from a hard rock through a soft soil, and softness of the sediments in a profile. These differences are also associated with the variation in density, depth of the overburden and degree of compaction of the material (see for example Wills and Clahan, 2006; Dobry et al., 2000; Robinson et al. 2006).

Based on the horizontal stratigraphy of geological units, seismologist have associated seismic amplification with the impact of velocity contrast between soil layers, a factor commonly referred to as impedance contrast in seismic wave propagation. This is exhibited in the transition boundaries between the relatively high velocity and Soil type C layers into low velocity and less Soil type C surface deposits. Seismic energy in this case is utilized in the displacement of the material particles and in increasing the amplitude of the seismic wave, this results to amplification of the seismic motion. A clear example of earthquake event which resulted to this kind of phenomena which is mentioned in several studies, is the Michoacán earthquake in Mexico (1985). It was observed that even though the epicenter was located more than 350 km away from the lake basin city; intensive damage could be observed in the areas underlain by soft deposits which were associated with the high impedance contrast of the seismic wave propagation. In addition the nature of the surface geology and geomorphology (soil cover and its depth) are also contributing parameters influencing seismic amplification (Tezcan et al., 2002). Towhata (2008), emphasized on the need for understanding the geology in earthquake hazard analysis activities. In earlier studies, (Seed et al. 1992; Chang et al. 1996), geological conditions such as the age and depositional environment of the near surface deposits are pointed out as factors influencing seismic induced ground shaking and the damage patterns. This has been evidenced from studies of accelerometer data deployed in the seismic zones in developed countries for example in Northridge in California, Kocaeli and Duzce earthquakes in Turkey, and Kobe in Japan (Hartzell et al., 1997 and Tsuda et al., 2006). Franco et al. (2011) highlighted several hazards posed by earthquakes in the megacity of Kolkata in India due to its seismic and geological settings. The study found that deep alluvial deposits in the city increased seismic hazard vulnerability and other phenomena such as landslides and liquefaction due to the amplification of the seismic energy propagation.

Computation of seismic amplification in different scales of coverage, has enabled many seismologists to establish the relationship between the spatial variation in the ground shaking and the topography. Topography has shown great influence on the intensity of ground motion as observed from the records and studies from the earthquakes events. In an example, Geli et al. (1988) applied some of the commonly used numerical modeling methods ranging from the finite element, finite difference, integral equation method, and boundary method with the theoretical background of seismic amplification which enable them to find out that, seismic amplification is most significant at the hill tops while complex pattern of the seismic wave is experienced on the hill sides. In their case study after the Haiti earthquake in 2010, Shafique et al. (2011a) proved this phenomenon by reporting that higher seismic amplifications were observed at the hill tops than in the flat areas. The Wenchuan earthquake (2008) in China also showed the same kind of relation (Zhang et al., 2008). In other related studies such as Chaljub et al. (2003), Komatitsch and Tromp (1999), Durand et al. (1999), and Komatitsch et al. (2004), the influence of topography is again attributed with the spatial variation in the level of ground shaking from one place to another in mountainous areas. In the recent studies by Lee et al. (2008), Anggreani (2010) and Shafique et al. (2011a) it has been pointed out that low lands especially the sedimentary basins and valleys near mountainous areas and the presence of fault zones have impact on the ground response to seismic motion. According to Lee et al. (2008) the interaction between the mountainous areas and the nearby sedimentary basin causes a complex amplification pattern which is controlled by the basin depth and shallow shear-wave speeds.

Some geotechnical properties of the soil such as the damping ratio, Poisson's ratio (v), and plasticity index (PI) as pointed out in Vucetic and Dobry (1991) and Arai and Tokimatsu (2005), can influence the level of ground shaking. From the previous field observations, the role of soil thickness in the distribution of ground shaking and damage is quite pronounced, for example the Caracas Valley Venezuela earthquake in 1967 (Papageorgiou and Kim, 1991), the San Francisco earthquake of 1989 (F. Naeim & Paz, 1994) and the Mexican city earthquake (1985) (Lomnitz, 1997). The variation in amplification at local sites overlaying varied soil thicknesses has been identified as the major cause for varied damage patterns experienced during the past earthquake events. See for example in a review study on seismic response of the Mexico City basin (Flores-Estrella, et al. 2007) and a numerical study by Tezcan et al. (2002) after the Kocaeli earthquake of August 17, 1999 in Avcılar town, Istanbul. In a case study carried out by Sitharam and Govindaraju (2004) following the Bhuj earthquake in India (2001), the field observations showed that in the Ahmedabad city which is located about 300 km away from the epicenter of the earthquake, a number of medium-to-high-rise residential reinforced concrete houses having four to ten storeys suffered extensive damage and/or collapse during the earthquake event. These collapse was associated with large settlement of silty sand deposits and amplification of the ground. In addition, Sitharam and Govindaraju observed that deep alluvial deposits dominated the sites where severe damage was observed. The amplification of the peak ground acceleration turned out to be about 1.66 at frequencies between 1.5 and 3.0 Hz. In a numerical study, Mohamedzein et al. (2006) investigated the effect of alluvial deposits in Central Khartoum, Sudan on the propagation of seismic motion parameters to the surface. They found that amplification of the ground motions was upto 4.93 due to the existence of the Nubian sandstone underlying a thick alluvial deposits at a depth of 25 m.

Additional evidence where seismic amplification has been associated with deep soil depth can be pointed out from some destructive earthquakes in the past. Rosset and Chouinard (2009) carried out a seismic site response study in the Montreal urban areas. From their field observations, they identified a significant relationship between soil thickness and the resultant seismic amplification in different sediments in the city areas. The characteristic PGA factor ranged from 2 to 4 at frequencies from 2 to 7 Hz. During the Kobe earthquake in Japan, the heavily damaged areas showed peak acceleration values ranging from 0.7-0.8 g and 0.3-0.6 g in the majority of other areas where varied extent of damages were observed (Zhao et al., 2004). Rezaei et al. (2009) also carried out a seismic ground response assesment study after the Bam earthquake (2003) in Iran. Based on the mechanical behavior of the soils and subsurface sediments in that area, they were able to observed non-uniform damage distribution pattern. They reported a great number of damaged buildings in the city areas dominated by silty and clayey soils, low permeability soils, as well as areas where the soils showed low wave velocity, high plasticity and relatively high compressibility. They also found that soil thickness, which was estimated using geophysical surveying method, showed a direct relationship with damage rate observations whereby areas with deep soil thickness were dominated with more damage and vice versa. Shafique et al. (2011) related qualitatively the soil thickness variation with the pattern of seismic damage experienced in Kashmir region after the Kashmir earthquake in 2005, where they found that huge damage occurred in areas with deep soil cover.

From this background it is undisputable that soil thickness is one of the attributes that can be help explain the spatial variation in ground shaking. From the previous studies, minimal studies have been done on the interaction between the soil layer and topographic amplification of seismic ground motion. Also in some instances for example in the numerical studies on the influence of topography on amplification of seismic ground motion, soil thickness has been assumed to be constant in several cases in the computations of amplification factor. Lack of soil data, the need for high computational power in 3D modeling and complexity in spatial variation of soil thickness are some of the issues which explain minimal effort in accounting for soil in the numerical seismic response analyses. Hence, the key factor influencing seismic response due to soil cover has not been addressed. This consideration is important in making precise estimation of seismic amplification in both regional and local scales. Delineating zones with the estimated magnitude of amplification is useful in the development of seismic microzoning maps showing the distribution of the low, medium and high risk zones and vulnerability to the intense amplification of the ground shaking in the event of an earthquake. Therefore, this study will take a step to investigate the role of the soil depth and its relation with the amplification of seismic ground motion.

The approach of this study will consider soil thickness among other parameters such as the shear velocity and density in numerical modeling of the distribution of ground shaking intensity. Our reference soil data set and area of study will be Muzaffarabad City area in north eastern parts of Pakistan. The data was collected after the Kashmir 8th October 2005 M_W7.7 earthquake. Several studies have been carried out since the earthquake happened with an aim to examine the major causal parameters which contributed to the extensive damage which was experienced especially in the city area. Soil thickness is well known as a contributing parameter in the seismic response of a particular site. In order to predict the level of ground shaking during an earthquake, this study explores the impact of varying soil layer thickness in the computation of the seismic ground motions. The investigation is performed by simulating a seismic motion propagation in 1D model. The analysis is done using the Edushake program which utilizes the equivalent linear sites response analysis in the computation for the ground motions. The results are applied to generate the relation between the ground motion parameter such as the amplification factor, the peak ground acceleration and the peak ground velocity with respect to the soil thickness. A comparison between these ground motion parameters and the distribution pattern of the earthquake damage is performed using the Muzaffarabad City in Pakistan as a case study, following the October 8th 2005 Kashmir earthquake damage that was observed in that city.

1.6. Significance of this study

The outcome of this study can be put into several useful. This study derives a model that can be applied to relate soil layer thickness with the amplification of the seismic motions, which can be used to predict the spatial distribution pattern of earthquake damage. The urban and rural developers may have an insight from this work, on the geotechnical conditions that are most likely to contribute to severe damage in earthquake prone areas. This is essential in designing and planning for earthquake mitigation measures. Liquefaction on weak grounds can be estimated. Constructors are able to design earthquake resistant building and infrastructures based on the estimated amplification peak frequencies at a site.

1.7. Research Approaches

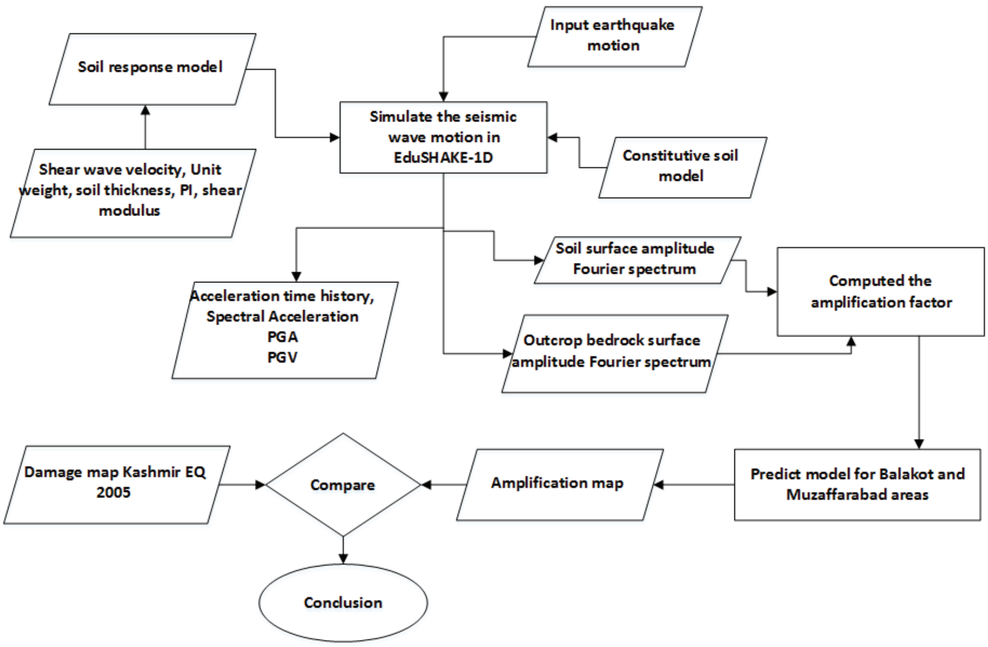


Fig. 1: The flow chart showing the methodology of the study. 1D simulation of ground motion is performed on three different soil types (soil types E, D, and C) to determine their response based on the different geotechnical conditions. The final stage involves comparing the amplification maps with the damage maps to see which model best explains the distribution damage.

1.8. Structure of the thesis

Chapter One: This chapter gives the general information of the study, historical background, research problem, objectives, research questions, and the significance of this study.

Chapter Two: A review of the literature contributing to this study

Chapter Three: Research methodology

Chapter Four: Results and discussions

Chapter Five: conclusion and recommendations

2. LITERATURE REVIEW

2.1. Seismic waves propagation in the ground

Seismic waves are responsible for ground shaking during an earthquake event. The main seismic waves are the body waves and the surface waves. The body waves include the primary waves (P-waves) and the secondary waves (S-waves). The surface waves include the Love waves and the Rayleigh waves. The propagation of the P-waves happens in a direction parallel to the vibration of particles. This causes compressional and extensional effect in the ground. The velocity of propagation of the P-waves is considered the highest and can pass through different media (solid, liquid, gas) with high frequency during an earthquake event, therefore they are recorded first in the seismograms. The S-wave are slower than the P-waves and the direction of propagation is perpendicular to the particle motion. The S-wave are also referred to as the elastic or shear waves due to their mode of propagation that causes shear stress in the ground. The S-waves are only propagated through solids, therefore the velocity of these waves is highly influenced by the medium through which they are travelling and specifically the density. The surface waves are generally spread in the few kilometre below the ground surface and are the slowest seismic waves which travel in solids. These waves however cause great damage especially in shallow earthquakes than in the deeper ones.

The seismic waves are known to cause different behaviour of the ground during an earthquake event. S-waves and the surface waves are considered most destructive due to their mode of propagation through the earth crust. However, the S-waves are more reliable than the other seismic waves in seismological studies since they can be used to estimate different components of the earth's crust including information about different rocks through which they are propagated. These waves can also reach the ground surface in case of shallow or deep earthquake focus. The difference in time of arrival between the P-wave and the S-waves is commonly used by the seismologists to establish some information such as the distance the epicentre and hypocentre (the point source of the earthquake), duration of the earthquake, and also estimating the mechanism of the earthquake. Several researchers have applied the S-waves and shown the reliability in modelling the ground response to earthquake shock in different ground conditions (Arai & Tokimatsu, 2005; Bauer, 2007; Hashash et al., 2010; Luzón et al., 1997; Papageorgiou & Kim, 1991; Schnabel et al., 1972).

2.2. Application of the seismic shear wave velocity in ground response analyses

The use of the spectral analysis of surface wave (SASW) and multichannel analysis of surface wave (MASW) in the characterization of the local site conditions are techniques which have been used in several decades in mapping of shear-wave velocity in seismic hazard and micro zonation studies (Kanlı et al., 2006; Nazarian & Stokoe II, 1983). The characterization of sites helps the seismologist and engineers to determine the safety of the ground against earthquake effects such as the site amplification and liquefaction. This exercise is performed in different site by evaluating the subsurface features, material types and properties in order to have an idea of possible point of damage occurrence in future earthquake events.

Shear wave velocity is therefore recognized as an important parameter essentially in the evaluation of soil behaviour in shallow subsurface. This has made it possible for the seismologist to calculate seismic hazards based on the near surface shear wave velocity values. The average shear velocity for the top 30m of soil is commonly referred to as the Vs30 (Kanlı et al., 2006). Following Dobry et al. (2000), soil profile consisting of *n* number of layers of soil or rock at the top 30m of the soil, each having a shear wave velocity V_s and thickness *h* then its Vs30 is computed as;

$$V_s 30 = 30 / [\sum (h / V_s)] \qquad \text{(Equation 1)}$$

Where the sum is done between the ground surface and 30m depth. This equation enables the soft soil site overlaying a rock to be classified as soil type E (Table 2.2), even when the depth of the rock is less than 30m (Dobry et al., 2000). This method of site classification is applied worldwide in including the National Earthquake Hazard Response Programme (NEHRP) in seismic hazard mapping and code provisions for earthquake engineering designs (Bauer, 2007).

Before describing the properties of the actual response model that was applied in the analysis, it was important to reflect on some of the geotechnical findings from previous research on the common characteristic and the basis of classification of the different soil types and geotechnical sites.

2.2.1. Summary of studies on soil classification based on the shear wave velocity

According to the USGS (2013b) Soil type E Vs 200m/s are characterized with artificial fill, water-saturated mud, clays and unconsolidated sands. Strongest seismic amplification is expected in this type of soils. The soil type D Vs 200 to 350m/s are defined with sands, silt and mud. Significant amplification in these soil type is expected. Soil type C Vs 350 to 750m/s, may include some Quaternary sands, sandstones, mudstones, and some Tertiary mud and sand deposits. Minimal amplification is expected in this type of soils. The soil type B are more compact and can be categorized with volcanic rocks and deposits. This soil type can be reached at deep levels with inclusion of Mesozoic deposits (http://earthquake.usgs.gov/regional/nca/soiltype). Soil type A and B are defined with high Vs from 750m/s to 1500m/s and >1500m/s respectively.

In the Borcherdt 1994b and Dobry et. al. 2000, the materials defined as hard rocks and soil type E were observed with shear velocities of more than 1300 m/sec and less than 200 m/sec respectively. Boore and Joyner 1997 conducted some field observations and categorized the Soil type D with shear velocity ranging from 255 to 310 m/sec and soil type C with Vs 520 m/sec shear velocity. According to their observations, the rock include materials such as the granites, chert, dolerite, limestone, greywacke, sandstone or siltstone. Borcherdt (1996) shows a different classification of different soil and sites which he used the lithology, hardness texture, fracture spacing, standard penetration resistance N (blows per foot) to group the deposits with the respective shear velocities. The description of different site classes defined by Borcherdt were corresponding to the current NEHRP site classes and soil types (Table 2.1). In his work, Borcherdt described different classes of soil as 1) firm and hard rocks (minimum Vs30=1400 m/s and average of 1620 m/s) which were characterized with very widely spaced fractures. The rock class which is defined as Class B in the NEHRP site classification, were defined with Vs 700 to 1400 m/s and an average of 1050 m/s (Table 3.2). This Class of soil were dominated with granites, igneous rocks, conglomerate, sandstones, and shales with close to widely spaced fractures (Borcherdt, 1996). Borcherdt also defined Soil type C as gravelly soils and soft to firm rocks defined with shear velocity ranging from 375 m/s to 700 m/s with an average of 520 m/s dominated with soft igneous and sedimentary rocks, sandstones and shale, gravel and soils with > 20% gravel.

Skarlatoudis et. al. (2011), defined soil type E and soil type C with shear velocity Vs30 180 and 700 m/s respectively while the rock sites were defined with Vs 2000 m/s. Gosar et. al. (2001) found low shear velocity deposits of sands and gravel with Vs 250 to 550 m/s while the stiff soils and clay debris of marine origin exhibited Vs of 300-600 m/s. Gosar et. al. also defined deposits with Vs 600-1400 m/s as Class B sites, characterized with conglomerates, sandstones and others debris of marine origin with low clay component. According to Gosar et. al. (2001) the hard rocks which are categorized as Class A, comprised of sandstone, marl, calcareous breccia with higher clay component from the study area.

Several other classification schemes are applied worldwide such as the UBC97, Turkey 98, Japan 1998, New Zealand 2000, Greek Seismic code and EC8. From the studies highlighted in the previous section, direct measurement of shear-wave velocity provides the most accurate characterization of a sites for the purposes of estimating amplification factors. This technique allows a site to be classified unambiguously (Borcherdt, 1994) with quantitative estimates of amplification. Even though Vs30 is not the only parameter that controls site amplification (Ibrahim et al., 2012), this parameter is primarily essential in special geotechnical projects (Dobry et al., 2000).

It is clear from the literature that the seismic ground response is dependent on the soil properties. This study applied three categories of soil sites defined with varied properties to investigate their influence in the intensity of ground motion. From the literature, the summary of the classification of different soil sites and types is based on NEHRP Vs values of the soil types and sites. This study adopts the average Vs of the soil types and geotechnical sites classification scheme (see Table 2.1), to define the soil types that are applied for investigation in this study. The soils are grouped into six types designated by letters A to F. The hard rock type is designated with letter A with Vs (greater than) >1500 m/s, soil type B represents the soils defined as rock with the V_S range of 760 to 1500 m/s and Soil type C with Vs 360 to 760 m/s. The Soil type D is defined with shear velocity of 180 to 360 m/sec. The soft and loose soils are characterized with shear velocity of less than 180 m/sec (Table 2.1).

Homogeneous layer models with shear velocities estimated for soil type E to soil type C were applied to define the material properties with Vs 150m/s, 280m/s and 500m/s (Table 2.2) and varied densities from 15kN/m^3, 17 kN/m^3 and 19 kN/m^3 respectively (see Table 3.1). To evaluate the difference due to varied stiffness of the bedrock, weak to firm bedrocks were applied with Vs30 750m/s and 1300 m/s with densities 20 kN/m^3 and 24 kN/m^3 respectively. These two site classes of bedrock are considered in this study since they do not contribute greatly into the site amplification (Dobry et al., 2000).

Table 2. 1: Classification of sites and soil types according to NEHRP (NEHRP, 2009).

Soil type	Soil Profile Name	VS30
A	Hard rock	>1500 m/s
B	Rock	760 to 1500 m/s
C	Very dense soil and soft rock	360 to 760 m/s
D	stiff soil	180 to 360 m/s
E	soft soil	<180 m/s
F	soils requiring site specific evaluation	-

Table 2. 2: Summary of soil classification

Reference Study	**Soil type E/F)** (Soft soil site)	**Soil type D** (Stiff soil site)	**Soil type C** (Very dense soil site)	**Soil type B** (Rock site)	**Soil type A** (Hard rock site)
NEHRP 2009 edition	<180 m/s	180-360 m/s	360-760 m/s	760-1500 m/s	>1500 m/s
Borcherdt 1996, Dobry et. al. 2000	<200 m/s	200-350 m/s	350- 800 m/s	800-1300 m/s	>1400 m/s
Boore and Joyner 1997, Joyner and Boore 1981	-	255-310 m/s	520 m/s	620 m/s	-
Borcherdt 1994	100-200 m/s	200-375 m/s	375-700 m/s	700-1400 m/s	1400-1620 m/s
Skarlatoudis et. al. (2011)	180 m/s	300 m/s	700 m/s	2000 m/s	3400 m/s (1000m)
Gosar et al. (2001)	-	250-550 m/s	300-600 m/s	600-1400 m/s	1400-1600 m/s
Estimated Mean value	**150 m/s**	**280 m/s**	**500 m/s**	**1100 m/s**	**1500 m/s**

*IBS-International Building Code

2.3. Site effects

Site effects have been recognized for more than a century since the earlier work by John Milne in 1898 cited in (Musson, 2013). Spatial distribution of soil amplification has been demonstrated in many past destructive earthquakes and has continued to draw more researcher interest. Conducting analysis on the soil amplification is a significant activity in the geotechnical practices since at some specific sites, the amplification of the seismic response can be very large. According to Tezcan et. al. (2002) soil amplification analysis may be performed following one of the methods; i) solution of differential wave equations, ii) lumped mass idealisation, and iii) finite element idealisation. The application of the first two methods is fit for the horizontally layered soils idealized in one dimensional models. Finite element method is ideal for two or three dimensional problems (Tezcan et. al. 2002 and Smerzini et. al. 2011).

Site amplification is a phenomenon which depends on several local geotechnical conditions of the ground. Studies have shown that ground response to seismic motions at a particular site is influenced by the nature of the existing soil or rock (Kramer, 1996). These conditions result to random spatial variation in the site amplification. Several studies have also included cases representing the influence of inclined soil layering (Semblat et al., 2005), the effect of incident angle in the seismic wave propagation (Semblat et al., 2000; Wang & Hao, 2002). Therefore, a comprehensive analysis on this phenomena demands for detail investigation of the site where the response analysis is evaluated. This involves the investigation into the geology, density, Atterberg limits, characterizing the stratigraphy, testing for the moisture content of the soils, describing the details of the rocks and soils in the area, strength properties of the rock, and also establishing shear wave velocity profiles in the different soils or rocks identified in the study area. All this are beyond the scope of this paper and therefore, a numerical analysis is adopted.

2.3.1. Material strength and the shear wave velocity influence on the site effect

Research shows that shear wave velocity of a soil deposit or a rock increases with depth (Ni, el. 1997). This is also related to increase in the vertical pressure and density (unit weight) and shear strength at a given water saturation level (Waltham, 2009). In Figure 2.1 the graph on the left is a representation of the variation of shear wave velocity (V_S) of a soil or rock profile as the depth from the ground surface increase. The illustration also shows in the equation that the V_S is directly proportional to the shear modulus of the material for instance, as the shear wave velocity of the material increases with depth, the shear modulus increases as well. The graph on the right hand side illustrates how the first mode frequency of the soil profile increases towards the shallow depths of the soil profile thickness. It is therefore equivalent to say the thick layers of the soil deposit transmit shear waves in longer period than the thinner layers. Considering the relation between the frequency and the wavelength of a seismic wave, the equation in the graph on the right hand side implies that the fundamental frequency is achieved when the wavelength is 4 times the height of the material profile. Following the relation between the shear modulus and the angular frequency when a soil deposit or a rock is exposed to a seismic motion can be computed from the relation given in Equation 2.

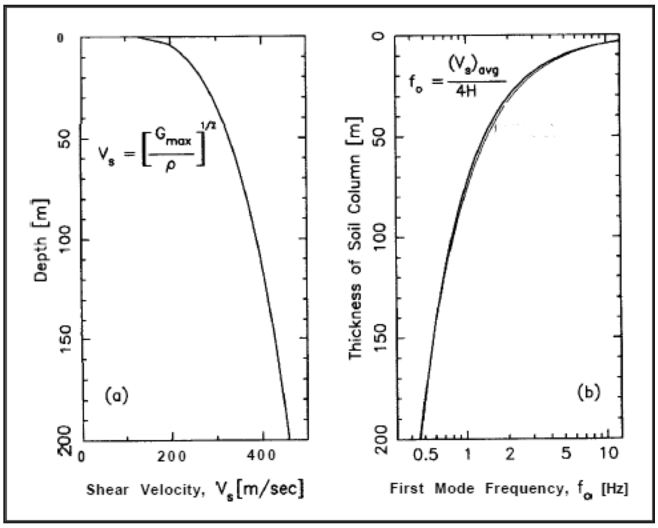


Figure 2. 1: The variation in shear wave velocity, Vs with depth and the relation of the fundamental frequency mode with the layer thickness, H, Adopted from (Ni et al., 1997)

$$\omega_1 = \frac{\pi}{2}\sqrt{\frac{G_{\max}}{\rho h^2}} \qquad \text{(Equation 2)}$$

Where Gmax is the maximum shear modulus, ρ is the density and h as the thickness of the soil column.

Following Vucetic and Dobry (1991) the stress-strain behaviour of the soil which is defined by the shear modulus and damping ratio, determines its response to seismic motion. The modulus and the damping effect are related to the plasticity index (P.I) of the soil. Plasticity index represents the range of water content across which soil is in a plastic state (Vucetic & Dobry, 1991). Soils with a low PI can change from a solid to liquid behaviour with little change in the moisture content. According to Vucetic and Dobry (1991) saturated soils show high spectral acceleration in thin layers than in thick layers at constant P.I. This information is helpful in this study when defining the parameters in the response model as described in Chapter 3.

Several field and numerical techniques have been applied in ground response analyses. Among the field methods include, real earthquake or micro-tremor measurements and in-situ laboratory (numerical) experiments for soil characterization (Semblat, 2000). One dimensional models have successfully been employed in performing linear and non-linear analyse (Vucetic and Dobry, 1991; Tsuda et. al. 2006; Zhang et. al. 2008 and Borcherdt, 2005).

3. RESEARCH METHODOLOGY

3.1. Introduction

This chapter gives the description of the study area and details of the technique which was applied in the ground response analysis. This involves the explanations on the parameterization and the steps taken to define the response model and simulation of ground motion in a soil profile.

3.2. Case study: Muzaffarabad city in Pakistan

This study applies the 8th October 2005 M_W7.7 Kashmir earthquake as the case study with incorporation of the soil thickness data that was collected by (Shafique et al., 2011a) in Muzaffarabad city in Pakistan (see Figure 3.2). This area is located in the north-western region of the Indian subcontinent at the north eastern parts of Pakistan (Figure 3.1). The area is located in one of the world known seismically active zones at the western parts of the Himalayan foothill. The two main tectonic plates namely Eurasian and Indian are responsible for seismicity in this region. The region is mostly characterized with high magnitude strike-slip earthquakes which happen as a result of sudden release of accumulated compressional forces experienced due to plate convergence between Indian (the subducting plate) and Eurasian (the overriding plate). Strong earthquakes greater than M_W8 have been recorded in this region (MonaLisa et al., 2007). Other strong events include the 30 May, 1935 M7.6 earthquake which occurred in Pakistan, killing about 30,000 to 60,000 people, the 17th August 1999, M7.6 Izmit earthquake near the Sea of Marmara, that killed approximately 17,000 people and the most recent event in April 16, 2013 M_W 7.8 earthquake east of Khash, Iran (USGS, 2013a). The area exhibits a soil cover of extensively varied thickness due to rugged terrain which range between 614 -3789 m above sea level. The geology of the area is comprised of sedimentary rocks dominated with shale, sandstone and siltstone.

This study extends the work performed and documented by Shafique et al. (2011) following the historical destructive 8th October 2005 M_W7.7 Kashmir earthquake. About 5,000,000 people were affected in Muzaffarabad, Bagh, Balakot and other areas in the Kashmir region in the northeastern Pakistan. Shafique et. al. (2011) mapped the distribution of damage in the Muzaffarabad city area. The neighbourhoods of the city faced moderately to severely damage after the earthquake especially in the populated zones located in the river basins (Figure 3.2).

Shafique et al. performed a qualitative analysis on the relationship between the observed earthquake damage and other conditions such as the soil thickness, quality of the houses, topography, and sedimentary nature of the geology. Each of these factors showed some relation with the damage distribution pattern in some demarcated zones. The distribution of damage could not be explained by the soil thickness only since at some points, severe damage was observed in some places with thin soil thickness (Figure 3.2). In addition Shafique et. al. also noted that in some zones, severe damage could be associated with the combination of rough terrain and poorly constructed houses despite the thin soil thickness. However, soil thickness was concluded as one of the factors that contributed to seismic amplification and the extent of the observed damage at some places.

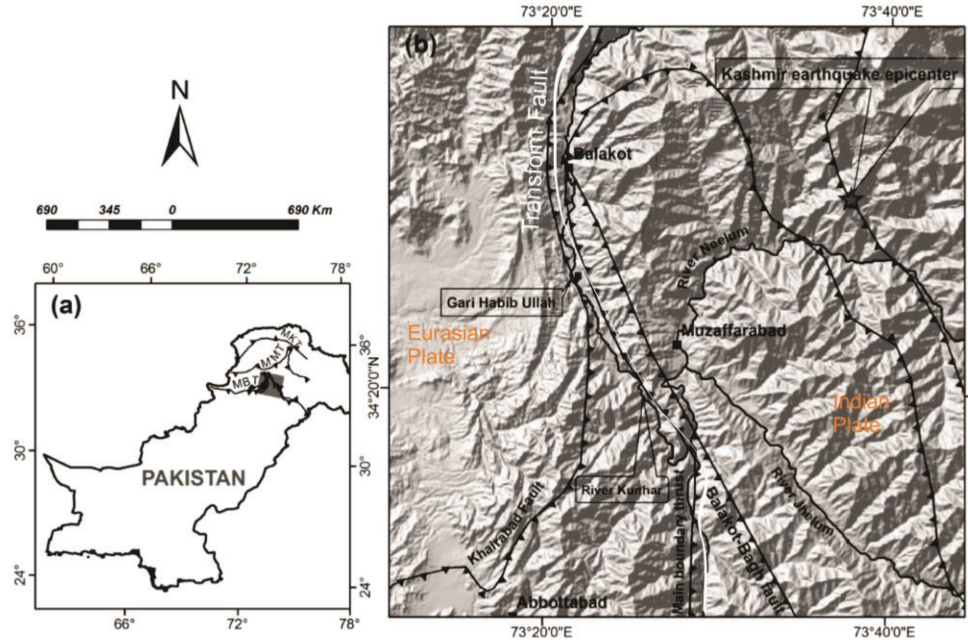


Figure 3. 1: The terrain map of the study area showing the location of the Muzaffarabad City, the major faults, the rivers, the epicentre of the 8th October 2005 M_W7.7 Kashmir earthquake and the tectonic plates in the area. The map was modified from Shafique et al. (2011).

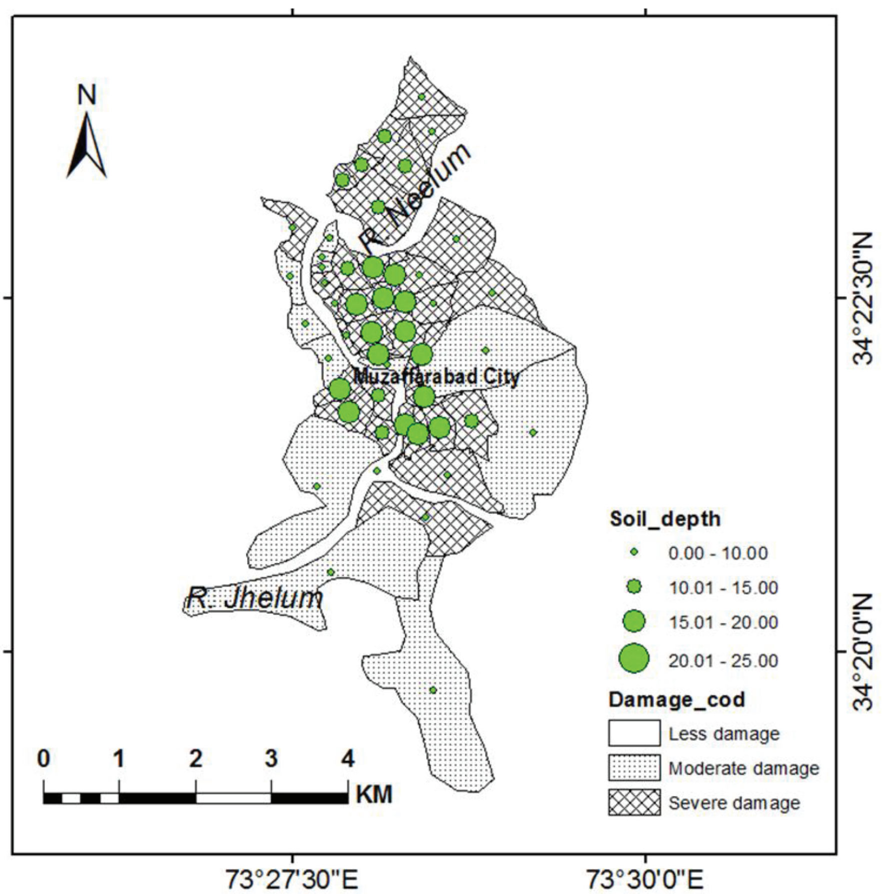


Figure 3.2: Soil depth distribution in the Muzaffarabad City area overlaid on a damage map. The soil data was collected and the damage map data were collected by Shafique et. al. (2011).

3.3. Ground response analysis in 1D model

The details of this approach is described in section 3.3.5 of this chapter. Before the details of the response model and the actual ground response analysis, it is instructive to describe some of the theoretical based mechanisms of the seismic shear wave propagation. This is described in the following paragraphs.

3.3.1. The mechanisms of seismic shear wave propagation

The analysis on seismic wave propagation in this study puts into consideration the three principle mechanisms of shear wave energy components as described in Tsang et. al. (2006) and Phanikanth et. al. (2011). The first component is the transmission of the seismic shear wave signals across the interface between two media for example the bedrock and the soil layer or the intermediate layers between the bedrock and the surface of the soil layer. The analysis in this study is based on the response of a seismic shear wave signal propagated from an elastic bedrock through the soil layer and then reaching the surface. The second component is the reflection of the seismic shear wave signals from the interface or within the soil medium or even from the soil surface. This component influences several things; the amount of seismic energy that finally reach at the soil surface, the amplitude of motion, and the amount of energy that remains stack within the soil layer. The third component is the hysteretic energy dissipation of the shear waves but not tackled in this study, it accounts for non-linear soil response to seismic motion due to shear strain as the shear waves are propagated vertically from the bedrock through horizontal layers to the soft ground surface. This component is influenced by the shear modulus and damping factor of the soil material. Figure 3.3 is an illustration of these mechanisms of shear wave propagation in one dimensional path.

When a strong motion is induced in the bedrock, the shear waves are propagated along a vertical path approaching the interface between the soil layer and the bedrock with a displacement amplitude denoted herein as A_i. Part of the energy of the wave motion is transmitted across the interface propagating through the soil layer of thickness *h* with a displacement amplitude denoted as A_T (Equation 3) within the layer. According to Tsang et. al. (2006) the transmitted wave amplitude denoted as A_T and the reflected wave amplitude A_R in the soil layer and bedrock are defined by the Equations 3 and 4 respectively.

$$A_T = \frac{2\alpha}{(1+\alpha)} A_i \qquad \text{(Equation 3)}$$

$$A_R = \frac{\alpha - 1}{\alpha + 1} A_i \qquad \text{(Equation 4)}$$

Where the alpha, α defines the impedance contrast of the soil-rock layers which determines the amount of energy reflected and or dissipated at the interface (Govindaraju & Bhattacharya, 2012) as expressed in Equation 5).

$$\alpha = \frac{\gamma_2 V_2}{\gamma_1 V_1} \qquad \text{(Equation 5)}$$

Where γ and V are the average density and mean shear wave velocity of the respective layers denoted by the subscript values. The subscript 1 represents the soil layer or intermediate layers in a soil profile and 2 represents the outcropping rock (see Figure 3.3). The impedance contrast, takes into account the degradation of the stiffness of the soil (Vucetic and Dobry, 1991) which influences its stress-strain behaviour when exposed to seismic motion. Some of the parameters that change as the seismic wave is propagated from the bedrock through the overlying soil layer and later to the ground surface include; the amplitude of the wave motion, the frequency content and also the period of the wave. The upward moving shear wave approaches the surface with the amplitude denoted as A_0 (Equation 7) after travelling through the soil layer at time T_0, which is expressed as an inverse function of the peak frequency mode of the soil layer (Equation 6).

$$T_0 = \frac{4h}{V_s} \qquad \text{(Equation 6)}$$

Where h is the soil thickness. The induced motion at the ground surface is accounts for the damping factor which is also referred to as critical or material damping (Tezcan et. al., 2002 and Tsang et. al. 2006) expressed as:

$$\beta = \left(e^{(-\pi\zeta)}\right) \qquad \text{(Equation 7)}$$

Where ζ is the damping ratio.

$$A_0 = \left(\beta^{(1/2)} A_T\right) \qquad \text{(Equation 8)}$$

Soils act as a filter and modify the characteristics of the ground motion (Kokusho, 2011) at different sites. This happens with the influence of the soil impedance contrast (Equation 5) which is as a result of change in the velocity and density between the layers as illustrated in Figure 3.3, where V_S1, γ 1 and V_S2, γ 2 represent the velocity and unit weight in the soil and in the rock respectively.

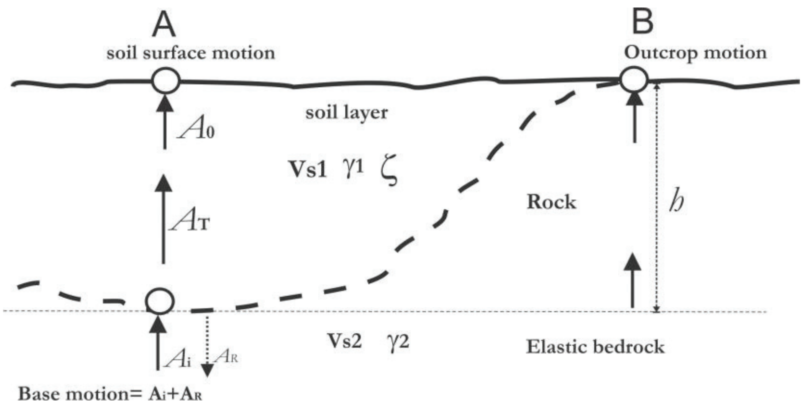


Figure 3.3: A schematic illustration of the mechanism of propagation of vertical seismic shear waves through the soil layer on an elastic bedrock. The letters, A_i, A_T, and A_0 symblize the amplitudes of the incidence seismic wave motion, the amplitude of the transmitted signal in the soil layer and the amplitude of the wave motion that reach the surface of the soil layer respectively.

3.3.2. Characterization of the seismic response model

Prior to the actual analysis, some parameters are specified in the response model. Among the parameters involves the keys ones such as the shear wave velocity, unit weight, shear modulus, modulus-damping soil model, the input motion characteristics, the number of layers in the soil profile and layer thickness. The specification on the parameters in the response model are entirely based on the literature review as shown in Chapter 2. This allows us to have more realistic prediction of the seismic ground motions based on the defined soil characteristics. This step is important since the response model is dependent on the limits defined in these parameters.

The analysis was conducted by applying two layer models of soil profile with definition of the key input parameters shown in Table 3.1. The shear velocity was applied as the control parameter in the determination of the average threshold of the other parameters in the response model in Table 3.1, with estimated values from the global literature. Each of the soil types or sites is characterized with its estimated value for the shear modulus, shear wave velocity, and the total unit weight (relative density). Investigation on the impact of soil thickness variation in the site amplification phenomenon at the three soil site categories, was performed based on the characteristics of the response model. The details of the response model are explained in the following paragraph.

Soil layer thickness

The ground response analysis was performed in each of the soil site categories by varying the soil layer thickness by 2.5m. Since we are dealing with uniform soil layers, with minimal variation in the other physical characteristics, this interval of thickness variation is anticipated to show minimal change in the amplification factor in response model applied in this study. The comparison on the response spectra and the amplification factor in every scenario was done in two different cases; one of the cases is when the underlying bedrock is considered as weak and the other case is when the bedrock is considered as firm based on the definition of the Vs30 value of the rock (Table 3.1). A total number of 12 simulations scenarios in one type of the soil site per the bedrock type were performed considering the thinnest soil layer of 2.5m and the thickest layer of 30m at intervals of 2.5m. This was done to ensure that the minimum (2.5m) and maximum (25m) of soil layers thickness, which was observed in the Muzafarrabad City as documented in Shafique et. al (2011), were represented for investigation in this study, which are later used in producing the amplification maps.

Two layer response models of elastic soil layer laying on an elastic bedrock of infinite depth, were applied in the evaluation of the relationship between soil thickness and site amplification with respect to the other characteristics indicated in Table 3.1. The amplification factor at varied soil thickness were computed as explained in the above section. From the relationship that was established between the soil thickness and the amplification factor, the maps showing the spatial distribution damage and the associated amplification factor were generated. An extended discussion on the relation between the distribution of damage pattern, amplification factor and the soil thickness is found in chapter 4.

The total unit weight of the soil and bedrock layers

The unit weight parameter defined in the response model can also be referred to as the weight of a unit volume of soil which expressed in SI units, kilo newton per cubic meter (kN/m^3). This parameter is influenced by the lithology and depth of soil deposit due to vertical pressure increase with the depth of the soil profile (MonaLisa & Khan, 2013). Younger soils occurring at shallow depths are likely to show low unit weight as compared to the deep occurring and consolidated layers due to the overburden. Unit weight can be calculated using the relation;

$$\gamma_d = \rho_d g \qquad \text{(Equation 9)}$$

where *d* denotes the soil depth (MonaLisa & Khan, 2013). In this study, different soil types were defined with estimated unit weight whereby 15kN/m^3 was used for the Soil type E, 17kN/m^3 for the Soil type D, and 19kN/m^3 for the Soil type C. The unit weight for the weak bedrock given as 20kN/m^3 and 24kN/m^3 for the firm bedrock (Table 3.1). The estimation of these values is based on the value of the Vs30 in each of the soil categories.

Shear modulus and Plasticity Index Value
Also known as modulus of rigidity, this parameter explains elastic properties of a material (Kawase, 2003). Expressed as G_{max}, shear modulus is expressed as a measure of the resistance of a material to shearing strains (Vucetic & Dobry, 1991). The shear modulus of soil (Equation 10) is a function of its unit weight, ρ and the square of the shear wave velocity, V_s (Vucetic & Dobry, 1991) which is used in the calculation of the response.

$$G_{\max} = \rho V_s^{\,2} \quad \text{(Equation 10)}$$

In this study the Soil type E are defined with shear modulus of 34MPa, 136MPa for the Soil type D and 484MPa for the Soil type C. Following the study by Vucetic and Dobry (1991) defining the value for the shear modulus and also Plasticity Index value in this study in every simulation is important since these parameters influence the soil shear-strain behaviour when exposed to a seismic motion hence the limit of the ground motion and the shear-strain relation curves shown in (Figure 3.5). When the shear modulus and the damping factor is nearly constant that is; when the shear strain is less than 10^{-4}, the amplification factor is nearly constant as well (Kawase, 2003; Suetomi et al., 2004). This imply that very hard rock or soils defined with high shear wave velocity, high shear strength and higher density are likely to show minimal amplification effect.

Table 3. 1: The input parameter in the response model

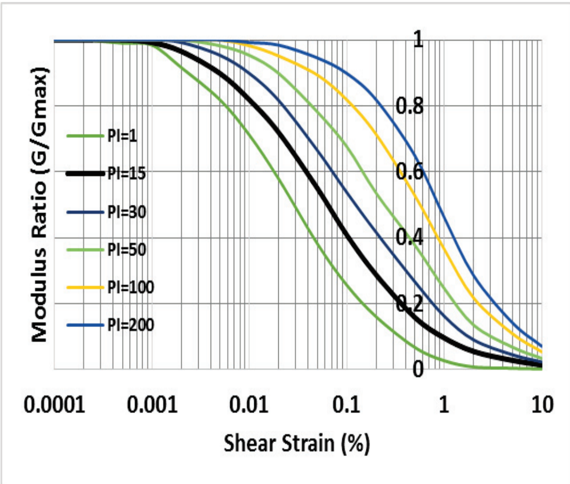
	Site type	Unit weight, δ (kN/m3)	(Gmax) (MPa)	(Vs30) (m/sec)	Plasticity Index (%)
1	Soil type E	15	34	150	15
2	Soil type D	17	136	280	15
3	Soil type C	19	484	500	15
Bedrock type					
1	weak bedrock	20	1147	750	
2	Firm bedrock	24	4136	1300	

*The different soil categories in this table are classified based on the NEHRP (2009 edition) (http://earthquake.usgs.gov/regional/nca/soiltype) using the V_S30 parameter. The literature describing the characteristics of each soil class is given in Chapter 2. The shear modulus (G_{max}) is computed from the product of the shear velocity squared and the unit weight. The PI is kept low in all the soil classes to ensure that the considered moisture content has negligible effect on the soil strength and also on the response models.

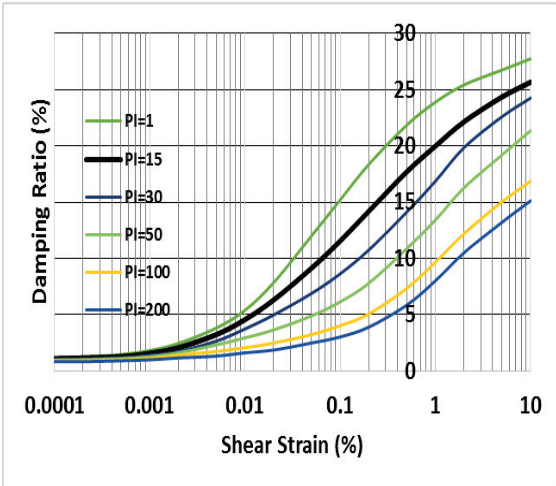
3.3.3. The setup of the response model

Two layers 1D response model was applied in the analysis; one layer of soil with defined thickness and the bedrock layer of infinite thickness. The details of the soil properties in the response models are summarized in Table 3.1. Each of the soil types in the response model were defined the unit weight, the shear modulus (computed from Equation 10), shear wave velocity, plasticity index value and the equivalent damping ratio in all the soil (ζ =5%). The damping ratio was defined in each soil type to emulate the dissipation of seismic energy in the computation of the response spectra (Naeim & Kircher, 2001).

Plasticity index value of the soil is a parameter that is known to influence ground response in seismic stress. The soil models by Vucetic and Dobry (1991) representing the modulus reduction and damping relationship curves with respect to the PI were utilized in the analysis to model the soils defined in this study. According to this soil model, the PI value determines the stress-strain behaviour of soils in a wide range of PI (%) values (0, 10, 30, 50, 100 and 200) (Vucetic & Dobry, 1991). The aim of this study was to establish the influence of soil thickness and therefore the analysis was done by applying low PI value of 15% in the response model. The representation of the soil model in this study showing the relationship between the modulus-reduction and damping ratio is shown in Figure 3.5. The PI value for the bedrock was set at zero (0) to imitate non silt or clay behaviour. The Edushake program does not support the computation of ground response with the influence of the pore water pressure, we assume that there is no influence of the soil moisture content and therefore, the level of ground water was set at zero



a)



b)

Figure 3.4: Vucetic and Dobry (1991) soil model applied in the analysis. a) Modulus reduction curve and b) damping ratio curves. The dark plot line shows the location of the soil model defined in this study with a P.I of 15%.

Figure 3.6 shows the graphical representation of the response model. The figure gives the impression of vertical variation of the soil properties shown with the attributes; number of layers in the response model, description of the layers, input motion, output motion, the shear wave velocity, and the average unit weight at each layer. This graphical representation gives the analyst a quick impression of the response model setup and the points where the soil properties is changing. The difference in the width of the shear wave velocity and the unit weight columns imply the difference in the value of the attributes. The open ovals at the top of the bedrock layer and on top of the soil layers shows the input motion and the output motions. In this method, the input motions are either defined as either “with-in motions” or “outcrop motions”. The analysis was concerned with the outcrop motion that is why we have an open oval presented at the bedrock layer in the motion attribute. The outcrop motion at the surface of the outcropping bedrock is important in the computation of the amplification of the seismic motion on the surface of the soil layers. The other open ovals shown in the attribute “output” indicate the point where the output motions are computed. This study was concerned with the motion at the surface of the soil layer and at the surface of the outcropping bedrock that is why we have open ovals at the surface of the two layers. Any computation of “with-in motions” could be indicated with red ovals. The shaded columns indicate that the shear wave velocity and the higher unit weight of the bedrock is larger than in the soil layer. This set up is used to investigate the site amplification phenomenon. This figure is important for confirmation so that the output can be discussed as per the specification of the response model. This is because different ground responses are observed depending on the location of the induced motion.

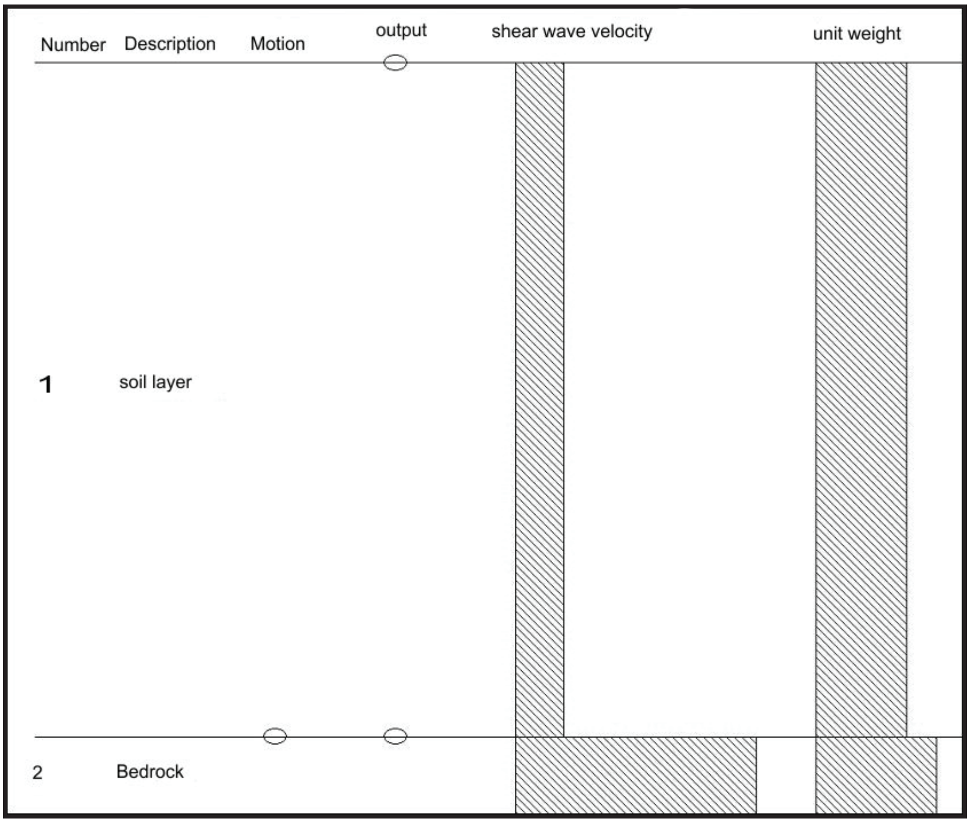


Figure 3.5: The soil profile of a sample response model with visualization of the distribution of some of the parameters assigned in the soil layer and in the outcrop bedrock layer. The width of the column suggests the value of the labelled attribute.

3.3.4. Selection of the Input ground motion

One input motion was induced at the base of the soil layer. The Northridge 17/01/1994 M_W 6.7 earthquake motion was introduced as the input motion with close similarity in the characteristics of the 8th October, 2005 Kashmir Earthquake (Rossetto & Peiris, 2009). Its mean period is 0.31 sec, which means it is a sufficient input motion as recommended by Phanikanth et al. (2011) for the analysis. The motion is defined with other parameter such as the peak displacement of 4.2 cm and peak velocity of 15cm/sec (Figure 3.4 and Table 3.2). The earthquake-motion was recorded on a rock outcrop in Topanga Fire station, California, U.S.A in 1994.

The selection of the input motion was based on the PGA of the available ground motions in Edushake database. It is well known that the PGA vary from one place to another during an earthquake event. The parameter is also applied in producing shake maps since it defines the intensity of the ground shaking during an earthquake in different geotechnical conditions. The PGA shows good correlation with the Modified Mercalli Intensity scale (Wald et al., 1999b) in low to moderate earthquake intensity. However, the peak ground velocity shows closer correlation with higher intensity ground shaking (Wald et al., 1999b). Previous research shows that applying very high or very low PGA influences the behaviour of the response model see for example in Suetomi (2004); Tezcan et al. (2002); and Shima (1978). There is no known documentation, to the author's knowledge, on the criteria on how to select the input motion but Idriss (1990) and Idriss (1991) recommend input motions of PGA range between 0.2 and 0.3g for numerical analyses. This range of PGA minimizes unusual soil response due to very strong shear strains, for instance the unusual amplification of the output motion when too low input motion is applied in the simulation and complex non-linear behaviour of the soils when the input motion is too high. The

Northridge Earthquake motion was applied in this study, defined with PGA =0.33g, velocity of 47.8cm/sec and a displacement of 4.09cm in time domain.

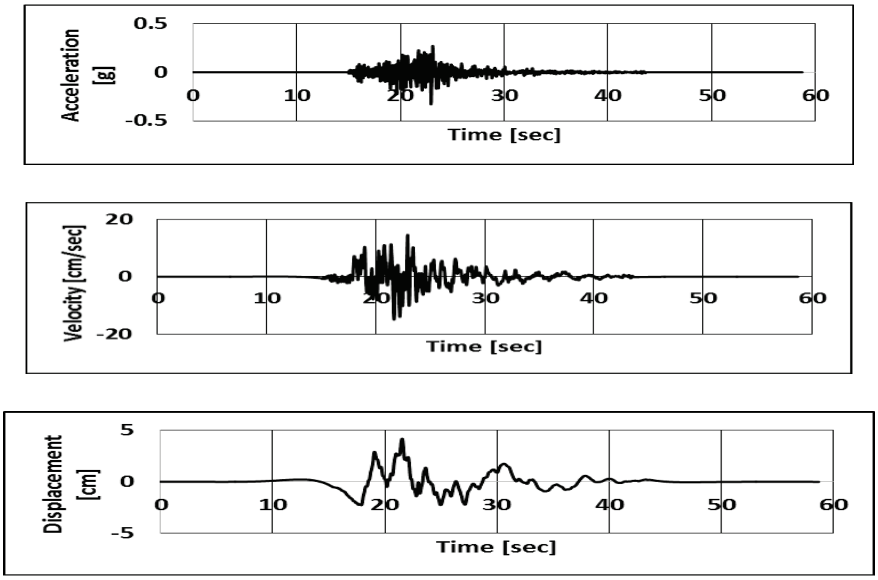


Figure 3. 6: Acceleration, velocity and displacement time history of the input motion applied in the analysis, Northridge 17/01/1994 M_W 6.7 earthquake motion. The history plots shows at least 20sec of ground motions which is sufficient to cause excitation with a peak at around 22sec.

Table 3. 2: Other parameters of the input Motion

Parameter	Value
Peak acceleration[g]	0.33
Peak velocity[cm/sec]	15.00
Peak displacement[cm]	4.20
RMS acceleration[g]	0.08
Arias intensity [cm/sec]	99.78
Response spectrum intensity [g^2]	1.32
Predominant period [sec]	0.31
Mean period[sec]	0.31
Bracketed duration[sec]	14.24
Trifunac duration[sec]	8.76
Spectral acceleration at 0.3 sec[g]	0.94
Spectral acceleration at 1.0 sec [g]	0.12
Characteristic intensity [g^1.5*1.5sec^0.5]	0.07

Once the soil properties are defined in the response model, the input motion is selected and the overall setup of the response model is confirmed, the next step was to simulate the input motion into the response model to compute for the ground motions.

3.3.5. Simulation and computation of the ground motions

The simulation of the seismic shear wave motion was performed in in Edushake program by inducing the Northridge Earthquake motion into the response model described in section 3.3.4. Simulation of the seismic wave motion in this case assumes the acoustic wave propagation theory (Schuster, 2007). The seismic wave motion is propagated from a relatively high shear wave velocity bedrock layer into a low shear wave velocity soil layer. The solution of the input seismic shear wave equation is performed in a Fourier transformation technique (Schnabel et al., 1972).

The analysis was performed by applying the equivalent-linear method (Schnabel et. al., 1972) to compute for the nonlinear soil response. This method is utilized to approximate for the inelastic soil response by applying an average shear modulus and damping ratio within the soil layer at an equivalent shear stress-strain level (Seed & Idriss, 1970). This technique was first implemented by Schnabel et. al. (1972) in SHAKE 91 code and in other subsequent versions (Idriss & Sun, 1992). Edushake has been widely applied in ground response analysis in varied ground conditions (Hori & Ichimura, 2008; Idriss & Sun, 1992; Mok et al., 1998; MonaLisa & Khan, 2013). The program is therefore well-grounded in performing this kind of analysis in this study. The program is also user friendly, has few requirements but one of the disadvantage is that the ground motions database cannot be modified by the user (Mok et. al., 1998).

To account for the nonlinearity of the soil, the equivalent linear method was performed in an iterative procedure (Schnabel et al., 1972). The first iteration step was performed by using the shear modulus and the damping ratios that correspond to the effective shear strain ratio of 0.65 (see Figure 3.5). The computed strain at each of the subsequent iterations is usually normalized with the modulus and damping values at that step. The effective shear strain is computed as a fraction of the maximum shear strain which is then used to determine the closest shear modulus reduction-damping relationship defined by the soil model shown in Figure 3.5. The maximum shear strain reached in the process is associated with the maximum number of iteration performed in the process. Following the work of MonaLisa & Khan (2013) and Idriss & Sun (1992) an approximate of 5 to 8 iterations is essentially enough to reach the appropriate equivalent strain level. This is defined when there is very minimal change between the computed shear modulus ratio and the shear strain from one iteration to the next (Kawase, 2003).

In order to determine the amplification factor of the seismic motion on the a soil layer, the transfer function was computed in Edushake based on the function defined by Schnabel et al. (1972) modified by Idriss and Sun (1992). The computation is expressed analytically as the transfer function of the ratio of the amplitudes Fourier spectrum of the soil surface motion and the corresponding amplitude Fourier spectrum of the nearby rock outcrop. The transfer function can be expressed in terms of Euler formula (Semblat, 2000).

$$|F_{1,2}(\omega)| = [\cos^2 p_1 h + q^2 \sin^2 p_1 h]^{-1/2} \qquad \text{(Equation 11)}$$

$$\text{With } p_1 = \frac{\omega \cos\alpha_1}{V_1} \text{ and } q = \sqrt{\frac{\rho_1 \mu_1}{\rho_2 \mu_2} \frac{\cos\alpha_1}{\cos\alpha_2}}$$

Where ω is the angular frequency of the harmonic wave, α_1 and α_2 are the angles of incidence (with respect to the vertical direction of the seismic shear wave propagation) in the soil layer and the rock outcrop respectively, p_1 represents a function of the complex angular wave number, $k = (\omega / V_1)$ which depends on the soil damping ratio. This means that Soil type E (lowest velocity) is most likely to give a relatively larger wave number (p_1 -value) than in the hard soils (higher velocity). The p_1 value is also dependent on the period of the seismic motion in the respective soil layer. The ratio of the product of the unit weight ρ and the shear modulus μ gives the impedance contrast between the soil material and the rock. The parameter denoted as q is a function of the complex impedance ratio (http://www.proshake.com/userman.pdf) expressed in terms of the product of the square root of the impedance ratio and the ratio of the soil-rock incident angle. It means that when we have very large p_1

and very small q then, a significantly high site amplification is expected. Equation 11 is already expressed as the final result of dividing the amplitude of motion on the soil layer by the amplitude of the motion at the outcropping rock. We therefore obtain an absolute value of the amplification factor which is an inverse of the square root of the sum of the squares of the real number (in-phase response) $\cos^2(p_1 h)$ and imaginary part (out of phase) ($q^2 \sin^2 p_1 h$) (Bernath, 2005).

Following Kramer (1996), Kawase (2003), Ni et al. (2000) and Gosar et al. (2001) the maximum amplification is observed at the fundamental frequency of the soil layer defined in Equation 12. In order to examine the effect of soil thickness on the seismic amplification, we considered the amplitude at the undamped fundamental frequency. The maximum amplification factor corresponds to the resonance frequency of the soil layer which is expressed in Equation 12.

$$f_0 = \frac{V_s}{4h} \qquad \text{(Equation 12)}$$

f_0 is the natural frequency of the soil layer V_s is the shear wave velocity and h is the layer thickness. This study performs investigation on the variation of the amplitude at the lowest frequency of the soil layer that is; first mode frequency. The computations are performed for the soil layers at minimum of 2.5m to a maximum thickness of 30m overlaying the bedrock.

Estimating the fundamental frequency of the soil was possible using Equation 12 even before the simulation. Suppose we have the soft soil with V_s =150m/s at a layer thickness of 30m, the first mode frequency of that layer is estimated to be around 1.3Hz. This estimation implies that the lowest frequencies in the Soil type E would be around 1.3Hz. The fundamental frequency in the thinnest layer of 2.5m would be around 16Hz in the same soil type in the similar computation. Evaluating the change in the peak amplitude of seismic motion on the soil surface at the first mode frequency is important in this analysis because when we know the fundamental frequency at a particular site, we can design structures which are less prone to earthquake damage by considering its natural frequency at that site.

To plot the amplification spectra, the peak frequency defined in Equation 12 for each of the soil layers was considered. For example to plot the Fourier spectrum of amplification at 2.5m of the soft soil and Soil type D soil with estimated fundamental frequency of 15Hz and 28Hz respectively, the sampling number of frequencies was set at a maximum of 600 with the frequency steps of 0.1Hz. This means the maximum frequency presented in the spectrum is about 60Hz that is defined as $(\{601-1\} * 0.1Hz) = 60Hz$ (http://www.proshake.com/userman.pdf). The same thing was done in the computation of the amplification factor in the soil type C but in this case the maximum number of sampling frequencies was set higher at 1000 at the same frequency step of 0.1Hz to represent a maximum frequency of 100Hz even though the estimated peak frequency of the thinnest soil type C is around 50Hz. This value was set higher to include the higher order frequencies in the high velocity soils and also for better visualization purpose. The next chapter is a detailed description and discussions on the results derived from the methodology presented in this chapter.

4. RESULTS AND DISCUSSIONS

4.1. Introduction

This section presents the results and discussion on ground response analysis in 1D approach. A comprehensive comparison of results on the main parameters of the seismic response on the different soil types were is presented. The results are based on numerical computation. One dimensional site response analyses were performed in Edushake program to evaluate seismic characteristics on the surface different soil thicknesses. The evaluations were performed on the soil type E (150m/s), soil type D (280m/s), and soil type C (500m/s). This chapter presents the results that were obtained from the analyses and the discussions.

4.2. The evaluation of soil response in varied layer thickness

The process of evaluation on the influence of the soil characteristics such as the soil thickness, shear velocity of the soil, the density (unit weight), and the soil type was performed in several simulations. Three sets of simulation involving the soil types with varied unit weights and shear velocities (Table 3.1) were considered for investigation. These included the soil type C (Vs 500m/s, 19kN/m3), soil type D (280m/s, 17kN/m3) and soil type E (150m/s, 15kN/m3). The simulation of the earthquake motion in each set of the soil types was done in varied soil thickness from the minimum of 2.5m up to a maximum of 30m. The results presented here include mainly the ground motion parameters that describe the intensity of the seismic motion which involve; the spectral acceleration presented in response spectra, peak ground acceleration, peak ground velocity, and the seismic motion amplification factor. The later parameter is later applied in mapping the predicted seismic amplification based on the soil thickness. The process involved in computing the amplification factor in each soil layer is described in the following paragraphs.

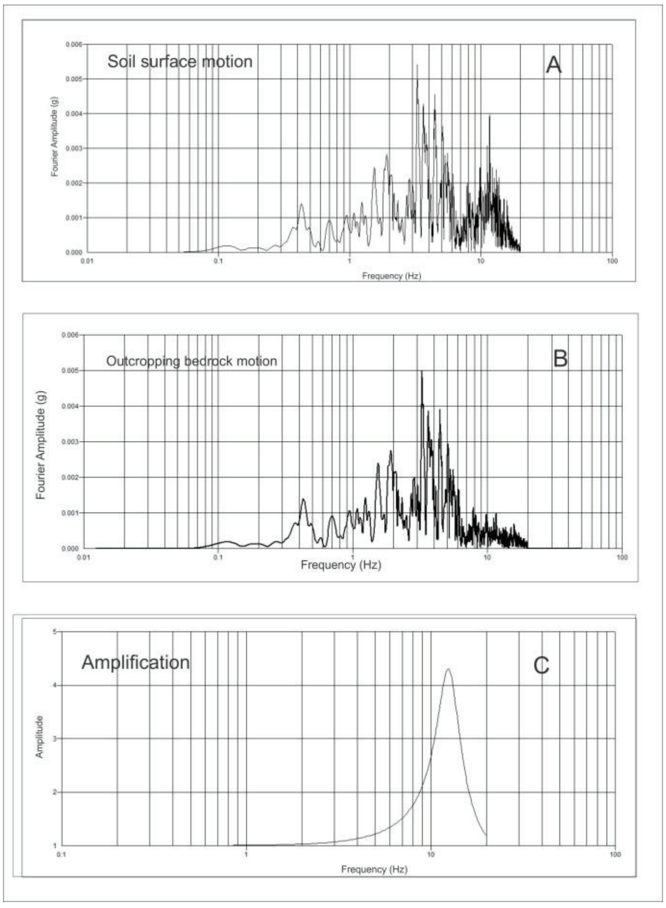


Figure 4. 1: The amplification factor of a seismic motion on the surface of soil motion as it is computed in Edushake program whereby A/B=C

The response model shown in Figure 3.6 is used to explain how the amplification of seismic motions was computed in each of the soil types. The simulation process involved Fourier transformation of the Northridge 17/01/1994 M_W 6.7 earthquake motion which was introduced as the input motion. Simulating this motion into the response model of a single layer of soil, (see Figure 3.6), results to surface motion of the amplitude represented in the Fourier amplitude spectrum shown in Figure 4.1 A. The difference between the soil surface motion and the motion at the outcropping bedrock can be seen in Figure 3.3 whereby, point A represents the surface motion while point B represent the seismic motion of the nearby outcrop. The simulation of the input motion therefore, induces the motion at the outcropping bedrock. The two main parameters applied in the computation of the amplification factor are the Fourier amplitude spectrum of the soil surface motion and the corresponding Fourier amplitude spectrum of the outcropping bedrock surface motion. The amplification factor from this computation is taken as the ratio between the soil surface motion and the outcropping bedrock motion based on Figure 4.1.

4.3. Response spectra

The response spectral were used to show the estimated acceleration of the soil surface motion with relation to the natural frequency of the soil layer. Figure 4.2 presents the response spectra at the soil layer thicknesses of 2.5m to 27.5m of the different soil types with 5% structural damping of the output motion.

The Soil type E shows the maximum acceleration of around 2.7 to 2.8g at a layer thickness of 7.5m at 3.5Hz in the weak to firm bedrock respectively, which imply that the bedrock outcrop motion was amplified to about eight times from 0.33g (Figure 4.2). The Soil type D soil overlaying the firm bedrock shows the maximum acceleration of 2.5 to 3.7g at the same natural frequency of 3.5Hz but in varied soil layer thickness of 12.5m and 17.5m respectively. The acceleration of this soil at the firm bedrock is relatively higher than in the soil type E even though the shear velocity of the later soil is lower. This is probably due to minimal damping effect in this soil which leads to higher energy reaching at the surface of the soil layer hence higher acceleration in soil type D. The influence of the stiffness of the bedrock is observed with higher acceleration at the firm bedrock site. It is also observed that at short period (less than 0.2sec), thin layers (<10m) experience a higher acceleration than the thicker layers in the soil type E. These observation imply that in real ground scenario, there would be minimal acceleration at some points especially in the thin layers of Soil type E due to damping affect and less effective pressure when the seismic wave is propagated through the soil layer.

At short period < 0.1sec at 10Hz, the thin layers, less than 7.5m of the Soil type E in both the cases of the underlying weak and the firm rock, there is a slight increase in spectral acceleration upto 1.0g. An increase in the spectral acceleration for the 7.5m layer at around 0.3sec is as a result of the maximum acceleration bedrock motion. The peak ground acceleration and peak ground velocity reached at different layers of the soils can be seen in Appendix 2 and Appendix 3 respectively. These parameter were computed at the soil surface. Different soils showed varied minimum and the maximum PGA whereby the soil type E (150m/s) gave PGA of 0.32-0.63g, soil type D (280m/s) gave 0.37-0.60g and for the soil type C (500m/s) the PGA was 0.39-0.58g. It was observed that the overall PGA on the soil surface decreased as the soil thickness increased and vice versa. The PGV increases steadily as the soil layer increases.

The spectral acceleration in different soils is vary from the higher frequency mode of around 10Hz in the thin layers to the low frequency of around 1Hz in the thick layers. The thickness of the soil layers is the major contributor in the difference in spectral acceleration. The likely cause of lower spectral acceleration at the soil type E soils (Vs 150m/s) laying on weak bedrock, could be associated with high damping effect due to the higher shear strains in this soil than in the other classes. The increase in shear velocity from the soft to the very dense soils is also another cause of the shift in natural frequencies at different soil types. The soil type C defined with Vs 500m/s exhibit very weak non linearity in the response especially in the case of the weak bedrock which is defined with shear velocity of 750m/s. This means that buildings on this soil type are likely to experience very low amplification of the spectral acceleration than in the soil type D and soil type C.

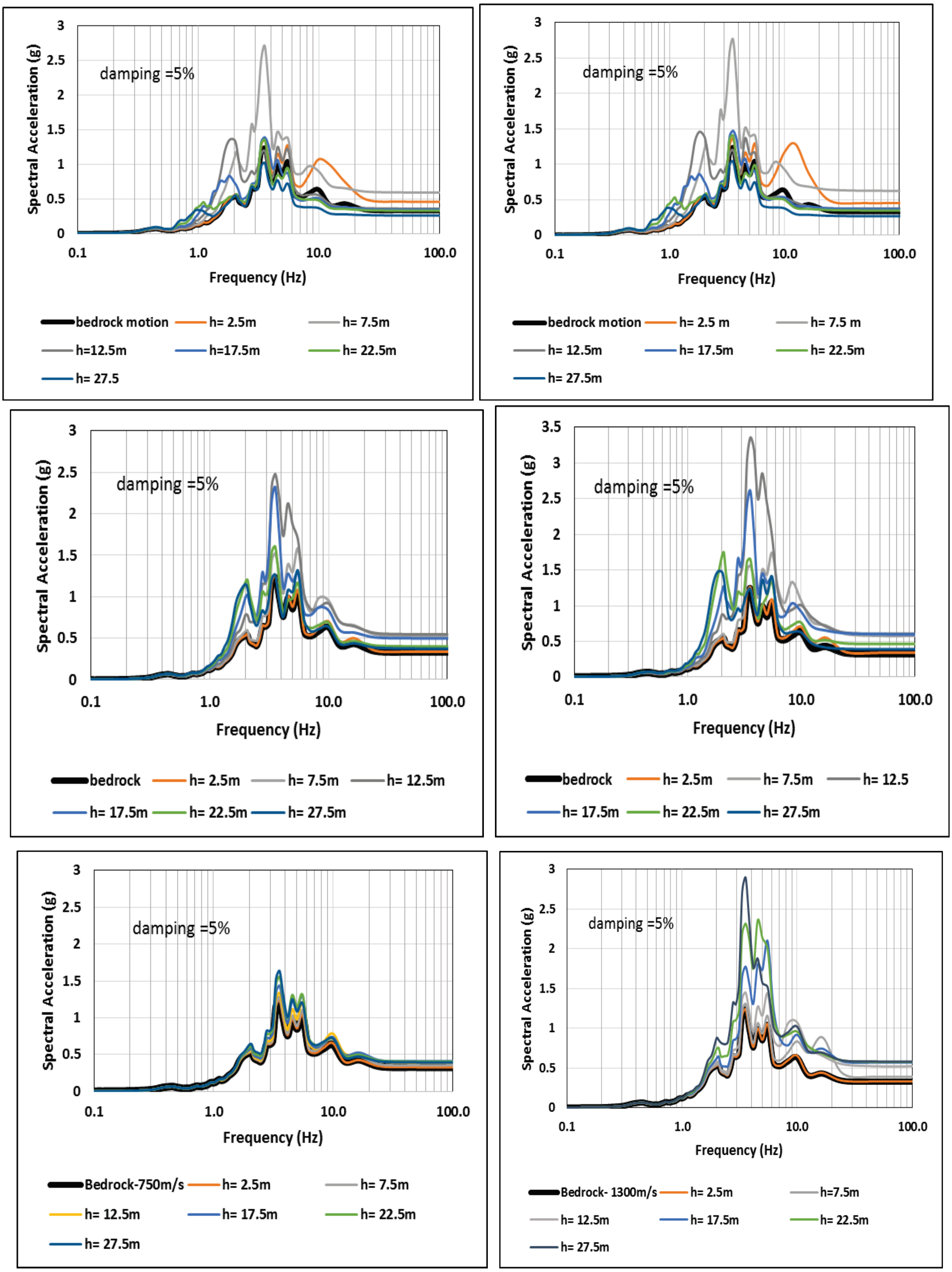


Figure 4. 2: The response spectra in varied soil sites Soil type E =*first row,* Soil type D =*second row* and the Soil type C =*third row*). The first column shows the response spectra of the soils overlaying weak outcropping bedrock while the second column is for the soils overlaying the firm outcropping bedrock. The solid black line shows the response spectrum of the input motion (PGA=0.33g).

The overall spectra acceleration in all the soil types overlaying on the firm bedrock site (Figure 4.2) is higher than in the weak bedrock site. There is averagely lower PGA observed in the thin layers at least <10m of Soil type C (0.33 to 0.47g) and Soil type D (0.34 to 0.57g) than in the Soil type E (0.45 to 0.66g) in the thin layers. These values can be observed at the intercept of the curves at frequency of 100Hz in Figure 4.1 or in the Appendix 2. The very dense soils (soil type C), are not expected to show high amplification compared to the soil type E (soft) and soil type D (stiff). In addition, the response spectra imply that there is lower chances of de-amplification of the seismic motion at the surface of the higher modulus soils that is; the soil type D and soil type C since the response spectra for these soils are higher than in the bedrock (see Figure 4.2). From the response spectra in all the sites, there is a clear evidence of the influence of the bedrock stiffness or rigidity which is defined by the shear velocity. The firm bedrock (Vs 1300m/s) tends to give relatively higher spectral acceleration of the soil than in the case of weak bedrock (Vs 750m/s). The increase in the impedance contrast and decrease in the shear modulus from weak to firm bedrock is deemed to be the contributing factor of the difference in the response spectra. The response of the soils at different layer thickness is also evident. These findings show consistence with empirical studies (Dobry & Iai, 2012; Ni et al., 2000; Tsang et al., 2006).

4.4. Amplification Spectra

4.4.1. Sensitivity analysis

The general ground response is dependent on some conditions. In order to evaluate get the true of that statement, a sensitivity analysis was done to evaluate the influence of the soil class and the bedrock type which were believed to be the key factors of great influence on response model with regard to the site amplification at varied soil thicknesses.

4.4.1.1. The influence of the Soil type on the ground response

The influence of the soil type on the ground response to earthquake was investigated by performing simulation same earthquake motion in Edushake program using the soil response models in different soil types. Equal soil layer thickness of 10m was considered in each of the soil types in this investigation. From the results presented in Figure 4.3, the amplification factor of the seismic motion at the soil type E is relatively higher (3.9) at a frequency of about 3.2Hz as compared to the soil types D which shows amplification factor of 3.7 at 5Hz and 2.7 at 12Hz in the soil type C. The difference in horizontal acceleration these soil types is interpreted as one of the contributing factor in the variation of the amplification factor in the three soil types. This is associated with the increase in the shear velocities of the soils from the soil type E to soil type C. This relation accounted in the Equation 11 which shows that when we have high shear velocity soils, the amplification tends to be lower than in the low velocity soils. The other factor is the difference in the natural frequencies where the soil reach a maximum amplification at the same layer thickness. This is observed to be decreasing as the shear velocity of the soils decreases. The decreasing trend in the amplification factor from the soil type E to soil type D and C is related to the increasing shear modulus in

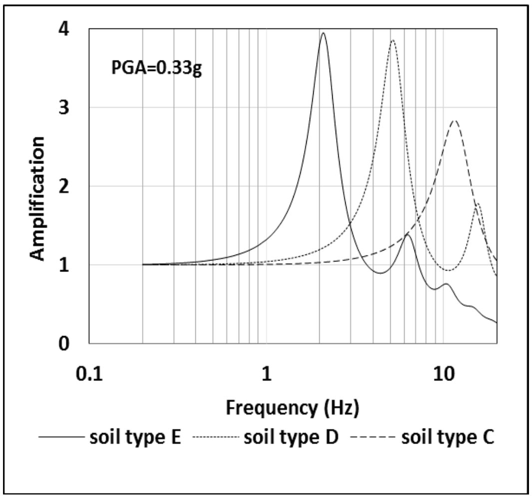


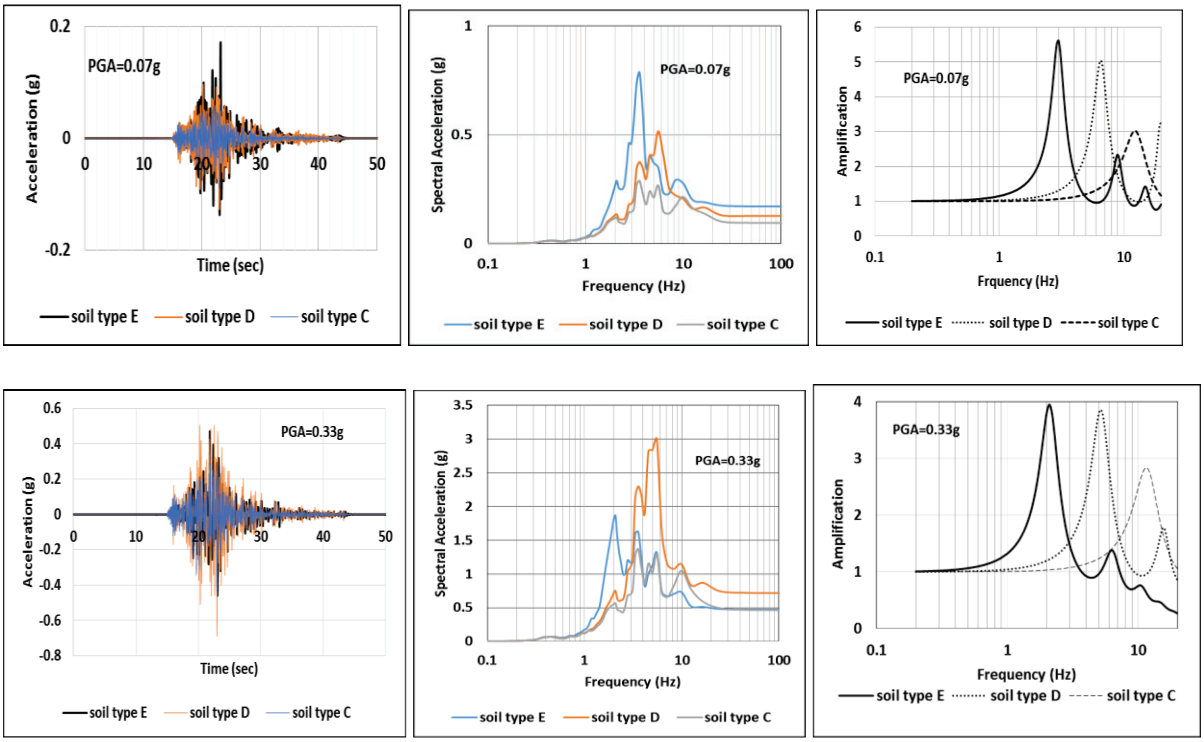
Figure 4.3: Comparison of site amplification based on varied soil types of equal thickness (10m), relative to the motion of the outcropping bedrock.

the soils. This results to decreasing impedance ratio from soil type E to soil types D and C respectively and consequently to low amplification. The same relation brings about the higher peak frequency of the soil type C (high velocity and short wavelength content) than in the soil type D and the soil type E (low velocity and long wavelength content) in that order (Figure 4.3).

From this investigation, it is clear that the selected soil types are expected to show differentiated response to seismic motion. The results on the general analysis different soil layer thickness are presented later. The relation of the level of shaking at the base of the soil layer, and the output motion on the soil surface was investigated is explained in the following section.

4.4.1.2. The relation between the input motion and the soil surface motion

This evaluation considered a single input motion of the 17th January, 1994 Northridge Earthquake, M_W 6.7 in the simulation. The PGA parameter was adjusted to represent the difference in excitation at the base of the soil layer. This was done to imitate the occurrence the weathered or weak bedrock and firm bedrock at the base of the soil layer. The input motions were simulated with the PGA of 0.33g and 0.07g. The comparison on the output surface motions was done on the acceleration time history, response spectra and the amplification at the surface of different soil types (Figure 4.4). The results in Figure 4.4 indicates that low excitation of the base of the soil layer resulted to a higher amplification on the soil surface. The amplification factor in the low intensity input motion (PGA=0.07g) is about 1.5 times higher the amplification in high intensity input motion (PGA=0.33g) especially at low velocity Soil type E (Figure 4.4).



a) b) c)

Figure 4. 4: Comparing the response on the soil surface when the excitation input motion is different (PGA = 0.33g and 0.07g). The first column shows the acceleration at the soil surface in time domain, the second column shows the response spectra with 5% damping, and the third column shows the nature of amplification at the natural frequencies of 10m layer thickness in different soils.

The difference in these results imply that the response on the soil surface is influenced by the intensity of the earthquake motion. Strong excitation at the base of the soil layer leads to strong shear strains in the soil which leads to inappropriate mechanism for the seismic shear wave propagation through the soil profile. This effect lead to minimal energy reaching the surface of the soil with lower frequency content than when we have less strong input motion. This can be observed in Figure 4.4 where the input motion with PGA of 0.33g gives lower amplification than in the case of PGA of 0.07g.

The general conclusion from this investigation is that there is a slight difference in the surface motion at the different soil types when the intensity of the bedrock motion is asynchronous. This phenomenon has also been observed in Dobry and Iai (2012). However, high density seismic events are likely to show almost similar ground motion and therefore the number of the seismic event may not be very relevant in this kind of analysis (Nakamura, 1989; Okuma et.al 1999). The following section shows the results obtained from the simulation of a seismic motion in the soil types C, D and E, on varied bedrock stiffness represented as weak bedrock (Vs=750m/s) and firm bedrock (Vs=1300m/s).

4.4.2. The overall site amplification in different soil types

Figure 4.5 shows the amplification curves which were obtained after computing for the soil response in varied soil thickness. The same procedure explained in section 4.2 on the computation for the amplification factor was applied to obtain the results presented in this section. The general observation that is made is that the estimated natural frequencies for the respective soil layer thicknesses was clearly associated with the soil thickness. The surface motion at the thin layers occur at higher frequencies than in the thick layers. The estimated seismic amplification in the soil type E was the highest reaching a maximum of 6 at 15Hz on the firm bedrock and minimum of 4.3 at 0.9Hz with reference to the weak bedrock. The highest amplification of the soil with reference to the weak bedrock outcrop is 4.2 at 12.7Hz. The amplification at the soil type C is lowest with relatively higher frequencies. This is related to high shear velocity of the soil type C which makes it easier for the shear waves to be transmitted with minimal horizontal acceleration which leads to low dilatation of the amplitude hence minimal amplification effect.

The amplification spectra confirm the relationship of the peak frequencies with the shear wave velocity at of particular soil layer defined in Equation 12. There is a clear evidence that the peak frequencies of the soils are increasing with increasing shear wave velocity from the soil type E to the soil type C. An insight into the reason why the amplification is decreasing with the increasing shear wave velocity of the soil can be deduced from Equation 11. Low velocity soils show higher seismic amplification than in the high velocity soils. For example, the amplification factor at 7.5m of the soft soil (V_S=150m/s) on weak bedrock is 3.4 at 3Hz which is higher than in the corresponding layer thickness in the other soils which is around 2.5 at 8Hz in the soil type D (V_S=280m/s) and 1.4 at 16.7Hz in the soil type C (V_S=500m/s). The interpretation of the possible cause of these observations are explained later in this section.

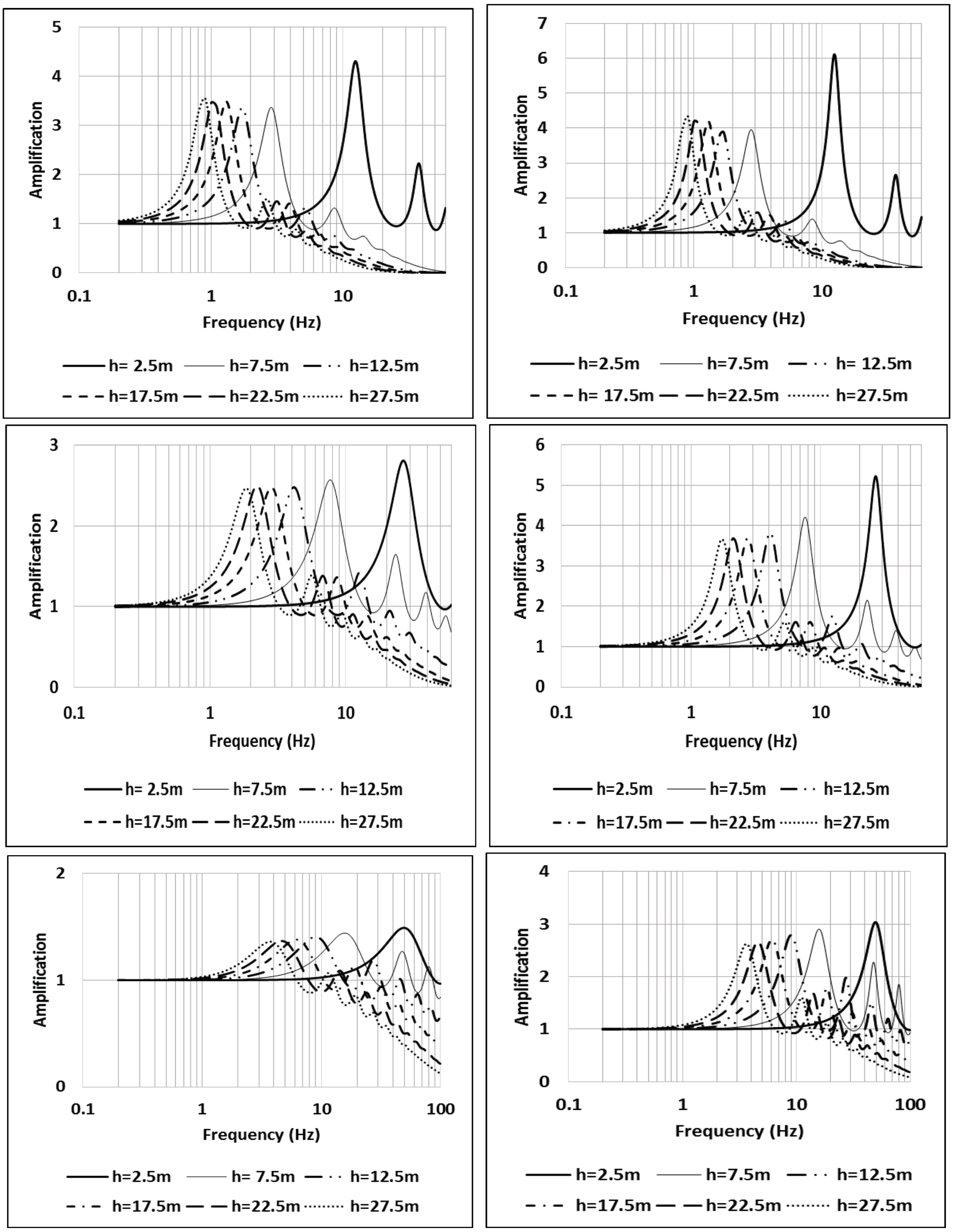


Figure 4. 5: The Amplification spectra in varied soil thicknesses Soil type E in the *first row,* Soil type D in the *second row* and the Soil type C in the *third row*. The difference in the amplification effect on the surface of the different soils, is observed when the outcropping bedrock is weak (*first column*) and when it is firm outcropping bedrock (*second column*).

The thinnest soil layer (2.5m) considered in the simulation shows the highest seismic amplification of 4 to 6 at about 13Hz in the soil type E, 2.8 to 5.2 at 28Hz in the soil type D and 1.4 to 3 at 50Hz in the soil type C. This effect is associated with the high frequency of shaking at the soil surface, which happens at a very short period with minimal loss of energy since the path of the seismic shear wave propagation is at the shortest distance at this layer thickness, therefore such a high amplification could be expected.

Since the input motion that was applied in the analysis was the same in all the simulations, it is clear to see the influence of the soil types on the estimated seismic amplification factor. To add on the explanation that was given in the previous section concerning the influence of the different soil types on the seismic amplification, it was confirmed that this phenomenon is associated with other parameters such as the shear velocity of the soils relative to that of the outcropping bedrock, the impedance contrast, layer thickness and the damping ratio in the respective soil types. To explain this interpretation, we take a case of the amplification spectra in different soil types with reference to the firm bedrock (the second column in Figure 4.5). Following the definition of the amplification factor in Equation 11, the value of the amplification factor in the Soil type E is generally higher due to the low shear wave velocity of the soils that give higher impedance contrast than in the Soil type D and Soil type C. The low velocity Soil type E exhibit ground shaking at relatively lower frequencies than in the other soils (Soil type D and the Soil type C) at the corresponding layer thickness. High impedance contrast between the bedrock and the Soil type E tends to result to high amplification factor of the seismic motion at the soil surface.

The response spectra and amplification spectra in Figure 4.2 and Figure 4.5 respectively, show that the soil layer thickness has influence in the response of the soil. In the Soil type E soil, apart from the thin layer of 2.5m, the rest of the soil columns greater than 7m show consistently increasing amplification factor with increase in the layer thickness. The response of the 2.5m layer in all the soil types appear with very high amplification of upto 6 at a frequency of around 13Hz which is relatively higher compared to the amplification on the other layers. This effect is likely to occur in the computation of the amplification due to the peaks in Fourier amplitude spectrum which may not have a lot of significance in the engineering applications however such a response can be associated with the behaviour of the shear waves at shallow layers where the vertical acceleration of the motion is most likely to occur than the lateral acceleration.

Unlike in the Soil type E, we see a decrease in the amplification factor in the Soil type D and the Soil type C. This can be explained by the increasing rigidity and the attenuation effect during the propagation of the seismic wave motion through the thicker columns of these soils. The deformation in this case would happen in shorter period in a ductile manner or sometimes brittle behaviour would be observed since the soils exhibit low elasticity as compared to the Soil type E. Therefore, the maximum amplification reached in the Soil type D and Soil type C is lower than in the Soil type E. Another contributing factor is the decreasing impedance contrast towards the Soil type C with respect to the increasing shear modulus ratio. This implies that there is less energy available to cause high amplification at the surface of the Soil type D and Soil type C. This relation is also associated with the stiffness degradation curve described in Figure 3.5a.

In general, Figure 4.5 shows a significant variation of the amplification factor across the different soils (*the spectra in the columns*) at corresponding layer thickness. The overall amplification is fairly dependent on the V_S of outcropping bedrock since higher amplification peaks are observed when we have the firm bedrock (V_S30=1300m/s) than in the weak outcropping bedrock (V_S=750m/s). The dominant role of the bedrocks in the variation of the site amplification at different soils sites is the acceleration (intensity) and the impedance contrast of the rock (Dobry & Iai, 2012). When compared to the weak outcrop motion, there is relatively lower amplification factor of averagely 2.5 in the Soil type D and about 1.5 in the Soil type C.

Table 4. 1: Margin of error in determining the peak frequencies at the maximum amplification.

Soil Thickness (m)	Soil type E (Vs 150m/s)			Soil type D (Vs 280m/s)			Soil type C (Vs 500m/s)		
	Calculated	estimated	Error (%)	Calculated	estimated	Error (%)	Calculated	estimated	Error (%)
2.5	15.0	12.7	15	28.0	27.1	3	50.0	51.1	-2
7.5	5.0	2.9	42	9.3	7.7	17	16.7	16.2	3
12.5	3.0	1.7	43	5.6	4.1	26	10.0	9.2	8
17.5	2.1	1.3	39	4.0	2.8	30	7.1	6.2	13
22.5	1.7	1.1	34	3.1	2.1	32	5.6	4.7	15
27.5	1.4	0.9	34	2.5	1.7	33	4.5	3.7	18

The lack of proper mechanism in the seismic wave propagation in the Soil type E soil, the anticipated higher damping effect and the disturbance due to the nonlinear behavior of the soil are some of the factors that are likely to contribute to the discrepancy in estimating the natural frequencies (see Table 4.1). The margin of error increases when estimating the peak frequency in the thicker layers but decreases from softer soils to the stiffer ones as observed in the Soil type D and Soil type C. The maximum amplification occurs at the lowest frequency mode of the soil layer (Equation 12) Dobry and Iai (2012). Edushake uses the peaks of the amplitude Fourier spectrum for the output motions to compute for the amplification factor at the soil surface. Due to lack of smoothening of the peaks in the amplitude Fourier spectra (Figure 4.1), the analyzer suggests that this process is likely to misrepresent the amplification and the actual natural frequencies of a soil layer. The PGA that characterizes the input motion, is also likely to influence the peak frequency of the soil response.

4.5. Spectral amplification

The estimation of the amplification factor by the division of the amplitude Fourier spectrum of the soil surface motion with the corresponding amplitude Fourier spectrum of the outcropping motion based on the transfer function given in Equation 11 is high at the thin layers <2.5m, while the amplification in the thicker layers shows minimal influence by the increase in the soil thickness and sometimes remaining constant. In order to examine this phenomena, we computed the ratios of the response spectra (RRS) given in Figure 4.6 in order to examine the similarities in the amplification spectra computed from the two methods. This method was also applied in Dobry et al. (2000) and Dobry and Iai (2012) among others studies. This computation shows how much the acceleration of outcropping bedrock motion is amplified at the soil layer, which is defined as the RRSmax. The amplification factor computed from the RRS_{max} at any soil type, appears at almost the same peak frequency of the layer as observed in the amplification spectra given in Figure 4.5. Despite that several researchers have applied the transfer function as the basis for determining the amplification of the seismic motion, Dobry et al. (2000) pointed out that determining the RRS is an alternative method which is also applicable in determining the seismic amplification. According to Dobry et al. 2000) this approach has shown matching results between theoretical models and the instrumental records. There are several studies in which the use of the RRS_{max} has been applied in ground response analysis (Chang et al., 1996; Dobry & Iai, 2012; Joyner et al., 1994)

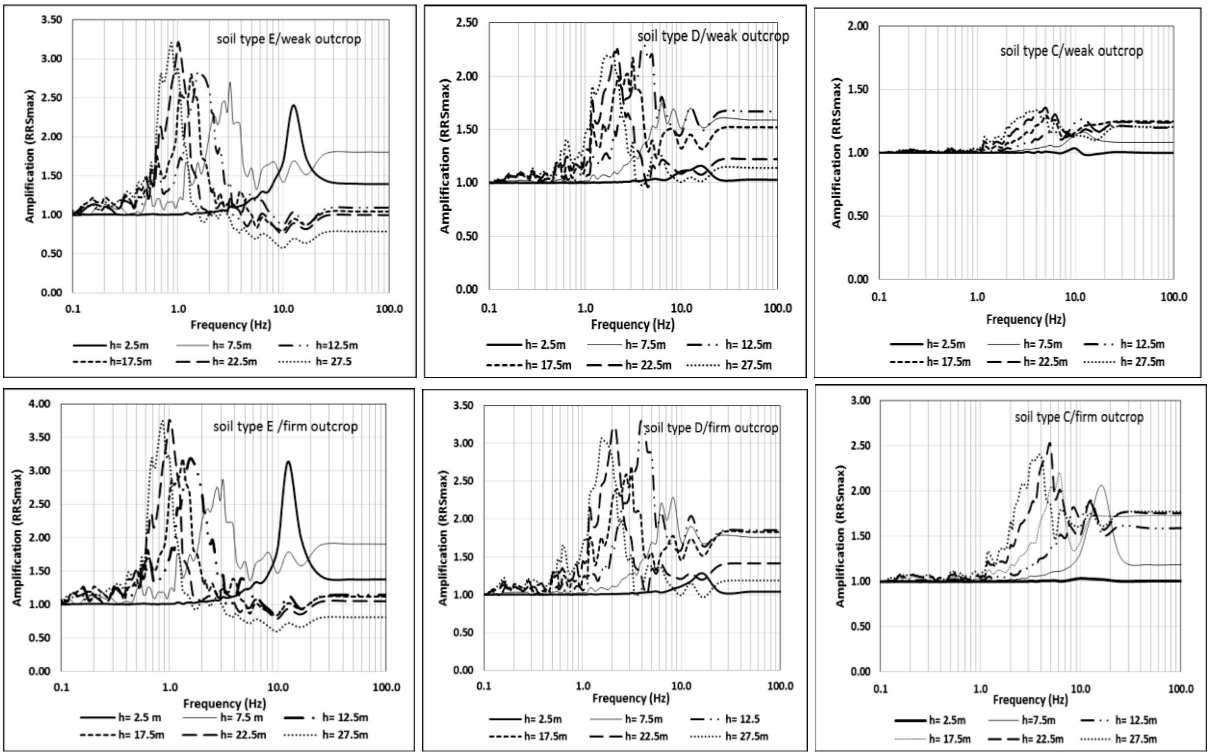


Figure 4.6: The spectral amplification computed as the ratio of the response spectra (RRS) between the soil surface and the outcropping bedrock motion. The rows shows the amplification in different soil types while the columns shows the comparison with reference to the weak and firm outcrop bedrocks.

The overall amplification factor obtained from this technique is relatively lower than in the first case shown in Figure 4.5. The comparison of the models can be compared in Figure 4.7.

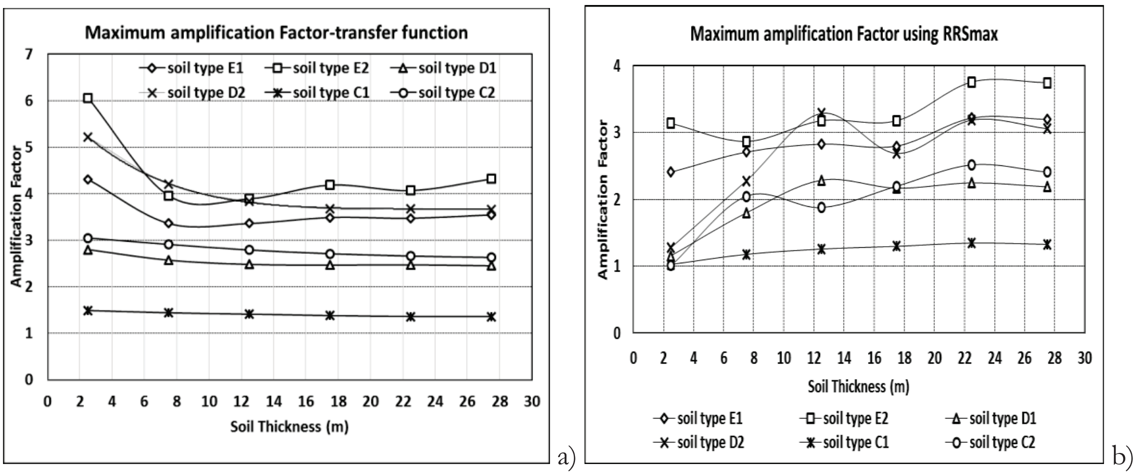


Figure 4. 7 : Comparison between the amplification factors a) computed using the transfer function defined in the Edushake program and b) the peaks of the response spectral ratios (RRS_{max}). The compiled simulation results which were used to generate this relations are presented in Appendix 1.

The results obtained using the RRS_{max} are derived from the ratio of the normalized response spectra with 5% damping. This normalization factor was based on the NEHRP damping adjustment factors in the guidelines for the seismic rehabilitation of buildings (FEMA, 1997) in (Naeim & Kircher (2001). The estimated spectral amplification factor from the RRS_{max} in different soils shows the evidence of increase of the amplification factor as the soil thickness increases. This trend can be explained by the effect of compaction, total pressure at the bottom of the soil layer

4.6. Discussion and relation to the previous findings

The three soil types investigated in this study shows clear relation in the amplification of the seismic motion with the change in the soil thickness. Even though the amplification of the seismic motion is relatively higher in soil type E than in the soil types D and C, the response of this soil type is rather non-linear as compared to the other soil types. This behaviour influenced the estimation of the natural frequency of the soil layers by an average of about 35% error in the soil type E, 20% in the soil type D and 10% in the soil type C. The natural frequency mode of soil layers decreases as the soil layer thickness increases. This relation causes a significant shift of the amplification peaks which can be useful in estimating the possible level of seismic motion that can lead to damage on a given building based on its height and the thickness of the soil layer underlying the building. Low frequencies in the thick layers of soils means that, in case of weak earthquakes which exhibit more energy at high frequency, only the higher modes of the seismic motion cause excitation of the soils in such a case.

The PI value for the soils considered in the analysis is low (15%). In reality low PI value would be associated with soil particles that are large and have less inter-particle contacts (Hardin & Drnevich, 1972). This implies that the gravitational forces on such soils and the associated friction between the particles may influence the response of the soil to the seismic stress. The total pressure exerted by the whole soil column is related to the depth whereby, at high depths the total pressure at the bottom of the soil layer is likely to be higher than at shallow depth. This means that the spaces between the particles are reduces in the deeper layers and as a consequence, a proper mechanism of wave propagation may be observed. Using this idea, we can say that the reason why the soil type E show lower amplification in the thin layers, is because there is poor mechanism of wave propagation which results to the shear strain in the soil type E but later the strains are exceeded in longer-period modes (low frequency at thicker layers) with large amplification. This would explain why strong earthquake motions of long period in the soft soil sites would cause high damage due to amplification of the seismic motion at the soil surface.

From the work of Shafique et al. (2011) the relationship between the regolith thickness and the earthquake damage in percentage (Figure 4.8) shows that severe damage above 80% were common at the sites where the soil thickness was above 13m. Less than 50% of the earthquake damage was observed at the sites with less than 10m regolith thickness. Only 38% (R^2=0.38) of the variability was described by the model. From our study, the numerical analysis shows that the Soil type E tend to give a relatively higher amplification factor. This suggests that higher ground shaking on such soils could be expected with the severe damage on the structures. These results also suggest structure with the natural frequency close to the resonance frequency of the Soil type D at these layer thickness range could experience severe damage.

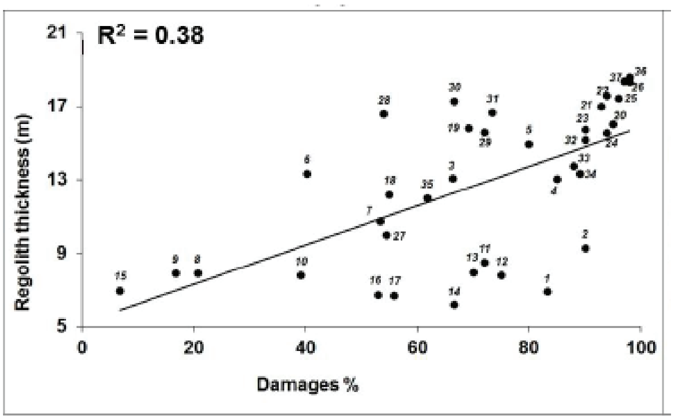


Figure 4. 8 : The correlation between the soil thickness and percentage of the damage observed in Muzaffarabad city. The numbers in the plot are associated with the damage zones established in the work of Shafique et. al. (2011).

To evaluation the relationship between the observed damage, for example in Muzaffarabad city, and the predicted amplification in that area, was established by performing a comparative analysis using the same damage data that was applied in the previous study. Using the predicted amplification model shown in Figure 4.7b, the spatial model of the soil thickness developed by Shafique et. al. (2011) was translated into the amplification factor for the respective soil thickness using the polynomial functions of power 2 shown in Table 4.2. The R^2 coefficient in all the predicted models show positive correlation between the predicted amplification and the soil thickness.

Table 4. 2: Predicted amplification model

soil type	Predicted amplification	R^2
soil type C	$A = -0.0007h^2 + 0.0325\ h + 0.9606$	$R^2 = 0.991$
	$A = -0.0027\ h^2 + 0.1311\ h + 0.8517$	$R^2 = 0.8543$
soil type D	$A = -0.0037\ h^2 + 0.1466\ h + 0.8714$	$R^2 = 0.9393$
	$A = -0.0055\ h^2 + 0.2278\ h + 0.8509$	$R^2 = 0.8471$
soil type E	$A = -0.0003\ h^2 + 0.0397\ h + 2.3511$	$R^2 = 0.8979$
	$A = 0.0017\ h^2 - 0.0183\ h + 3.0816$	$R^2 = 0.8199$

The correlation between the amplification factor and the observed damage in Muzaffarabad city were computed using three soil type models. The result given in Figure 4.9 shows that even though there is a close relation between the predicted amplification models, the amplification in soil type E could be used the same way as the regolith thickness was used in Shafique et. al. 2011 to explain the distribution of the earthquake damage that was observed in Muzaffarabad city. However the amplification factor increases as the percentage of damage increases. The high velocity soil type zones are likely not to experience a lot of damage.

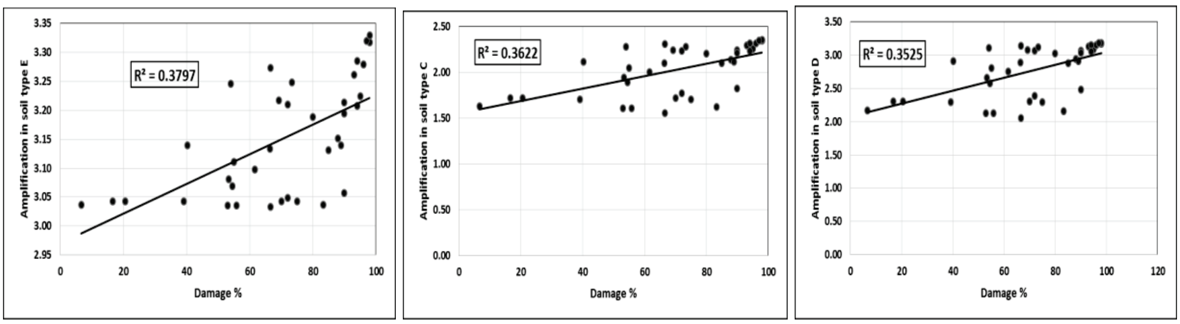


Figure 4. 9: Comparative analysis of the relation between the observed damage in Muzaffarabad city and the predicted amplification of the seismic motion in different soil types.

The map in Figure 4.10 shows an integrated map of the distribution of damage, the soil thickness in the depositional landscape in the Muzaffarabad neighbourhood and the predicted site amplification. The type E was suggested as the major contributor of severe damage along the basin of River Neelum and River Jhelum which are the main rivers in that city.

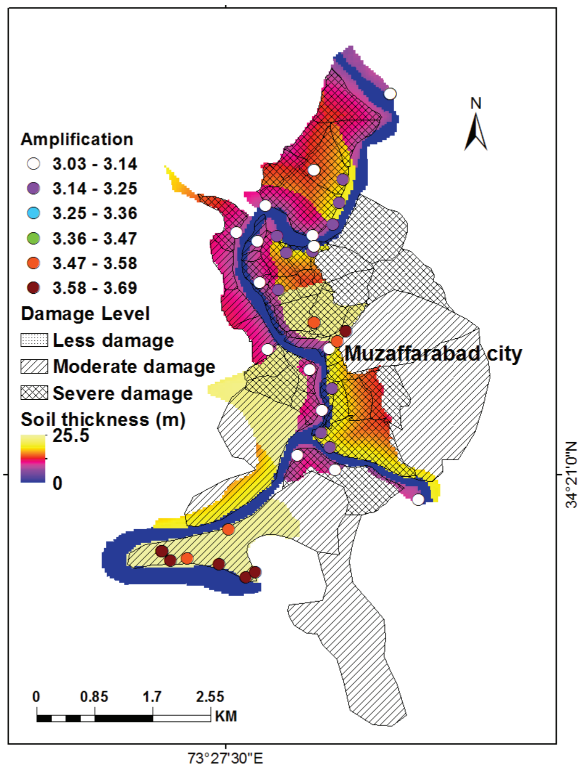


Figure 4. 10: Comparison of the predicted amplification, soil thickness and the level of damage that was observed in Muzaffarabad after the Kashmir Earthquake in 2005.

The predicted site amplification based on the soil type E, was applied to map in Muzaffarabad city since it was observed with the highest average amplification factor, therefore it was the worst scenario that would be expected in future earthquake. Buildings located in such sites are likely to experience severe earthquake damage. It is also observed from the map (Figure 4.10) that the zones which were demarcated as severely damaged after the Kashmir Earthquake in 2005, are still predicted as the zone with strong amplification of the ground motion in future earthquakes. The amplification factor of 3.1 to 3.7 can be experienced in future in the zones where the dominated with the soil type E. The other soil types C and D are also prone to site amplification effect but relatively lower at 1.21 to 3.21 in the soil type D and 1.04 to 2.44 in the soil type C. The predicted amplification in Muzaffarabad and Balakot city and other parts along the depositional landscape were computed based on the prediction models shown in Table 4.2.

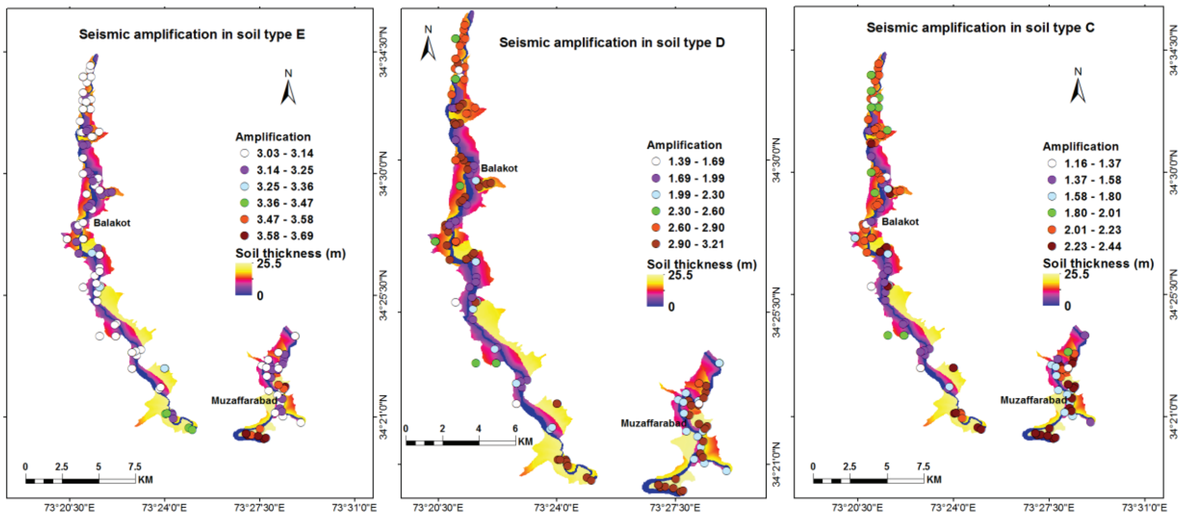
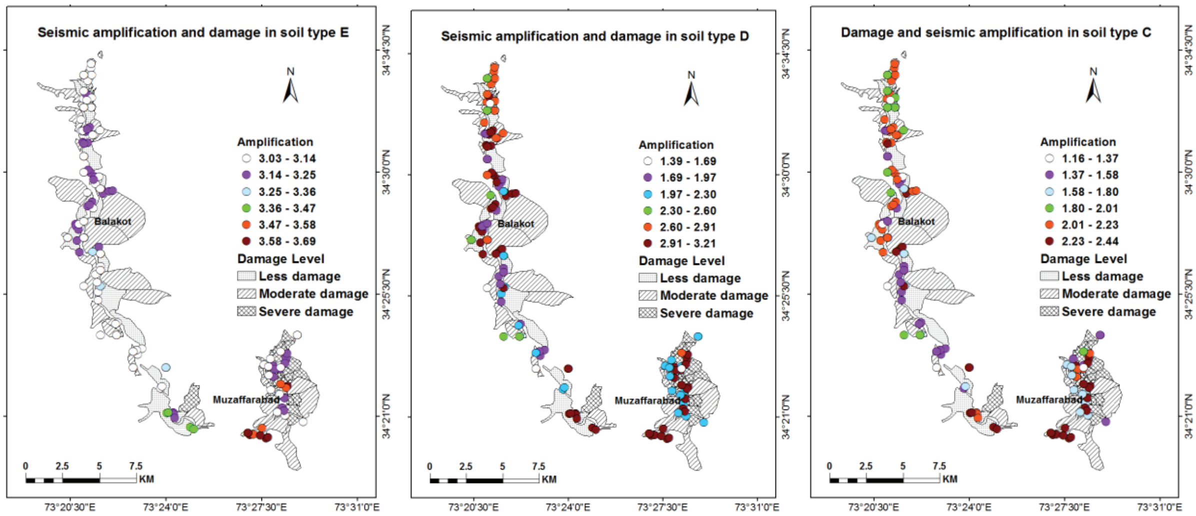


Figure 4. 11: The predicted site amplification in different soil types related to the distribution of the soil thickness along the depositional landscape where most settlements were observed by Shafique et, al. 2011.

Figure 4.12 shows the relations of the damage maps with the distribution of the predicted amplification. It was observed that the distribution of the points where high amplification was predicted appeared in the same zone where moderate to severe damage was observed. The example of that is Muzaffarabad city which is located at the lowlands Gari Habib Ullah town, where strong site amplification was predicted with maximum of 3.69 in soil type E, 3.21 in soil type D and 2.44 in soil type C.



a) b) c)

Figure 4. 12: The maps showing the damage zones produced by Shafique et. al. 2011b after the 2005 Kashmir earthquake covering Balakot and Muzaffarabad city distribution pattern of site amplification in different soil types a) soil type E, b) soil type D, and c) soil type C,.

4.7. Summary

After exploring into the influence of varied soil types in seismic response, this study suggests that the Soil type E with V_S of 150m/s was the major contributor to the damage that was observed following the Kashmir earthquake 2005. The soil thickness and the soil types were observed with great significance in the variation of the site amplification effect. The study has identified the most likely soil characteristics that would contribute to high soil amplification of the earthquake motion. The amplification model applied in this study can be used in other studies where the soil parameters are almost the same as those estimated in this study.

The results presented in this chapter are site specific with the defined soil conditions and that puts them as very useful geotechnical practises for example in highway construction, local site investigations, dam siting, tunnelling and other construction works. 1D modelling has shown the importance of performing first, a simplified analysis on the seismic amplification. This study found that the most significant soil type which exhibited strong seismic amplification was the soil type E. A spatial 3D model showing the amplification effect in the depositional landscape can be developed with more details of the characteristics of the soil type E included to examine the influence of the basin in site amplification phenomena. Due to time limitation, this study could not go into this step.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This study evaluated the amplification effect in different geotechnical soil types which included the Soil type E, Soil type D and Soil type C based on NEHRP classification of soils. The key parameter used to define the soils is the shear wave velocity (Vs). Equivalent linear analysis approach is applied in analysing seismic shear wave propagation in one-dimensional path in Edushake program. The ground surface motion parameters which are associated with the level of damage during an earthquake are computed. These parameters involve the amplification factor, spectral acceleration, the PGA and PGV in the three different soils of interest in this study.

The simulation of the ground motion in 1D shows that the soil thickness has a great influence on the natural frequency at which the maximum amplification occurs in a soil layer. The thin layers of 2.5m in soil type E (soft) showed a maximum natural frequency of about 13Hz, while 2.5m of soil type D (stiff) showed natural frequency of 27Hz and 51Hz in the soil type C (very dense soil) at the same layer thickness. This means that the ground shaking at the sites covered with soft soils would happen in lower frequencies than in the very dense soils. The same applies to the damage experienced whereby the high frequencies would lead to stronger shaking in the low laying structures on soil types D and C and minimal shaking of one storey buildings laying on soil type E. The lowest natural frequencies at the soil thickness of >27m in all the soil types, are associated with the shaking of 11 storey building at 0.9 Hz on soil type E, 6 storeys at 1.7Hz on soil type D and 3 storeys at 3.7Hz on soil type C. The influence of the soil types was observed in the level of amplification which was highest in the soft soils in lower frequencies than in the very dense soils at high frequencies.

The natural frequency of shaking was observed to be influenced by two factors, one, was the soil type: the ground motions of the soil type E (150m/s) was observed to occur at relatively lower frequencies than in the denser soils (soil type D (280m/s) and soil type C (500m/s). Two, soil thickness: thin layers of soil surface motion were observed at higher natural frequencies as compared to the thick layers in all the three soil type. On the other hand the maximum and minimum amplification of the seismic motion in terms of the amplitude of acceleration and the response spectra, was determined by the soil thickness. Thicker layers of soils showed higher amplification than in the thin layers probably due to the increase in vertical total pressure in the soil profile that is suggested to make an efficient mechanism of seismic wave propagation with higher energy than in the thin layers.

The peak ground acceleration and peak ground velocity reached at different layers of the soils showed varied minimum and the maximum PGA whereby the soil type E (150m/s) gave the lowest PGA of 0.32g and the highest maximum value of PGA of 0.63g in the thicker layers compared to the soil type D (280m/s) which gave minimum of 0.37g and maximum of 0.60g and for the soil type C (500m/s) that was observed with PGA of 0.39g and 0.58g respectively. This means that areas covered with thick layers of soft soils are more risky than in areas covered with stiffer soils. It was observed that the overall PGA on the soil surface decreased as the soil thickness increased and vice versa. The PGV increased steadily as the soil layer increases and was also associated with the amplification of the seismic motion at the thicker soil layers.

The study uses the soil thickness data derived from the model by Shafique et. al 2011b for the case of Balakot-Muzaffarabad cities in Kashmir region, Pakistan. The predicted amplification model of the soil type E shows that the estimated amplification is 3 times that of the soil type C in the thin layers <10m and about 1.5 times in the thick layers >20m. The models are also correlated with the level of damage that was observed in the Muzaffarabad city after the Kashmir earthquake in 8th October, 2005. The relation between earthquake damage and the amplification factor of the soil type E was R^2=0.38, R^2=0.36 in the soil type D and R^2=0.35 in the soil type C. The soil type E shows similar correlation as that of the regolith thickness with the level of damage in the same area. The study predicts that severe damage is likely to be observed in the soil type E since the amplification is higher than in the other soil types. This study suggests that the areas covered with Soil type E in Balakot-Muzaffarabad region are likely to have experienced severe damage since a close match in the damage map is observed.

The influence of the stiffness of the outcrop bedrock was observed with high amplification when the bedrock was firm and low amplification when the bedrock was weak. The amplification of the seismic motion for case of the firm bedrock (1300m/s) is about 1.4 time higher in soil type E (150m/s), 1.9 in times for the case of soil type D (280m/s) and 2times in soil type C (500m/s) than in the case of the weak bedrock (750m/s). Amplification of the seismic motion at the thin layers <5m of soil type E (150m/s) was 3 times higher than in the thin layers of the stiffer soil. This confirms the soft soils as risky and would lead to heavy damage on buildings when earthquake motions are intensive in such sites.

The maps showing the predicted seismic motions based on the soil thickness of Balakot- Muzaffarabad areas showed that the sites which are covered with the soft soils (150m/s) are likely to experience severe damage in future earthquake events is no mitigation measures are incorporated in constructing residential buildings in those areas. The predicted site amplification slightly matches with the damage pattern that was observed after the Kashmir earthquake.

5.2. Recommendations

This findings of this study very crucial for local site investigation in the study area. However, a more complex step to analyse site amplification phenomenon in 3D model can help to investigate on the influence of the basin geometry and also the terrain in the neighbourhoods of Muzaffarabad and Balakot areas. Even though the soil data has several uncertainties, predicting the ground motions in 3D would give a clearer impression of impact of an earthquake and establishing the possible sites where heavy damage is likely to occur in such a depositional landscape.

Studies which may not have the shear wave velocity measurements may apply the Standard Penetration Test (SPT) to define different soil types for investigation as used in this study.

The Edushake program has been reliable in very many studies for so many years since 1972 in performing ground response analysis. The program is user friendly but the discrepancies in the estimation of ground motion by less experienced researchers can be evaluated by exploring into the DEEPSOIL software (Hashash 2000, 2012) which was discovered during the literature review of this study. The software is flexible in equivalent linear analyses as well as Non-Linear analyses. It incorporates the latest soil models by Darendeli (2001) and Menq (2003) which consider the influence of the organic carbon ratio in the soil on the seismic induced motions. The output response can be calculated in three methods: Frequency domain, Duhamel integral and Newmark methods which make the software more preferable in different applications. The computation of the pore water pressure (PWP) and defining the nature of the bedrock-soil interface can also be done.

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APPENDICES

Appendix 1: Maximum amplification factor

a) Maximum amplification Factor derived from the transfer function (Equation 11)

Soil Thickness (m)	Soil type E (Vs=150m/s)		Soil type D (Vs=280m/s)		Soil type C (Vs=500m/s)	
	Case 1-weak rock	Case 2- firm rock	Case 1- weak rock	Case 2- firm rock	Case 1-weak rock	Case 2- firm rock
2.5	4.31	6.064	2.8	5.22	1.49	3.05
7.5	3.361	3.959	2.571	4.208	1.44	2.91
12.5	3.36	3.891	2.48	3.833	1.41	2.79
17.5	3.488	4.187	2.465	3.676	1.38	2.71
22.5	3.473	4.069	2.471	3.683	1.36	2.66
27.5	3.546	4.318	2.451	3.66	1.36	2.63

b) Maximum amplification Factor using RRSmax

Soil Thickness (m)	Soil type E		Soil type D		Soil type C	
	Case 1- weak rock	Case 2- firm rock	Case 1- weak rock	Case 2- firm rock	Case 1- weak rock	Case 2- firm rock
2.5	2.41	3.14	1.16	1.28	1.03	1.01
7.5	2.71	2.87	1.8	2.28	1.18	2.05
12.5	2.83	3.18	2.29	3.29	1.26	1.88
17.5	2.8	3.18	2.17	2.69	1.30	2.20
22.5	3.22	3.76	2.25	3.19	1.35	2.52
27.5	3.20	3.75	2.19	3.06	1.33	2.41

Appendix 2: Peak Ground Acceleration (PGA) (g) in different soil classes

Soil Thickness (m)	Soil type E		Soil type D		Soil type C	
	Case 1- weak rock	Case 2- firm rock	Case 1- weak rock	Case 2- firm rock	Case 1-weak rock	Case 2- firm rock
2.5	0.460	0.453	0.339	0.342	0.328	0.331
5	0.636	0.659	0.44	0.461	0.339	0.341
7.5	0.594	0.626	0.523	0.579	0.356	0.391
10	0.443	0.473	0.556	0.719	0.379	0.466
12.5	0.360	0.375	0.548	0.608	0.394	0.524
15	0.320	0.333	0.555	0.696	0.406	0.536
17.5	0.344	0.368	0.5	0.601	0.410	0.569
20	0.369	0.387	0.438	0.484	0.409	0.603
22.5	0.330	0.346	0.402	0.464	0.400	0.577
25	0.288	0.297	0.382	0.445	0.404	0.559
27.5	0.260	0.266	0.375	0.39	0.395	0.583
30	0.251	0.262	0.347	0.367	0.390	0.577

Appendix 3: Peak Ground Velocity (PGV) (cm/sec)

Soil Thickness (m)	**Soil type E (Vs=150m/s)**		**Soil type D (Vs=280m/s)**		**Soil type C (Vs=500m/s)**	
	Case 1- weak rock	Case 2- firm rock	Case 1- weak rock	Case 2- firm rock	Case 1- weak rock	Case 2- firm rock
2.5	16.6	16.81	15	15.00	14.84	14.84
5	25.33	27.03	16.19	16.70	15	15.06
7.5	26.75	28.44	16.87	16.87	15.23	15.58
10	28.99	31.35	21.52	25.00	15.26	16.3
12.5	32.71	33.52	22.45	27.31	15.48	16.56
15	25.62	26.45	24.08	30.46	15.68	17.28
17.5	20.83	21.86	24.61	27.17	15.79	19.13
20	20.79	22.4	24.61	27.87	16.26	20.37
22.5	19.43	20.56	25.47	30.64	16.36	22.09
25	17.68	18.62	26.75	33.70	16.4	23.57
27.5	16.77	17.42	27.3	33.87	16.67	25
30	16.67	17.58	26.39	31.35	16.87	25.19