# SEISMIC HAZARD ASSESSMENT FOR COLOMBO CITY WITH LOCAL SITE EFFECTS

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(118625T)



Degree of Master of Engineering

Department of Civil Engineering

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## DECLARATION

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Last but not least, I present my deepest thanks to all other members of academic staff and non-academic staff of Civil Engineering Department, University of Moratuwa who gave me the support in various means to finalize this project successfully.

**SEISMIC HAZARD ASSESSMENT FOR COLOMBO CITY WITH LOCAL SITE EFFECTS**


## Abstract

Sri Lanka was believed to have no seismic threat compared to other natural hazards such as floods, droughts, landslides etc. Due to the experiencing of ground shaking in last few decades and the disaster on 26th December, 2004 due to tsunami, Sri Lanka cannot further treated as an earthquake damage free country. Few research has been carried out to investigate seismic hazards at Colombo city area and the response spectrum at rock level for Colombo city area has been proposed with the PGA (Peak Ground Acceleration) of 0.1g. However, no studies have been carried out to develop earthquake response spectrum for Colombo city with local soil variations.

This study discusses generalized soil profiles for Colombo city and earthquake response spectrum with local site effects for Colombo city area.

77 borehole logs done at the study area are collected and locations were plotted on a map of study area. Eight vertical sections were obtained through the study area and using them eight soil profiles which have horizontal soil layers were developed. All eight profiles highlight that the average soil cover in Colombo city area is about 20m. Just above the basement rock dense to very dense silty sand/ sand layer is present. Topmost layer also having loose to dense sandy soil. In between both of sand layers, very loose to loose clay/ silt or organic material layer is encountered in all boreholes.

The developed soil profiles were used to analyze with earthquake motions using the computer software called EduShake. The six earthquake motions are applied at rock level as input motions. The response spectra at rock level and the response spectra with the local soil effects were obtained as the output file. The program was run for the eight soil profiles and obtains the average value of both output files as final result. Finally, earthquake response spectrum has been proposed for Colombo city area and it was compared with existing response spectrum at rock level for Colombo city.

According to this study, the PGA with local site effects is 0.13g for Colombo city area.



**Key words**: *Colombo city, local site effect, seismic hazard analysis, intra-plate earthquakes.*


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## Notations

| | | |
|---|---|---|
| A | - | Crosssectional area |
| E | - | Young's modules |
| f,g | - | Arbitrary functions |
| G | - | Shear modulus |
| J | - | Polar moment of inertia of the rod about its axis |
| k | - | Wave number |
| K | - | Stiffness of the object |
| M | - | Constrained modulus |
| m | - | Mass of the object |
| PGA | - | Peak ground acceleration |
| PHA | - | peak horizontal acceleration |
| PHA | - | Peak horizontal acceleration |
| RSRL | - | Response spectrum at rock level |
| RSLSE | - | Response spectrum with local site effects |
| SPT | - | Standard Penetration Test |
| SCPT | - | Standard Cone Penetration Test |
| $S_a$ | - | Spectral acceleration |
| t | - | Time |
| T | - | Period, torque |
| $T_n$ | - | Natural period of object |
| $\bar{T}$ | - | Period of the applied loading |
| x | - | Distance |
| $u, v, w$ | - | Particle displacement in x,y and z directions respectively |
| $v_p$ | - | Longitudinal wave propagation velocity |
| $v_s$ | - | Torsional wave propagation velocity |
| (t) | - | Steady state harmonic stress |
| $\lambda$ | - | Wave length, Lame constant |
| $\mu$ | - | Lame constant |
| $\varpi$ | - | Circular frequency |
| $\nu$ | - | Poisson ration |

| | | |
|---|---|---|
| $\rho$ | - | Density of element |
| $\xi$ | - | Damping ratio |
| $\sigma_x, \sigma_y, \sigma_z$ | - | Normal stress in x, y and z-direction respectively |
| $\sigma_0$ | - | Stress wave amplitude |
| $\varepsilon_x, \varepsilon_y, \varepsilon_z$ | - | Strain in x, y and z-direction respectively |
| $\bar{\varepsilon}$ | - | Dilatation |
| $\Phi, \Psi$ | - | Potential functions |

# 1. INTRODUCTION

## 1.1 Background

Normally, Sri Lanka faces threats from a variety of natural hazards like floods, droughts, landslides etc. Seismicity in Sri Lanka is not considered as an important design factor for design and construction of structures so much though it has been discussed by few authors. During last few decades, Sri Lankans experienced the ground shaking due to earthquakes. Increasing population puts greater demands on housing, energy, water and transport needs of the society. To achieve these needs the construction activity of buildings, dams, reservoirs, bridges, power plants etc, have to be increased. Thus, even in areas of low seismic activity, the loss due to unexpected earthquakes may be high clearly due to heavy infrastructure development, unless the built-up structures are engineered.

The tsunami on 26th December 2004 having magnitude 9.3Mw Sumathra Earthquake struck most of the coastal areas in Sri Lanka. From that tsunami, more than 30,000 lives were lost, one and half millions of people were displaced from their homes and most of the coastal areas were devastated. However no damage was observed due to direct effect of ground shaking. Various parties like Engineers, construction companies, insurance companies etc, highlights that the necessity of designing more robust buildings and structures for seismic and tsunami loads.



When an earthquake occurs, seismic waves radiate away from the source and spread rapidly through the earth's crust. They transfer to another site or location through the bedrock. Then the wave comes up to the surface through soil overlying the rock. This phenomenon is known as local site effects. Depending on the ground condition, the waves are amplified or de-amplified.

## 1.2 Earthquakes

### 1.2.1 Type of Earthquakes

The earth's crust is divided into six continental-sized plates (African, American, Antarctic, Indo-Australian, Eurasian and Pacific) and about 14 sub-continental size plates. Those are named as tectonic plates. Out of them, Sri Lanka is situated in Indo-Australian plate.

Earthquakes occur at plate boundaries as well as within the plates. The earthquakes occur at plate boundaries, are known as interplate earthquakes and earthquakes occur within the plates are known as intraplate earthquakes. The major tectonic structures around Sri Lanka are located on the plate boundaries of the Indo-Australian plate. Sumathra Subduction zone to the East is the nearest tectonic structure to Sri Lanka. Second is the extensional/ transform fault structure of the central Indian ridge to the West. However the above zones are at least 2000 km away from Sri Lanka. Generally the direct effective zone of an earthquake is taken as the circle of 300 km radial distance from the epicenter. Since Sri Lanka is far enough from the plate boundaries, it can be considered as Sri Lanka has no threat from interplate earthquakes but experiences intraplate earthquakes.



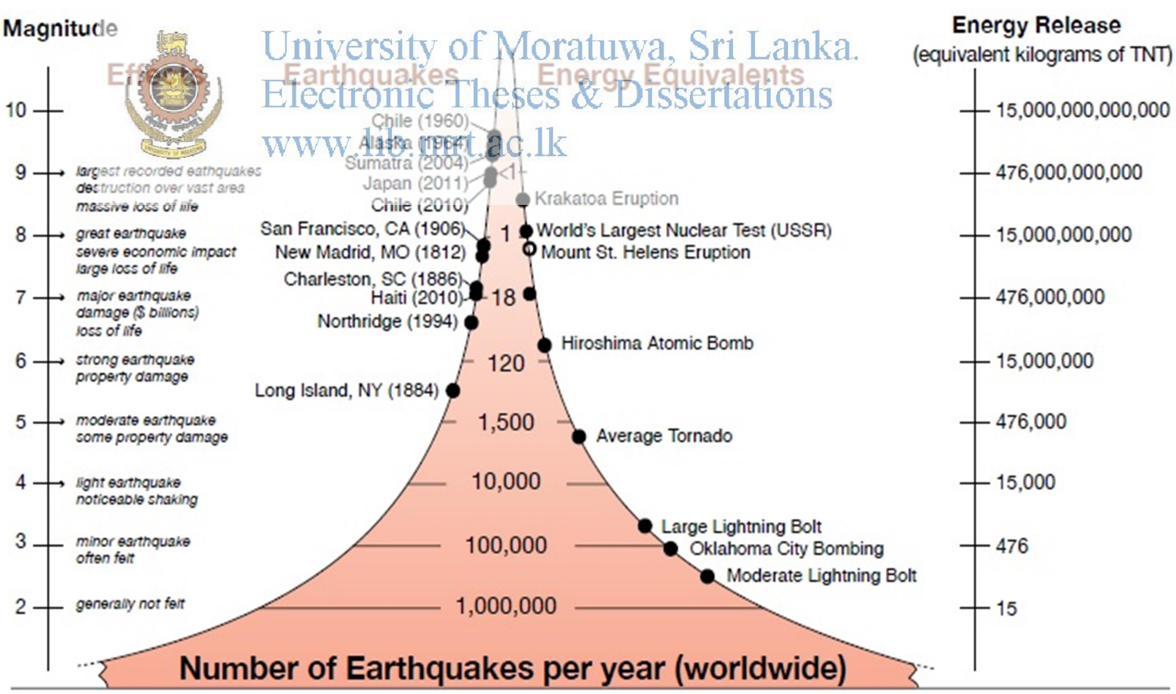



**Figure 1.1 :Number of earthquakes per year (worldwide)**
Source : IRIS, Education and outreach series No.03, June 2011

### 1.2.2 Earthquakes in the world

Magnitude 2 or smaller earthquakes occur several hundred times a day worldwide. Generally more than 1,000,000 earthquakes (magnitude>2.0) occur in each year around the world. Out of them, 100,000 earthquakes (magnitude>3.0) are felt by people and about 100 earthquakes cause damage. Major earthquakes (magnitude >7) happens more than once per month. The great earthquakes (magnitude≥8) occur about once a year. Figure 1.1 shows the number of earthquakes per year. Left side of the figure describes the earthquake magnitude of the events and on the right side of the figure show equivalent energy release in TNT. One kg of TNT =4184 kJ (IRIS, June 2011).

The largest recorded earthquake was the Great Chilian Earthquake of 22nd May 1960 which had a magnitude of $9.5M_w$ (IRIS, June 2011).

### 1.2.3 Earthquakes in and around Sri Lanka



S.B.S.Abayakoon (1996) reported that seven earthquakes have been recorded with epicenters within about 20 km of Colombo since 1819. Five of these events have magnitudes 5.7, 5.0, 3.7, 3.7 and 3.0 while the magnitudes of the other two are not in records. The first one occurred on 9th February 1823, with the epicenter at about 15 km North-East of Colombo. As per the data recorded at National Archives and reported by Wimalarathne (1993) and Vithanage (1995), an event with an estimated magnitude of 6.6 and the epicenter within or very close to Colombo occurred on 14th April 1615. It has estimated that 200 houses destroyed and over 2000 casualties occurred. Further, Vithanage (1995) reveals an earthquake occurred in 1814, having its epicenter in Batticoloa, caused severe damage to same town. In addition to that, according to Wimalarathne (1993) and Vithanage (1995), two earthquakes have occurred on 7th and 18th of April 1891, having its epicenters at about 10 km North of Mahiyangana. Further an earthquake has occurred on January 1882, having its epicenter at Trincomalee. The epicentral locations of these events are by the side of Mahaweli river.

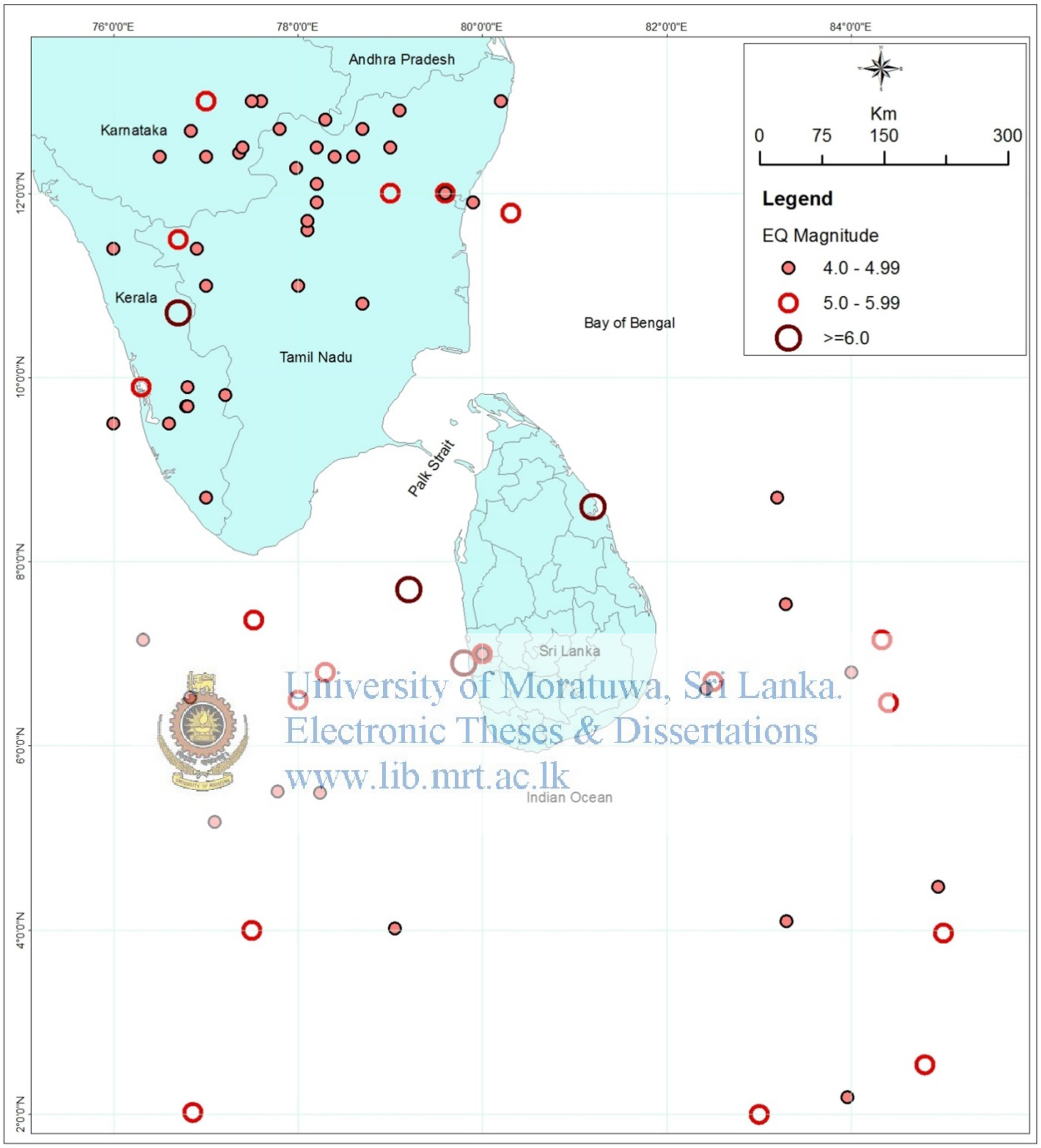



**Figure 1.2 : Earthquakes in and around Sri Lanka**



According to Fernando and Kulasinghe (1986), reported by S.B.S.Abayakoon (1996), there are several other events felt within the country at various places, since 1944. Out of them, two were felt at Tangalle and Mahailuppallama and the others were felt in the up country. Further, they report the results of a study carried out to monitor the seismic events in the hill country, due to the filling of Kotmale reservoir. For this purpose, data from four seismographs installed in the project area were taken between 1982 and 1985. During this period 87 events were recorded and the maximum observed magnitude was 2.25. Out of those 87 events, the epicenters of about 40 events are within the island and most of them are within the up country.

Sri Lanka is situated in Longitude 79-82E and Latitude 5-10N. About 77 earthquakes which have magnitude greater than 4.0 $M_w$ have been occurred in and around Sri Lanka, from 1615 to 2015 as shown in Figure 1.2. The earthquake data are present in Annexure 3. The historical and instrumental data was collected from different sources such as Chandra (1977), Rao and Rao (1984), Iyengar et.al. (1999), Jaiswal and Singha (2007), Abayakoon (1995), Navin Peiris (2007), internationally recognized earthquake databases on the internet such as the National Earthquake Information Center (NEIC), International Seismological Center (ISC) and Incorporated Research Institutions for Seismology (IRIS). All of these events are intraplate earthquakes.



Instrumental earthquake data can be obtained from 1967. The historical data are recorded depending on the archives. Large earthquakes are recorded since the people felt them and might experience damages to their houses or other manmade structures and/or their lives. However, there is a possibility to not recording low magnitude earthquakes.

## 1.3 Scope and Objectives

Colombo is the main commercial city in Sri Lanka. Day by day, Sri Lanka is developing rapidly. High rise buildings, roads, bridges and other infrastructure facilities are improving faster after the end of civil war in 2009. Designing and construction of earthquake resistant structures considering local site effects are playing a major role in infrastructure development. There are no specific guidelines developed for that except few studies have been done to local site effects in Colombo city by author like S.B.S. Abayakoon (1993).

Earthquake hazard is controlled by three factors: source properties, path characteristics and local site effects. In this study, it is focused to study earthquake hazard governed by the local site effects. The peak ground acceleration (PGA) and spectral acceleration ($S_a$) values at ground surface may vary significantly from the values at bed rock level. These variations, either amplification or de-amplification, will depend upon the site condition.

Peiris L.M.N. and Uduweriya et.al. (2013) has discussed about the seismic hazard at Colombo city area. S.B. Uduweriya et.al. (2013) has developed the response spectrum at rock level with the PGA is 0.1g for Colombo city area. No detail study has been done to develop response spectrum with local site effects. The study area of this research work is also Colombo city area and is shown in Figure 1.3.

To study the local site effect, underground soil properties are required. Those are obtained from the borehole data collected from National Building Research Organisation (NBRO) at No.99/1, Jawatta road, Colombo 05. The locations of boreholes are also shown in Figure 1.3.



Using "Google map" the latitude and longitude values of borehole locations were obtained. Using Kandawala coordinates the latitude and longitude values were converted into x and y coordinates. Kandawala coordinates are developed taking top of Piduruthalagala mountain as (200,000 m, 200,000 m). Then the elevation of borehole locations were obtained using the 1:10,000 scale maps developed by Survey department and the elevation model developed in NBRO.

The main objectives of this research project are :

1. Development of generalized soil profiles for Colombo city area.
2. Obtain response spectrum for Colombo city with local site effects and compare it with existing seismic hazard data available in Sri Lanka.

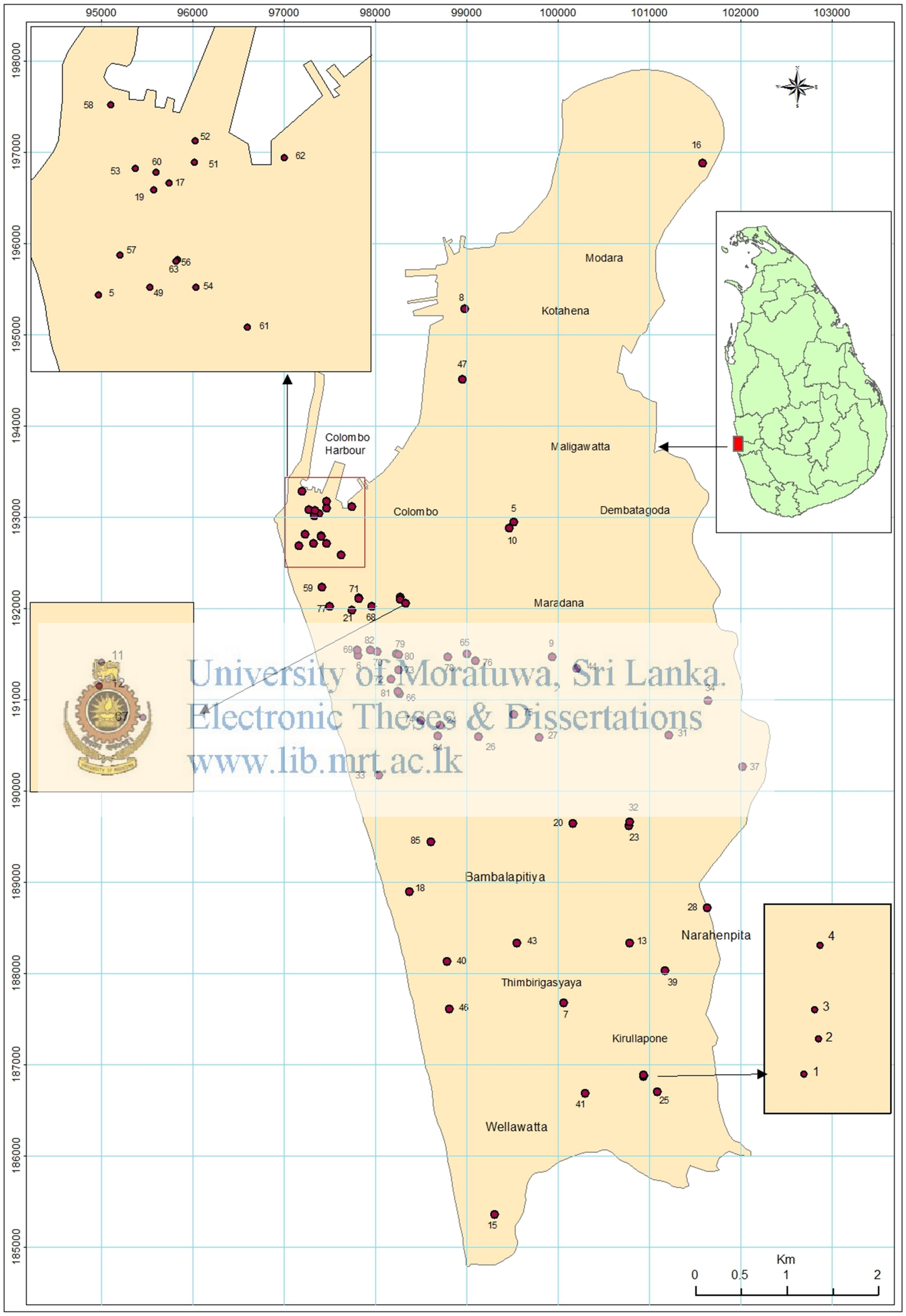




**Figure 1.3 : Study area with borehole locations**

## 1.4 Overview of the Report

Design of earthquake resistant structures is a new direction for Sri Lanka. In the recent past, the practicing engineers have been directed to provide earthquake resistant details for important buildings. There are some studies have been done and proposed design response spectrum at rock level. About 15-25m thick overburden soil layer is found on that basement rock in Colombo Area. There is no proper research have been done to study the effect of those site effects. This study has been focused to fill that gap for some extent.

Studying of seismic waves and their behavior is important to analyse the wave transform from rock to soil layers. Seismic waves, wave propagation, obtaining of wave propagation velocity of soils based on SPT 'N' values and related theories are discussed in chapter 2.



Chapter 3 bears the main body of the study in which the methodology is described. Obtaining soil profiles using borehole data in study area and wave propagation velocity, computer medelling etc. are described. For this study area 8 profiles were developed. 1-D soil profile idealization is introduced in this chapter because the software used to analyse soil profile is limited to 1-D. The basic steps of this software (EduShake) to analyse soil profiles is also described. Six numbers of time histories available in the software (The software is allowed only available time histories) were applied at the basement rock level as input motion.

The program was run for the six available input motions for eight profiles. The mean value of input and output motions were obtained for the all soil profiles. Finally the average value of above 8 profiles was taken. This method and related details are shown in chapter 4.

The amplification due to the local site effects was taken as the difference between the mean value of response spectrum with local site effects and the response spectrum at rock level. When the design response spectrum at rock level is available, adding the above difference to the design spectrum, the design spectrum at surface level can be obtained. S.B. Uduweriya (2013) has suggested a response spectrum at rock level. The design spectrum with local site effects was obtained based on that. This is the main objective of this report and this area is described in chapter 5, Conclusion and Recommendation.

# 2.0 LITERATURE SURVEY

## 2.1 Terminology

***Response history or time history***

The response history is a ground motion plot of the acceleration (Figure 2.1), velocity and displacement of a point on the ground surface as a function of time for the entire direction of earthquake. Figure 2.1 shows the plot of an acceleration record which is known as accelerograph of an earthquake. The recordings of an accelerograph provide the values of acceleration as a function of time at the location of the seismic instrument.

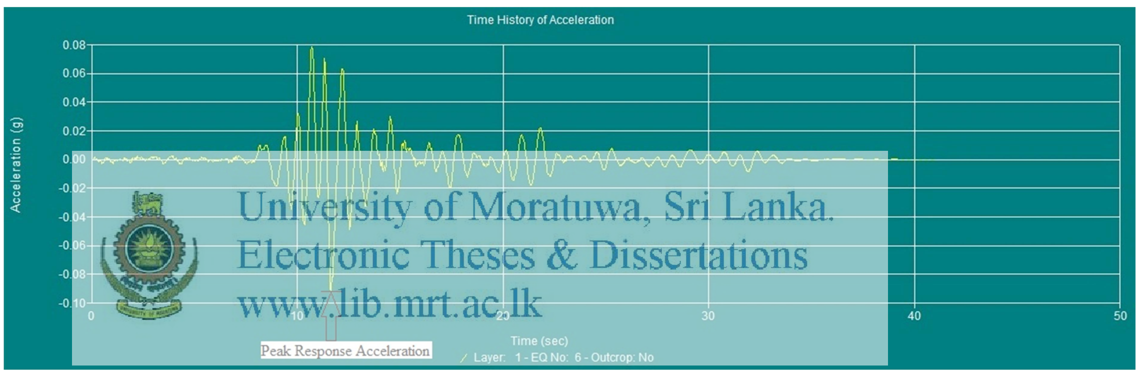




**Figure 2.1- Sample of an accelerograph**

***Peak response acceleration***

The maximum amplitude of the recorded acceleration (Figure 2.1) is termed as peak response acceleration and similarly the peak response velocity and the peak response displacement are the maximum amplitude of the recorded velocity and displacement respectably.

***Spectral Acceleration***

Maximum acceleration of an object which is subjected to an earthquake, specifically a damped, harmonic oscillator moving in one dimension.

***Response Spectrum***

$$T_n = \sqrt{\frac{m}{k}}$$

$T_n$ depends on the m & k. For a given earthquake, set of spectral acceleration ($S_a$) values, T values can be obtained for different values of m and k. The plot of $S_a$ vs T for a particular damping ratio (generally ξ=5%) is known as response spectrum.

**Strong motion**

Strong Motion is commonly known as a shaking with large amplitude and long duration represented by the acceleration – time history as shown in Figure 2.1. The characteristics of strong motion earthquakes are as follows.

***Duration***: In general the time history of an earthquake ground motion consists of following.

- An initial segment in which the energy and vibration levels rapidly increase to high values.
- A segment of uniformly strong shaking at these high values for longer period.
- A segment of gradually attenuating vibration.



The time interval between 5% and 95% contribution of energy of vibration is considered as the significant duration of strong motion. A longer duration of earthquake gives rise to yielding and repeated loading in to plastic range followed by the deterioration of stiffness and strength of the structure. The longer duration of earthquake also leads to more number of loading, unloading cycles, causing fatigue in the structure. The damage potential of the long duration earthquakes is large.

***Frequency content:*** A typical strong motion accelerogram can be thought of as a superimposition of simple,constant amplitude sinusoidal waves, each with a different frequency, amplitude and phase.

The dominant frequency components out of these are of importance as the same may lead to the phenomenon of resonance (Maximum response to earthquake excitation) when coinciding with the dominant natural frequency of the structure.

***Amplitude:*** PGA is presently considered as a measure of strength of ground shaking, as it relates directly to the maximum inertial forces generated in the structure. The seismic forces on the structure are estimated based on the amplitude of response.

***Attenuation of the ground motion:*** Attenuation or decrease in the amplitude and change in the frequency content of seismic waves with distance of the site from the source happens due to reflection, refraction or scattering of seismic waves through the medium and the energy absorption (damping).

Attenuation depends on the distance of the site from the source of the seismic activity and the medium of wave travel (soil, sand, rock, water etc.). The attenuation is faster if the seismic waves are intercepted by the water bodies such as ponds.

The attenuation occurs at a faster rate for higher frequency (short – period) components than for lower frequency (long – period) waves.



***Peak ground acceleration (PGA):*** For an infinitely rigid structure (natural period, $T_n$ = 0) the man does not experience any motion relative to the base, and therefore, the acceleration response of the mass will be the same as the acceleration of the ground. The response acceleration at $T_n = 0$ is, therefore, termed as PGA.

***Design Response Spectrum:*** The response spectrum for actual ground motion is quite irregular and hence the individual spectrum is not convenient for the use in the design. The individual spectrum can be used for analysis to asses response to a particular earthquake. The design response spectrum is based on the statistical analysis of the response spectra for the ensemble of ground motions which is smooth and representative. The design response spectrum is not intended to match the response spectrum of any particular ground motion. But it represents the average of response spectra of several ground motions.

## 2.2 Geological and Tectonic Structures

### 2.2.1 Geologic Structures of Sri Lanka

90% of the island consists of Precambrian metamorphic and granitoid rocks. The Precambrian basement of island is divided into three major units called:

- Central Highland Complex (HC)
- Wanni Complex (EC)
- Vijayan Complex (VC)

The Kadugannawa Complex (KC) is a minor unit within the Highland Complex. HC is the oldest unit thrusting upward to form the Central Highlands with the highest uplift along a SW-NE-ENE belt from Galle – Rakwana – Horton plains to Batticoloa. The uplift in the Jurassic (post – Precambrian) period was attributed to the movement of the Sri Lanka mini-plate in S-SE direction relative to the Indian plate. Numerous lineaments were therefore identified in the HC with major lineaments along the belt of highest uplift and the N-S trending Mahaweli lineament where the Mahaweli river takes a straight course for about 60km. The micro – seismicity within the island recorded by the Kotmale micro-seismic network could be closely associated with these lineaments in the central highland region.



### 2.2.2 Internal Structure of the Earth

The field of *seismology* (from the Greek *seismos* for earthquake and *logos* for science) developed from understanding of the internal structure of the earth and their behaviour specially related to earthquake phenomena.

The earth is roughly spherical, with an equatorial diameter of 12,740 km.The earth weighs some 4.9 x $10^{21}$ MT, which indicates an average specific gravity of about 5.5. Since the specific gravity of surficial rocks is known to be on the order of 2.7 to 3, higher specific gravities are implied at greater depths.

One of the first important achievements in seismology was the determination of the internal structure of the earth. As the different types of seismic waves travel through the earth, they are refracted and reflected at boundaries between different layers, reaching different points on the earth's surface by different paths.

The crust, on which human beings live, is the outermost layer of the earth. The thickness of the crust ranges from about 25 to 40 km beneath the continents to as thin as 5 km or so beneath the oceans. (Figure 2.2) Since it is exposed to the oceans or the atmosphere, the crust is cooler than the materials below it. In addition to being thinner, the oceanic crust is generally more uniform and denser than the continental crust.

A distinct change in wave propagation velocity marks the boundary between the crust and the underlying mantle. This boundary is known as the Mohorovicic discontinuity, or the Moho, named after the seismologist who discovered it in 1909. Although the specific nature of the Moho itself is not well understood, its role as a reflector and refractor of seismic waves is well established. The mantle is about 2850 km thick and can be divided into the upper mantle (shallower than about 650 km) and the lower mantle. No earthquakes have been recorded in the lower mantle, which exhibits a uniform velocity structure and appears to be chemically homogeneous, except near its lower boundary. The mantle is cooler near the crust (temperature is about 3000°F) than at greater depths (temperature near outer core is about 4,700°F). As a result, the mantle materials are in a viscous, semimolten state. They behave as a solid when subjected to rapidly applied stresses, such as those associated with seismic waves, but can slowly flow like a fluid in response to long-term stresses.



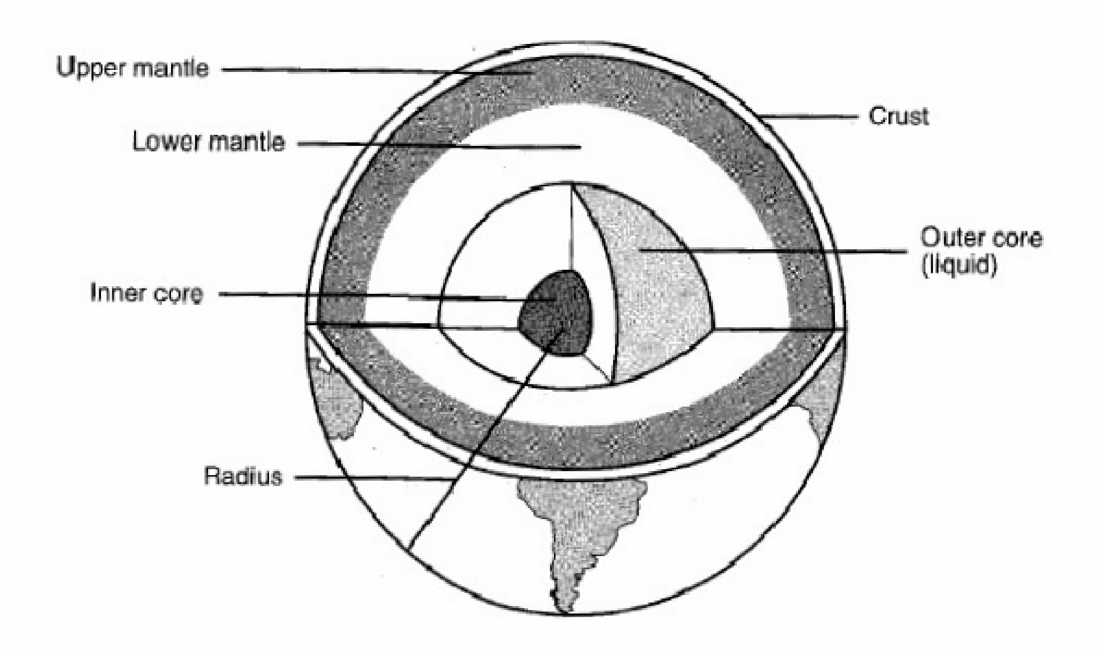



**Figure 2.2 : Internal Structure of the Earth**

Source : Geotechnical Earthquake Engineering by S.L.Kramer, 1996.

The outer core or liquid core is some 2,260km thick. In liquid, s-waves cannot transmit. Hence, the s-wave velocity drops to zero at the core mantle boundary. This boundary is known as Gutenberg discontinuity. Also in this core-mantle boundary, p-wave velocity also drops suddenly. The outer core consists of molten iron and hence its specific gravity increased into the order of 9 to 12. The inner core consists of nickel-iron material. The inner core is in solid state having specific gravity up to about 15 and temperature is estimated at about 5,000°F.

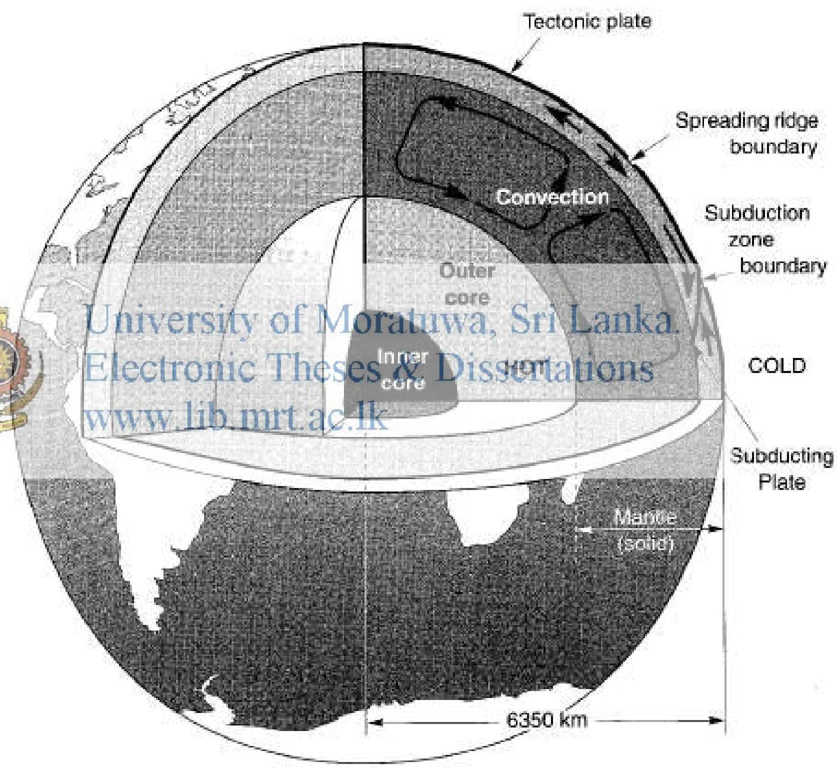





**Figure 2.3 :Convection currents in mantle**

Source : Geotechnical Earthquake Engineering by S.L.Kramer, 1996.

Plate movement explains on the requirement of thermomechanical equilibrium of the earth's material. The upper portion of the mantle is in contact with the relatively cool crust while the lower portion is contact with the hot outer core. Obviously, a temperature gradient must exist within the mantle. The variation of mantle density with temperature produces the unstable situation of denser (cooler) material resting on top of less dense (warmer) material. Eventually, the cooler, denser material begins to sink under the action of gravity and the warmer, less dense material begins to rise. The sinking material gradually warms and becomes less dense; eventually, it will move laterally and begin to rise again as subsequently cooled material begins to sink. This process is the more common one of convection.

Convection currents in the semi-molten rock of the mantle, imposes shear stresses on the bottom of the plates, thus 'dragging' them in various directions across the surface of the earth as shown in Figure 2.3. These plate movements create earthquakes in plate boundaries.

## 2.3 Seismic Waves

There are mainly two types of seismic waves produced during an earthquake occurs. They are known as body waves and surface waves. The waves travelling through the interior of the earth are known as body waves and the waves travel along the surface of the earth are known as surface waves. There are two types of body waves called P- Waves and S- Waves. The deformations create by body waves are shown in Figure 2.4.



P- Waves also known as primary, compressional or longitudinal waves involve successive compression and rarefaction of the materials through which they pass. They are like sound waves; the motion of an individual particle that a -P wave travels through is parallel to the direction of wave travel. Like sound waves, P- waves can travel through solids as well as fluids.

S- waves also known as secondary, shear or transverse waves undergo shearing deformations as they travel through a material. The motion of an individual particle is perpendicular to the direction of S- waves travel. The direction of particle movement can be used to divide S- waves in to two-components SV (Vertical plane movement) and SH (horizontal plane movement).

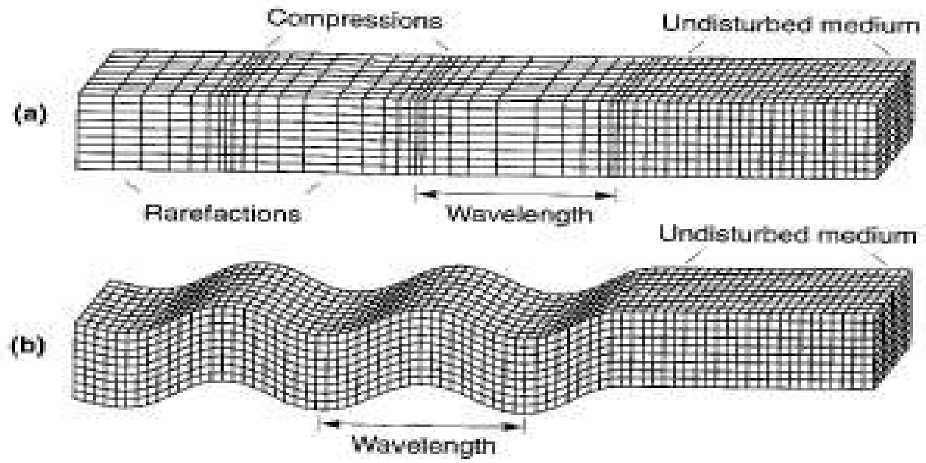



**Figure 2.4- Deformations created by body waves: P-waves and SV-waves**

Source : Kramer S.L., 'Geotechnical Earthquake Engineering', 1996



The Speed of the body waves varies with the stiffness of the material through which the wave travels. Since the geologic materials are stiffest in compression, P-waves travel faster than other seismic waves and hence they reach to a particular site faster than other waves. Fluids which has no shearing stiffness, cannot sustain S- waves.

Surface waves occur at the interaction between body waves, surface and surficial layers of the earth. They travel along the surface of earth with decreasing the amplitude roughly exponentially with depth as shown in Figure 2.5. Because of the nature of the interactions required to produce them, surface waves are more prominent at distances further from the source of the earthquake. At distances greater than about twice the thickness of the earth's crust, surface waves rather than body waves will produce peak ground motions.

Though there are several types of surface waves, Rayleigh waves and love waves are the most important surface waves in Engineering purpose. Rayleigh waves produced by interaction of P and SV waves with the earth's surface, involve both vertical and horizontal particle motion. They are similar on some aspect to the waves produced by a rock thrown into a pond. Love wave results from the interaction of SH-waves with a soft surficial layer and have no vertical component of particle motion.

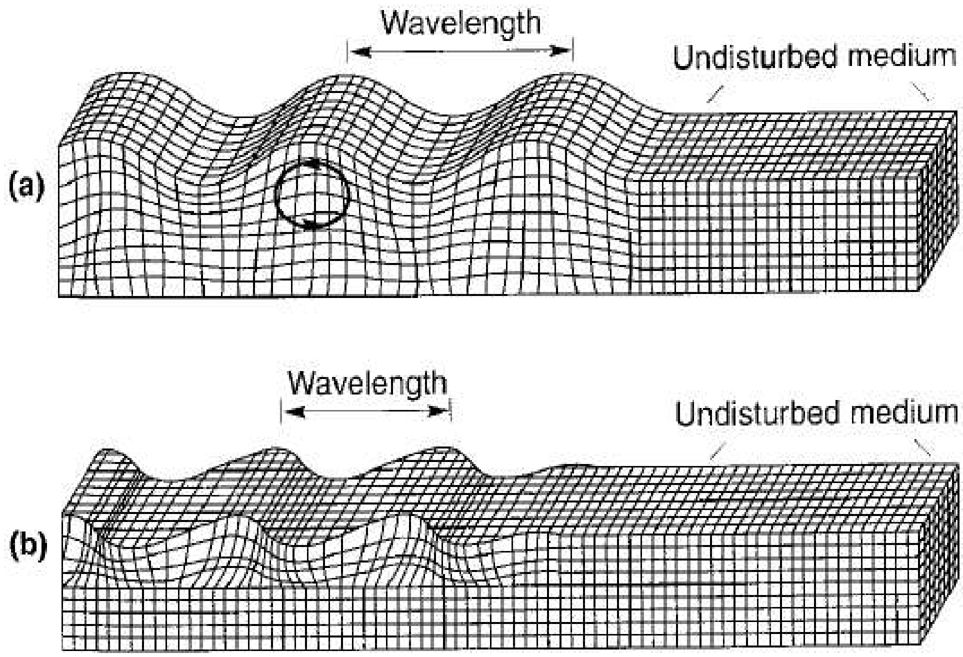



**Figure 2.5– Deformations created by surface waves a). Raleigh waves, b). Love waves**

Source : Kramer S.L., 'Geotechnical Earthquake Engineering', 1996



## 2.4 Wave Propagation

Most structures can be modeled as assemblages of discrete masses with discrete sources of stiffness. But geological material cannot do so. They must be treated as continua and their response to dynamic disturbances must be described in the context of wave propagation. Depending on the media wave propagation can be categorised as follows:

- Unbounded media
- Bounded media
- Layered media

## 2.5 Waves in Unbounded Media

In this case, it is assumed that the media is unbounded or extends infinitely in the direction(s) of wave propagation.

### 2.5.1 One dimensional wave propagation in unbounded media

One dimensional idealization of an unbounded medium is that of an infinitely long rod or bar. The one dimensional wave equation is derived based on:

- Equilibrium of forces and compatibility of displacements
- Strain - displacement and Stress – strain relationships

Three different types of vibration can occur in a thin rod.

- Longitudinal vibration during which the axis of the rod extends and contracts without lateral displacement.
- Torsional vibration in which the rod rotates about its axis without lateral displacement of the axis.
- Flexural vibration during which the axis itself moves laterally.



Flexural vibration is not so important in seismic hazard analysis. Hence only other two types of vibrations are considered further.

#### 2.5.1.1 Longitudinal waves in an infinitely long rod

Consider the free vibration of an infinitely long linear elastic, constrained rod having following properties shown in Figure 2.6

- Cross – Sectional area A
- Young's modules E
- Poisson's ratio ν
- Density ρ
- Roller supports represents the constraint against radial straining

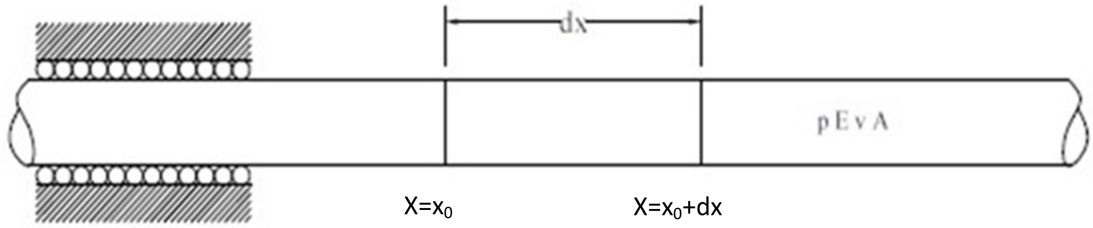



**Figure 2.6 – Infinitely long linear elastic, constrained rod**

Since the rod is constrained against radial straining, particle displacements caused by a longitudinal wave must be parallel to the axis of the rod.

***Assumptions***

- Material is linear elastic
- Cross – Sectional planes will remain planer
- Stresses will be distributed uniformly over each cross section
- Material is homogeneous



When a stress wave passes the element having length dx, as shown in Figure 2.6, the axial stress at the left end of the element ( $x = x_o$) is $\sigma_{xo}$. At the right end ( $x = x_o + dx$), the axial stress is $[\sigma_{x0}+\frac{\partial\sigma x}{\partial x}.dx]$. For dynamic equilibrium;

$$[\sigma_{x0}+\frac{\partial\sigma x}{\partial x}.dx]A-\sigma x_0.A = A \quad .\rho.\frac{\sigma^2 u}{\sigma t^2} \tag{2.1}$$

Where u is the displacement in the x – direction. The left side of the equation represents the unbalanced external forces acting on the element. The right side of the equation indicates the internal force induced by acceleration of the mass of the element. Hence the one dimensional equation of motion can be simplified as

$$\frac{\partial\sigma_x}{\sigma x} = \rho.\frac{\partial^2 u}{\partial t^2} \tag{2.2}$$

This equation is valid for any stress – strain behavior. But this equation cannot be solved directly because it mixes stresses with displacements.To simplify the equation, the stress - strain relationship of$\sigma_x = M\varepsilon_x$ is used.

Where, the constrained modules M= $\left\{\frac{1-\upsilon}{(1+\upsilon)(1-2\upsilon)}\right\}E$ and

Strain - displacement relationship $\varepsilon_x = \frac{\partial u}{\partial x}$

$$\sigma_x = M.\frac{\partial u}{\partial x} \text{ and}$$

$$\frac{\partial \sigma_x}{\partial x} = M.\frac{\partial^2 u}{\partial x^2}$$

From equation (2.2) $$\frac{\partial^2 u}{\partial t^2} = \frac{M}{\rho}.\frac{\partial^2 u}{\partial x^2} \quad (2.3)$$

Then, the one dimensional wave equation can be written as

$$\frac{\partial^2 u}{\partial t^2} = v_p^2.\frac{\partial^2 u}{\partial x^2} \quad (2.4)$$

Since $v_p = \sqrt{\frac{M}{\rho}}$, wave propagation velocity ($v_p$) depends only on the properties of the rod material: stiffness and density. $v_p$ is independent of the amplitude of the stress wave. (Wave propagation velocity is proportionate to square root of stiffness and inversely proportionate to square root of density.)



The wave propagation velocity is the velocity at which a stress wave would travel along the rod. Particle velocity ($\dot{u}$) is the velocity at which a single point within the rod would move as the wave passes through it.

From the strain – displacement relationship $\partial u = \varepsilon_x.\partial x$

From the stress-strain relationship $\varepsilon_x = \frac{\sigma_x}{M}$

and from the definition of wave propagation velocity $\partial x = v_p \partial t$

Then the particle velocity

$$\dot{u} = \frac{\partial u}{\partial t} = \varepsilon_x.\frac{\partial x}{\partial t} = \frac{\sigma_x}{M}.\frac{\partial x}{\partial t} = \frac{\sigma_x}{M}.v_p = \frac{\sigma_x}{\rho v_p^2}.v_p = \frac{\sigma_x}{\rho.v_p} \quad (2.5)$$

According to above equation, particle velocity is proportional to the axial stress in the rod. The coefficient of proportionality, $\rho v_p$, is called the specific impedance of the material. The specific impedance is another important property that influences the behavior of waves at boundaries.

### 2.5.1.2 Torsional waves in an Infinity long rod

Torsional waves involve the rotation of the rod about its own axis. In longitudinal waves, the direction of particle motion was parallel to the direction of wave propagation. In torsional waves, particle motion is constrained to planes perpendicular to the direction of wave propagation.

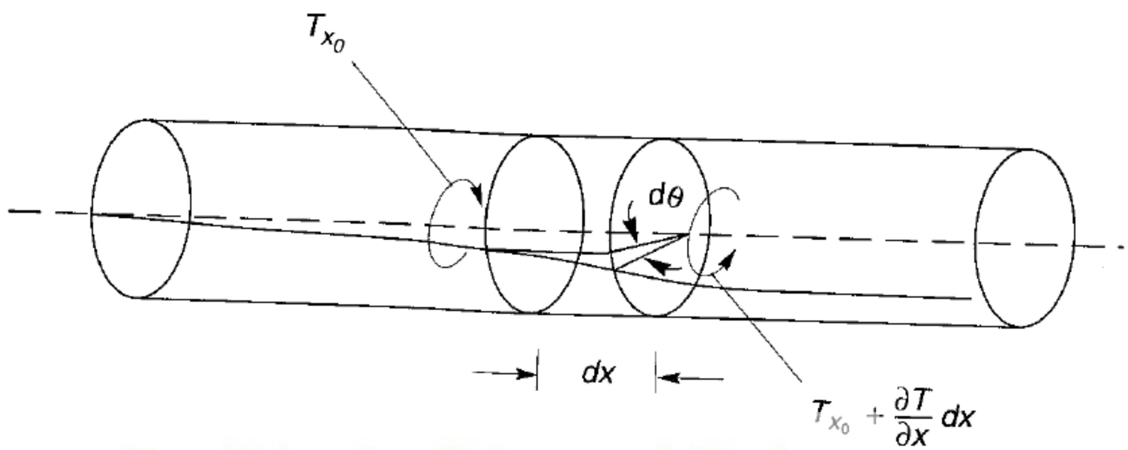



**Fig. 2.7** – **Torque and rotation at ends of element of length dx and cross-sectional area, A.**

Source : Kramer S.L., 'Geotechnical Earthquake Engineering', 1996



Consider a small segment having length, *dx* of figure 2.7. A torsional wave of torque amplitude 'T' travels along the rod. For the dynamic torsional equilibrium, unbalanced external torque should be equal to the internal torque.

$$\left(T_{x0} + \frac{\partial T}{\partial T}dx\right) - T_{x0} = \rho J.dx.\frac{\partial^2\theta}{\partial t^2} \tag{2.6}$$

The equation of motion can be obtained as

$$\frac{\partial T}{\partial x} = \rho \ .\frac{\partial^2\theta}{\partial t^2} \tag{2.7}$$

Also the torque-rotation relationship

$$\mathrm{T} = GJ.\frac{\partial\theta}{\partial x} \tag{2.8}$$

$$\frac{\partial T}{\partial x} = GJ.\frac{\partial^2\theta}{\partial x^2}$$

$$\frac{\partial^2\theta}{\partial t^2} = \frac{G}{\rho}.\frac{\partial^2\theta}{\partial x^2}$$

$$\frac{\partial^2\theta}{\partial t^2} = v_s^2.\frac{\partial^2\theta}{\partial x^2} \tag{2.9}$$

Where $v_s = \sqrt{\frac{G}{\rho}}$

$V_s$ depends only on the polar moment of inertia of the rod about its axis and density. Torsional wave propagation velocity is also independent of the amplitude of the stress wave.

#### 2.5.1.3 Solution for the one dimensional equation of motion

Commonly one – dimensional wave equation is in the form of

$$\frac{\partial^2 u}{\partial t^2} = v^2 \frac{\partial^2 u}{\partial x^2} \tag{2.10}$$

Where, $v = v_p$ for longitudinal waves

$v = v_s$ for torsional waves

The general solution for the equation is in the form of



$$u(x,t) = f(vt - x) + g(vt + x) \tag{2.11}$$

Where $f$ and $g$ are any arbitrary functions of (vt- x) and (vt+x) which satisfy the equation (2.10). In order to $F$ remains constant when x increases with time (at velocity v) and $g$ remains constant when x decreases with time. Hence, the solution of equation (2.11) shows a displacement wave$[f(vt - x)]$ travelling at velocity, v in positive x direction and another $[g(vt + x)]$ travelling at the same speed in the negative x-direction. It also implies that the shapes of the waves do not change with position or time.

If the rod is subjected to some steady state harmonic stress $\sigma(t) = \sigma_0 cos\omega t$, the solution can be written in the following form with wave number, k,

$$u(x,t) = Acos(\bar{\omega}t - kx) + Bcos(\bar{\omega}t + kx) \tag{2.12}$$

First and second terms of the right side described harmonic waves propagating in the positive and negative x – directions, respectively. The wave number k is related to the wave length, $\lambda$ as follows.

$$\lambda = v\bar{T} = \frac{v}{\bar{f}} = \frac{2\pi}{\bar{\omega}} v = \frac{2\pi}{k} \tag{2.13}$$

According to equation (2.13) at a given velocity the wave length, increases with wave propagation velocity. Equation (2.12) shows that the displacement varies harmonically with time and position as shown in figure (2.8).

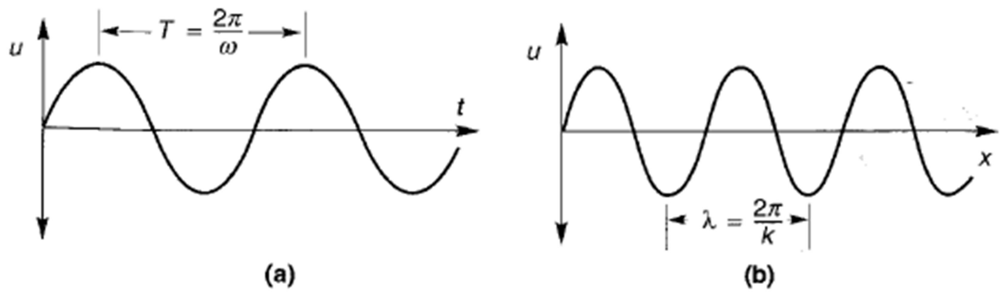



**Figure 2.8 : Particle displacement a). as function of time b). as function of position along the rod.**

Source : Kramer S.L., 'Geotechnical Earthquake Engineering', 1996



If wave propagate only in positive x direction , B=0

Then $u(x,t) = A\cos(\varpi t - kx)$

$$\frac{\partial u}{\partial t} = -A\varpi\sin(\varpi t - kx)$$

$$\frac{\partial^2 u}{\partial t^2} = -A\varpi^2\cos(\varpi t - k\ \ )$$

$$\frac{\partial u}{\partial x} = Ak\sin(\varpi t - kx)$$

$$\frac{\partial^2 u}{\partial x^2} = Ak^2\cos(\varpi t - kx)$$

From equation (2.10), $-A\varpi^2\cos(\varpi t - k\ \ ) = -Ak^2v^2\cos(\varpi t - kx)$ (2.14)

$$\varpi^2 = k^2v^2$$

$$\varpi = kv$$

Using complex notation, the equivalent form of the solution can be written as

$$u(x,t) = Ce^{i(\varpi t - kx)} + De^{i(\varpi t + kx)} \tag{2.15}$$

## 2.6 Estimation of Shear Wave Velocity

In seismic ground response analysis, stiffness of geomaterial is a very important parameter. Soil stiffness is represented by either shear wave velocity or shear modulus. Small strain shear wave velocity ($v_s$) is directly related to small strain shear modulus ($G_{max}$) as follows.

$$G_{max} = \rho . v_s^2 \qquad (2.16)$$

Where $\rho$ – Soil density

$G_{max}$ and $v_s$ are primarily functions of soil density, void ratio and effective stress. Secondarily, they are functions of soil type, age, depositional environment, cementation and stress history. Table 2.1 sumarises the effect of increasing various parameters on $_{Gmax}$ and $v_s$.

**Table 2.1 : Effect of increase of various factors on $G_{max}$ and $V_s$.**

| Increasing Factor/Parameter | Influence on $G_{max}$ and $V_s$ |
|---|---|
| Confining Pressure or Overburden Stress ↑ | Increases with $\sigma'_{vo}$ ↑ |
| Void Ratio ↑ | Decreases with increased Void Ratio ↓ |
| Geologic Age ↑ | Increases with Geologic Age ↑ |
| Cementation ↑ | Increases with Cementation ↑ |
| Overconsolidation Ratio ↑ | Increases with OCR ↑ |
| Strain Rate or Frequency of Cyclic Loading ↑ | Increases with Strain Rate ↑ |



Source :Dobry and Vucetic (1987) reported by PEER, December 2012.

There are various laboratory and geophysical tests used to obtain $v_s$. Laboratory tests required high quality undisturbed samples. Obtaining high quality undisturbed samples are very costly and not practicable in cohesionless soils. Unlike laboratory testing, geophysical tests do not require undisturbed sampling. Seismic cone penetration test (SCPT) and standard penetration test (SPT) are the more common geophysical tests. In Sri Lanka, no enough SCPT data are available. Hence this study is based on SPT values.

| Era | Period | Epoch | Years Ago |
|---|---|---|---|
| Cenozoic | Quaternary | Holocene | 11,700 |
| | | Pleistocene | 2.6 M |
| | Tertiary | Pliocene | |
| | | Milocene | |
| | | Oligocene | |
| | | Eocene | |
| | | Paleocene | 65.5 M |
| Mesozoic | Cretaceous | Late | |
| | | Early | 145 M |
| | Jurassic | Late | |
| | | Middle | |
| | | Early | 200 M |
| | Triassic | Late | |
| | | Early | 251 M |
| Paleozoic | | | |



**Figure 2.9 : Geologic time scale**

Source : PEER, December 2012.

### 2.6.1 Geologic Considerations

Geologic considerations are important in calculating the Vs through correlations between Vs and soil and rock properties. Figure 2.9 presents the geologic time scale.

### 2.6.2 Site classification

The Caltrans Seismic Design Criteria classifies sites based on the $V_s$ of top 30 m of the soil profile ($V_{s30}$). It is defined six site categories (soil profile types A through F) as presented in Table 2.2.

**Table 2.2 : Caltrans/NEHRP soil profile types**

| Site Class | Soil Profile Name | $V_{S30}$ | SPT N-Value | Undrained Shear Strength |
|---|---|---|---|---|
| **A** | Hard Rock | > 5,000 ft/s<br>>1,500 m/s | ---- | ---- |
| **B** | Rock | 2,500 to 5,000 ft/s<br>760 to 1,500 m/s | ---- | ---- |
| **C** | Very Dense Soil and Soft Rock | 1,200 to 2,500 ft/s<br>360 to 760 m/s | > 50 bpf | > 2,000 psf<br>> 100 kPa |
| **D** | Stiff Soil | 600 to 1,200 ft/s<br>180 to 360 m/s | 15 to 50 bpf | 1,000 to 2,000 psf<br>50 to 100 kPa |
| **E** | Soft Soil[1] | < 600 ft/s<br>< 180 m/s | < 15 bpf | < 1,000 psf<br>< 50 kPa |
| **F** | Soils Requiring Site-Specific Evaluation[2] | ---- | ---- | ---- |

Source : PEER, December 2012.

For site classification, $V_{s30}$ is calculated as the time for a shear wave to travel from a depth of 30 m to the ground surface as shown in equation (2.17)

$$V_{s30} = \frac{30}{\sum\left(\frac{d}{v_S}\right)} \qquad (2.17)$$



The Catrans Seismic Design Criteria specifies site classification based on uncorrected SPT N values [Caltrans 2006].

### 2.6.3 Shallow velocity profiles and intermediate sites

In many cases in Colombo city, overburden soil layer thickness does not extend to a depth of 30 m. In such cases, extrapolation of shallow velocity data is required to estimate $V_{s30}$. Boore (2004) proposed an extrapolation method based on statistical analysis of borehole data to calculate $V_{s30}$ for "intermediate" sites (sites containing both soil and rock within the top 30m). Boore proposed the equation (2.18) to calculate $V_{s30}$.

$$logV_{s3} \ = a + b.logV_{sd} \qquad (2.18)$$

The coefficients a and b are presented in Table 2.3 for depth ranging from 10 to 29 m.

**Table 2.3 : Regression co-efficient**

| Depth (m) | Regression Coefficients a | b |
|---|---|---|
| 10 | 0.042062 | 1.0292 |
| 11 | 0.022140 | 1.0341 |
| 12 | 0.012571 | 1.0352 |
| 13 | 0.014186 | 1.0318 |
| 14 | 0.012300 | 1.0290 |
| 15 | 0.013795 | 1.0263 |
| 16 | 0.013893 | 1.0237 |
| 17 | 0.019565 | 1.0190 |
| 18 | 0.024879 | 1.0144 |
| 19 | 0.025614 | 1.0117 |
| 20 | 0.025439 | 1.0095 |
| 21 | 0.025311 | 1.0072 |
| 22 | 0.026900 | 1.0044 |
| 23 | 0.022207 | 1.0042 |
| 24 | 0.016891 | 1.0043 |
| 25 | 0.011483 | 1.0045 |
| 26 | 0.006565 | 1.0045 |
| 27 | 0.002519 | 1.0043 |
| 28 | 0.000773 | 1.0031 |
| 29 | 0.000431 | 1.0015 |



Source : Boore (2004), reported by PEER, December 2012



### 2.6.4 SPT N-value and Vs correlations for sands

A set of SPT-Vs correlation equations for sands proposed by various authors and reported by Pacific Earthquake Engineering Research Center (PEER) in December 2012, are presented in Table 2.4.

### 2.6.5 SPT N-value and Vs correlations for clays and silts

A set of SPT-Vs correlation equations for clays and silts proposed various authors and reported by Pacific Earthquake Engineering Research Center (PEER) in December 2012, are presented in Table 2.5.

**Table 2.4 : SPT – Vs correlation equations for sands**

| Study | Soil Type | Geology | | $V_S$ based on Uncorrected N-value (m/s) |
|---|---|---|---|---|
| | | Age[a] | Deposition[b] | |
| Kanai (1966) | Sand | ---- | ---- | $18.9 \; N^{0.6}$ |
| Shibata (1970) | Sand | ---- | ---- | $31.7 \; N^{0.5}$ |
| Imai & Tonouchi (1982) | Sand | H | A | $87.8 \; N^{0.29}$ |
| Imai & Tonouchi (1982) | Sand | P | A | $110.0 \; N^{0.29}$ |
| Sykora & Stokoe (1983) | Sand | ---- | ----- | $100.6 \; N^{0.29}$ |
| Dickenson (1994) | Sand | ---- | ---- | $88.4 \, (N + 1)^{0.3}$ |
| Hasncebi & Ulusay (2007) | Sand | Q | A | $90.8 \; N^{0.32}$ |
| Seed et al. (1983) | Silty Sand & Sand | Q | ----- | $56.4 \; N^{0.5}$ |
| Lee (1992) | Silty Sand | H | A | $104.7 \; N^{0.30}$ |
| Pitilakis et al. (1999) | Silt & Sand | ---- | A | $145.0 \; N_{60}^{0.18}$ |
| Ohta & Goto (1978) | Fine Sand | Q | A | $90.1 \; N^{0.34}$ |
| Ohta & Goto (1978) | Fine Sand | H | A | $98.3 \; N^{0.25}$ |
| Ohta & Goto (1978) | Fine Sand | P | A | $142.4 \; N^{0.25}$ |
| Ohta & Goto (1978) | Medium Sand | Q | A | $81.3 \; N^{0.34}$ |
| Ohta & Goto (1978) | Medium Sand | H | A | $94.3 \; N^{0.25}$ |
| Ohta & Goto (1978) | Medium Sand | P | A | $135.6 \; N^{0.25}$ |
| Ohta & Goto (1978) | Coarse Sand | Q | A | $80.1 \; N^{0.34}$ |
| Ohta & Goto (1978) | Coarse Sand | H | A | $96.7 \; N^{0.25}$ |
| Ohta & Goto (1978) | Coarse Sand | P | A | $140.1 \; N^{0.25}$ |



Source : PEER, December 2012.

**Table2.5 : SPT – Vs correlation for clays and silts**

| Study | Soil Type | Geology | | $V_S$ based on Uncorrected N-value (m/s) |
|---|---|---|---|---|
| | | Age[a] | Deposition[b] | |
| Ohta & Goto (1978) | Clay | Q | A | $85.6\ N^{0.34}$ |
| Ohta & Goto (1978) | Clay | H | A | $93.1\ N^{0.25}$ |
| Ohta & Goto (1978) | Clay | P | A | $134.8\ N^{0.25}$ |
| Imai & Tonouchi (1982) | Clay | H | F | $98.4\ N^{0.25}$ |
| Imai & Tonouchi (1982) | Clay | H | A | $107.0\ N^{0.27}$ |
| Imai & Tonouchi (1982) | Clay | P | A | $128.0\ N^{0.26}$ |
| Lee (1992) | Clay | H | A | $138.4\ (N+1)^{0.24}$ |
| Pitilakis, et al. (1999) | Clay | Q | A | $132.0\ N^{0.27}$ |
| Jafari et al. (2002) | Clay | ---- | ---- | $27.0\ N^{0.73}$ |
| Hasncebi & Ulusay (2007) | Clay | Q | A | $97.9\ N^{0.27}$ |
| Jinan (1987) | Silt & Clay | H | A | $116.1\ (N+0.32)^{0.20}$ |
| Lee (1992) | Silt & Clay | H | A | $129.4\ (N+1)^{0.26}$ |
| Lee (1992) | Silt | H | A | $104.0\ (N+1)^{0.33}$ |
| Imai & Tonouchi (1982) | Peat | H | A | $63.6\ N^{0.45}$ |



Source : PEER, December 2012.

# 3. METHODOLOGY

## 3.1 General

When an earthquake is occurred in a place, the waves radiate from the origin to any other place or site through the basement rock. From basement rock to ground level the seismic waves come through the soil layers. Its amplification or deamplification depends on the properties of the overburden soil layers.

To study the properties of subsurface soil layers, 77 numbers of borehole logs were able to collect from National Building Research Organisation within the Colombo city area.A sample borehole log is attached in Figure A1 in Annexure 1. Borehole log comprises client, location, date of boring, borehole number etc. as general data and soil type, location, layer changes, SPT N-value, ground water table etc as technical data.



## 3.2 Obtaining Sections Through Boreholes

First the borehole locations were plotted on a map as shown in Figure 3-1. It is planned to obtain sections parallel to and perpendicular to the coastal line. Since coastal line in study area is almost parallel to North-South direction, it is decided to obtain sections parallel to and perpendicular to the North-South direction.

Four sections are obtained parallel to the coastal line through 1-1, 2-2, 3-3 and 4-4 and other four sections obtained perpendicular to the coastal line through A-A, B-B, C-C, D-D as shown in Figure 3-1.The obtained sections are given in Annexure A4.

For the seismic analysis of sections, the software, EduShake is used. According to software limitations, only horizontal layered sections can be analysed. Hence based on above sections, more simple sections were developed and those are known as developed profiles. Those profiles are shown in Figure 3-2. The procedure followed to develop profiles is briefly discussed in section 3.3.

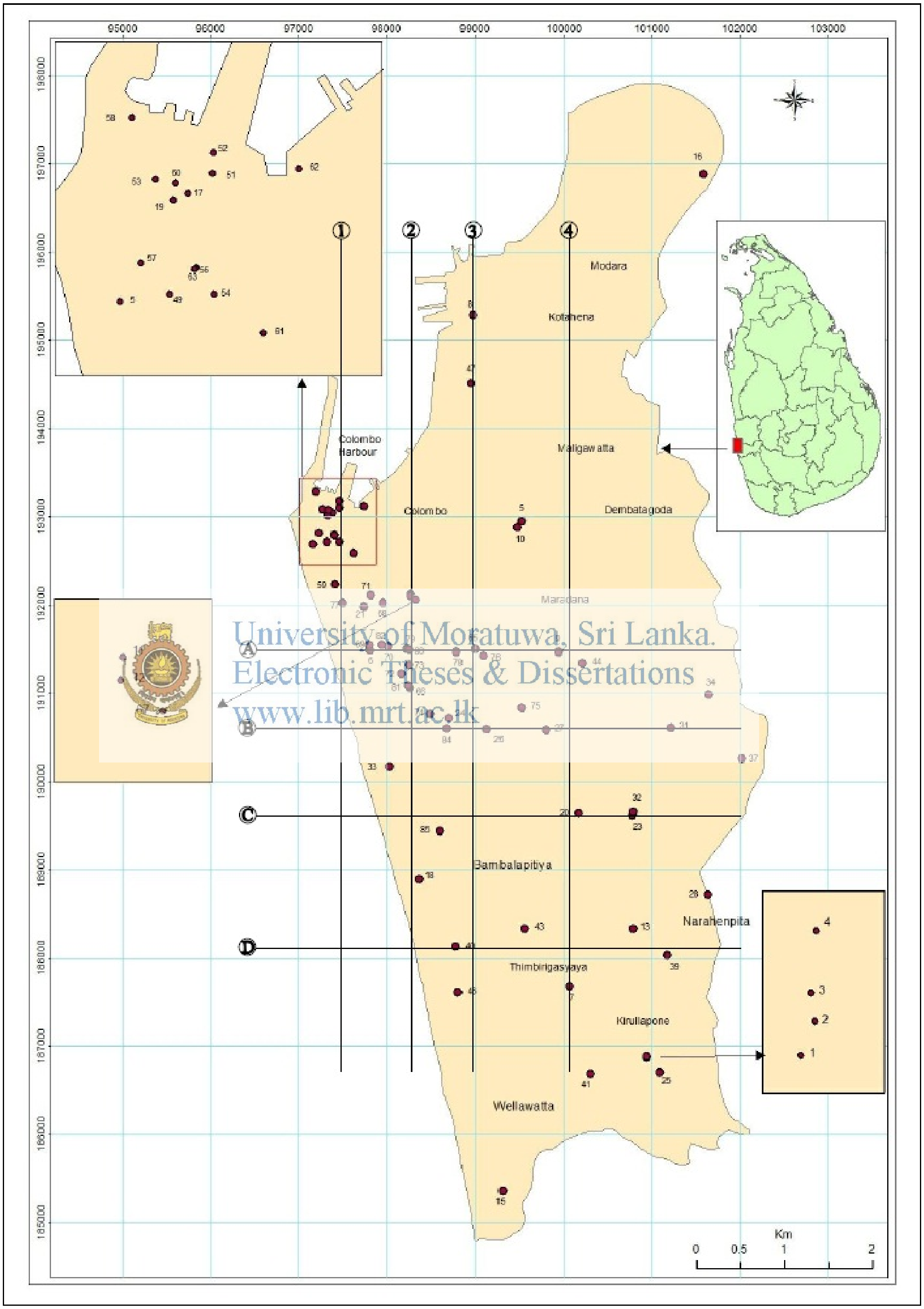





**Figure 3.1 : Locations of sections**

### 3.3 Development of profiles

According to borehole data, some are drilled down to the hard stratum or the bed rock while some are terminated within the soil. As the soil type and layer thickness are varying from borehole to borehole in complex way without having proper patterns. Sections shown in Figure A4.1-A4.8 in Annexure 4, vertical sections were plotted based on their spacing and elevations. Depth from ground level, SPT N-value, soil type and layer changes are shown with the borehole. The developed soil profiles are also shown in these figures. Those sections were simplified to obtain developed profiles. These simplifications are described with an example. For this purpose select profile B-B in Figure 3-2.

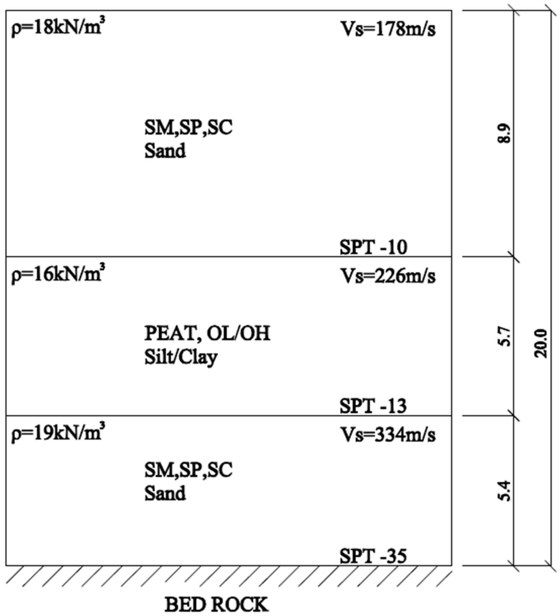
In order to develop profile B-B in Figure 3-2, the section B-B in Figure A4.2 in Annexure 4 shall be used. This section comprises 8 boreholes (BH74, BH84, BH26, BH75, BH27, BH31, BH34 and BH37). According to Figure 3-1, BH84, BH26, BH27 and BH31 are almost online. Though other four boreholes are not online, those are assumed to close enough to represent the section. Out of the eight boreholes, six were penetrated up to bedrock level and other two has been stopped at mid level. At the end of borehole line, one of 'R'or'S' is marked to represent whether the borehole is penetrated up to bedrock or not. 'R' indicates that the borehole is penetrated down to the hard stratum or rock level and 'S' indicates that the borehole is terminated within the soil. The average depth of six boreholes which were penetrated up to rock level was taken as the depth to rock level (Figure 3-2) from ground level.



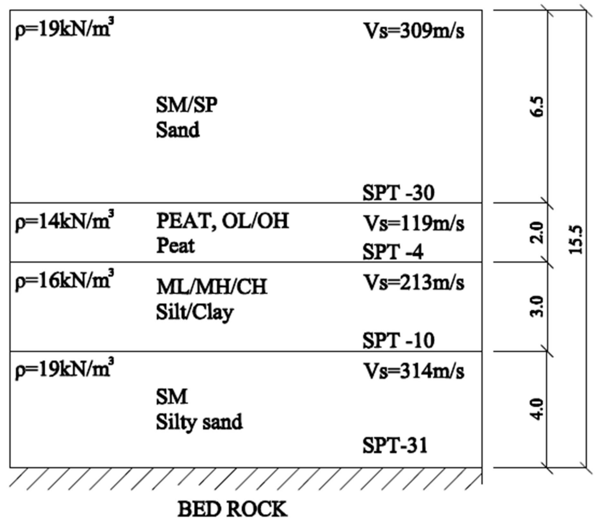
Depth to rock level = (17+14+16+14+16+15)/6 = 15.33m Say 15.5 m (Round off to 0.5m)

#### 3.3.1 Development of bottom most SM layer

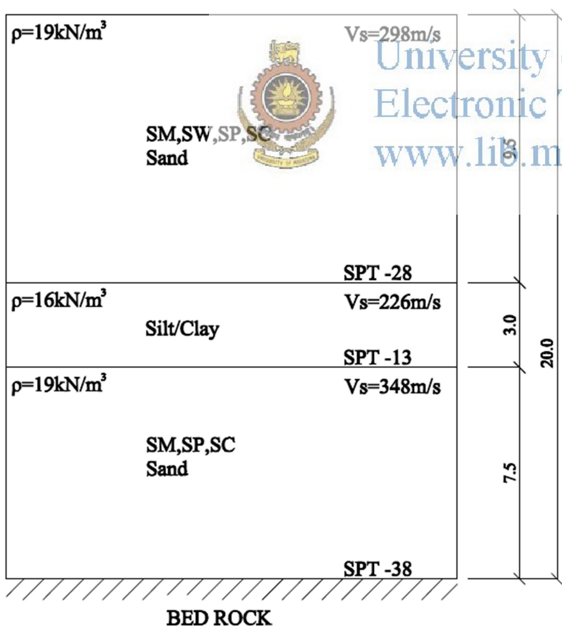
Above the bedrock level, SM (Silty Sand) layer was observed in five boreholes out of six boreholes which were penetrated up to rock level. In BH1, Sandy Silt (MS) layer was encountered. The MS layer was encountered in BH31 and BH34. Since MS layer was not defined in profile B-B and it has intermediate property of Sand and Silt that intermediate layer was shared between previously introduced SM layer and the overlying Silt layer.



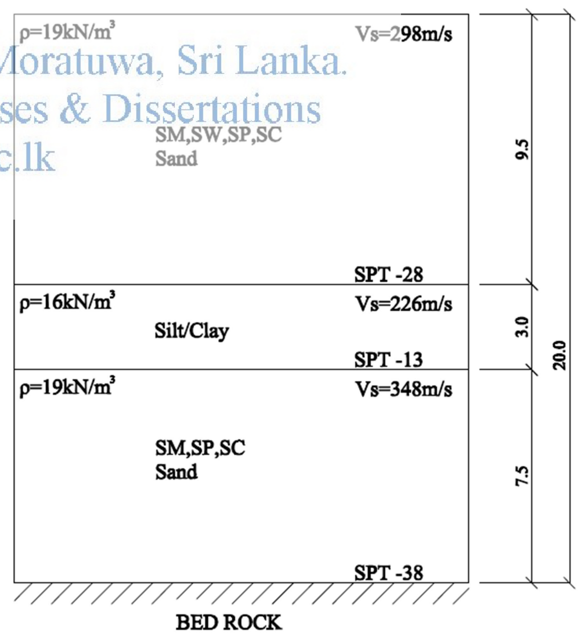

a).Profile A-A




b).Profile B-B




c).Profile C-C




c).Profile C-C

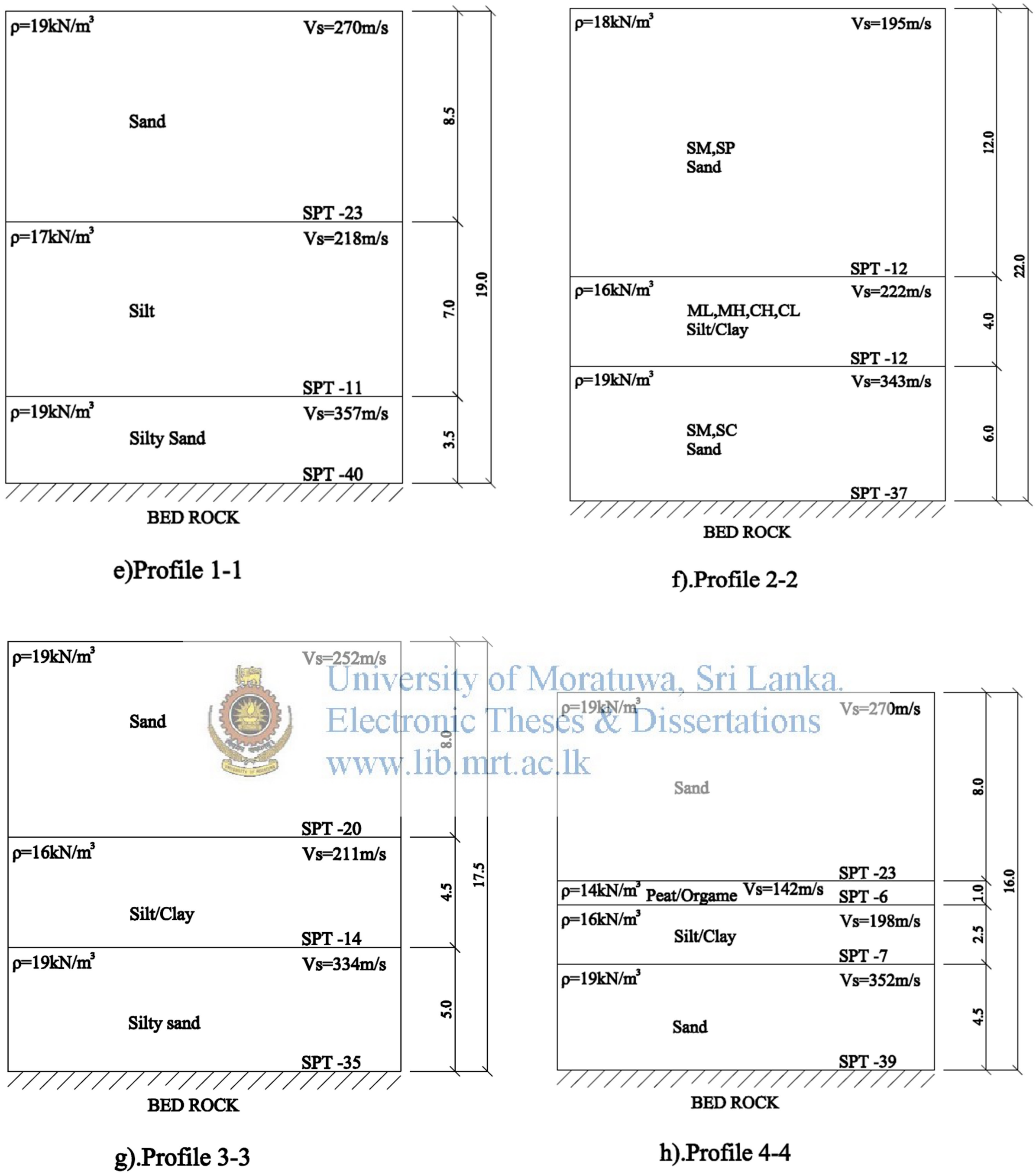




**Figure 3.2 : Developed profiles**

The calculation of average SPT N-value in tabular form is shown in Table 3-1. According to that the average SPT N-value for the SM layer is 34.

**Table 3-1 Calculation of average SPT-N value for bottommost SM layer**

| Borehole No. | Description | No. of Locations | Total SPT N-value |
|---|---|---|---|
| BH74 | SPT N-value for15m and 16m (50+50) | 2 | 100 |
| BH84 | SPT N-value for 12m,13m and 14m (15+50+50) | 3 | 115 |
| BH26 | SPT N-value for 14m and 15m (33+50) | 2 | 83 |
| BH31 | SPT N-value for 11m,12m and 13m (1+7+50) | 3 | 58 |
| BH34 | SPT N-value for 10m to 16m (12+13+16+15+16+21+50) | 7 | 143 |
| BH37 | SPT N-value for 9m to 17m (5+47+8+15+50+50+50+50+50) | 9 | 325 |
| | Total | 26 | 816 |
| Average SPT-N value | | 816/26 = 31 | |



The calculation of average layer thickness of the SM layer in tabular form is shown in Table 3-2. According to that the layer thickness is 3.9m. However the layer thickness is round off to 0.5m. Then the layer thickness was taken as 4m.

**Table 3-02 Calculation of average depth of the bottommost SM layer**

| Borehole No. | Depth range | Layer thickness |
|---|---|---|
| BH74 | 15m - 17m | 2 |
| BH84 | 12m - 14m | 2 |
| BH26 | 14m - 16m | 2 |
| BH31 | 11m - 14m | 3 |
| BH43 | 10m – 16.3m | 6.3 |
| BH37 | 9m - 17m | 8 |
| Σ(layer thickness) | | 23.3 |

Average depth of bottommost SM layer $= \frac{\Sigma(layer\ thickness)}{number\ of\ boreholes} = \frac{23.3}{6} = 3.9m \sim 4m$



### 3.3.2 Other Layers

Overlying the SM layer, Silt and/or Clay layer can be encountered in boreholes BH74, BH84, BH26 and BH 34. This layer comprises of low plasticity Clay (CL), high plasticity Clay (CH), Silt with low plasticity clay particles (ML) and Silt with high plasticity clay particles (MH).

In BH31 and BH37 Organic Clay or Peat layer is overlying the SM layer. Due to this complexity, two layers are defined: Silt/Clay layer and Peat layer. The layer thickness of Silt/ Clay layer and Peat layer are calculated as in Section 3.3.1 and round off to 0.5 m are 3.0 m and 2.0 m respectively. Also the average SPT-N value are 10 and 2 for Silt/Clay layer and Peat layer respectively.

The topmost layer comprises of various type of Sand: Silty Sand (SM), Poorly Graded Sand (SP), Clayey Sand (SC) etc. Hence this layer is identified as a Sand layer. The calculated layer thickness is 6.5m and the average SPT N-value is 30.

## 3.4 Estimation of Shear Wave Velocity Profiles

### 3.4.1 Bottommost SM Layer

This layer can be assumed as a residual soil. Hence, the equation (3.1) proposed by Seed et.al.(1983), in Table 2.5 can be used.

$$V_s = 56.4N^{0.5} \qquad (3.1)$$

Where, N is uncorrected SPT N-value

From Figure 3.2, N=31

Therefore, $V_s$=314 m/s

### 3.4.2 Silt/Clay Layer

The average value of equation (3.2) and (3.3) proposed by Jinan (1987) and Lee (1992) respectively in Table 2.6 are used.

Jinan (1987) equation for Silt and Clay

$$V_s = 116.1(N + 0.32)^{0.20} \qquad (3.2)$$

Lee (1992) equation for Silt and Clay

$$V_s = 129.4(N + 1)^{0.26} \qquad (3.3)$$



For this layer, N=10

From equation 3.2 $V_s = 185$m/s

From equation 3.3 $V_s = 241$m/s

Therefore average $V_s = 213$m/s

### 3.4.3 Peat Layer

This is an alluvium deposit and hence the equation proposed by Imai Tomochi (1982) in Table 2.6 are used.

$$V_s = 63.6N^{0.45} \qquad (3.4)$$

Since N=4, $V_s = 119$m/s

### 3.4.4 Topmost SM/SP Layer

This layer is a deposit and hence the average value of following two equations given in Table 4.6 is used.

Seed et.al. (1983) $V_s = 56.4N^{0.5}$ (3.5)

Since N=30, $V_s = 309\text{m/s}$

## 3.5 Unit Weight of Soil ($\gamma_{wet}$)

The other important soil parameter for ground response analysis is the unit weight of the soil. Table 3.1 shows the variation of unit weight with SPT-N value for granular soil.

**Table 3.3 – Variation of unit weight with SPT-N value**

| Description | Very loose | Loose | Medium | Dense | Very dense |
|---|---|---|---|---|---|
| Relative density $D_r$ | 0 | 0.15 | 0.35 | 0.65 | 0.85 |
| SPT $N'_{70}$: fine | 1–2 | 3–6 | 7–15 | 16–30 | ? |
| medium | 2–3 | 4–7 | 8–20 | 21–40 | > 40 |
| coarse | 3–6 | 5–9 | 10–25 | 26–45 | > 45 |
| $\phi$: fine | 26–28 | 28–30 | 30–34 | 33–38 | |
| medium | 27–28 | 30–32 | 32–36 | 36–42 | < 50 |
| coarse | 28–30 | 30–34 | 33–40 | 40–50 | |
| $\gamma_{wet}$, kN/m$^3$ | 11–16* | 14–18 | 17–20 | 17–22 | 20–23 |



Source : Foundation Analysis and Design, 5$^{th}$ Edition, Joseph E. Bowles

For top Sand layer SPT-N value is in the range of 10 to 30. This soil layer comprises of Silty Sand (SM), Poorly graded Sand (SP), Clayey Sand (SC) and well graded Sand (SW). SM is the common soil type. Hence it is assumed as fine grained soil.

SPT-$N'_{70}$is the corrected SPT-N value. However in this analysis it is assumed that the field SPT-N value is equal to SPT$-N'_{70}$. Then this layer has medium dense and dense fine grained Sand. According to SPT-N value the selected $\gamma_{wet}$ with SPT-N value are as follows.

$10 \leq SPT - N\ value < 20$ $\gamma_{wet}$ =18 kN/m$^3$

$20 \leq SPT - N\ value \leq 30$ $\gamma_{wet}$=19 kN/m$^3$

For other layers the unit weight was taken as follows

Peat layers $\gamma_{wet}$ =14 kN/m$^3$

Silt/Clay layers $\gamma_{wet}$ =16 kN/m$^3$

Rock $\gamma$ =22 kN/m$^3$

## 3.6 Computer Analysis with EduShake

This section describes the procedure of analyzing profile B-B with the ground motion analysis software 'EduShake'.



### 3.6.1 Input data

Select the Input Manager from the initial EduShake screen. The first screen of EduShake is shown in Figure 3.3. In this screen three longer button present:Profile, Input Motion and Report. Hit on 'Profile' button to define soil layers and their properties. First, type 'Profile B-B' under 'Profile Title'. This title shall identify the soil profile. Then hit the Tab Key to move the cursor to the next field.

Enter 5 in the space for no. of layers. This will provide 4 soil layers and the underlying half space. EduShake provides 5 tabs when the number of layers is entered where each tab will allow you to input the appropriate data for the corresponding layer. Because Edushake performs total stress analysis, 'Depth to Water Table' is kept as zero for the ground response analysis. EduShake allows to enter input data in either US or SI units, and to mix and match units.

In order to enter input data for the first layer, make sure that the tab for layer 1 is active. ( It should be at the front of the stack of tabs, with the layer number displayed in blue. Then enter the 'Material Name' as Sand.

The next step is selection of 'Modules Reduction Curve'. To see the list of built in curves in EduShake, click on the button at the right side of the 'Modulus Reduction Curve' field. For this example select "Sand( Seed&Idriss) Average". EduShake initially sets the 'Damping Curve' as identical to the 'Modulus Reduction Curve' by default. Modulus reduction and damping curves can be observed by clicking on the button labled 'Plot Modulus and Damping Curves'.

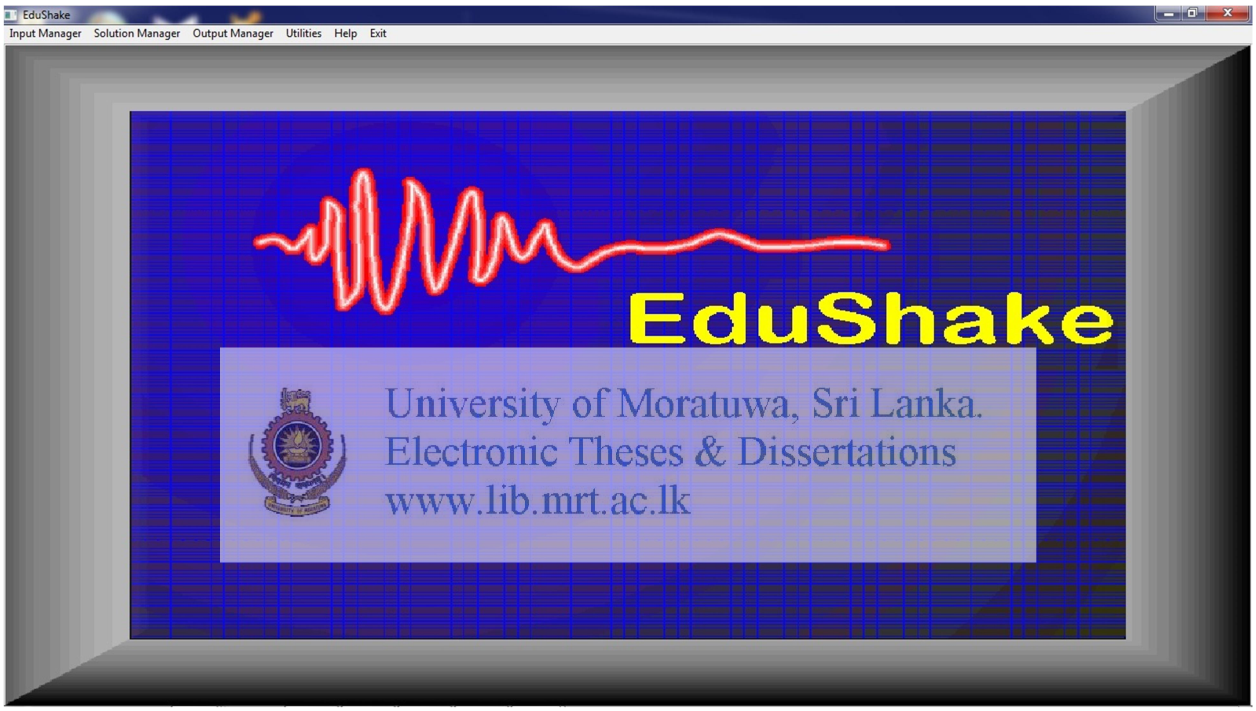




**Figure 3.3 : First screen of EduShake**

Move the cursor to either of the "Thickness" fields. Enter 6.5m for this layer. Enter 19kN/$m^3$ for 'Unit Weight' field. Now the low – strain stiffness of the first layer can be specified. This can be done either by entering the maximum shear modules, Gmax or by entering the shear wave velocity. In this case enter 300 m/sec. in shear wave velocity field. The calculation of shear wave

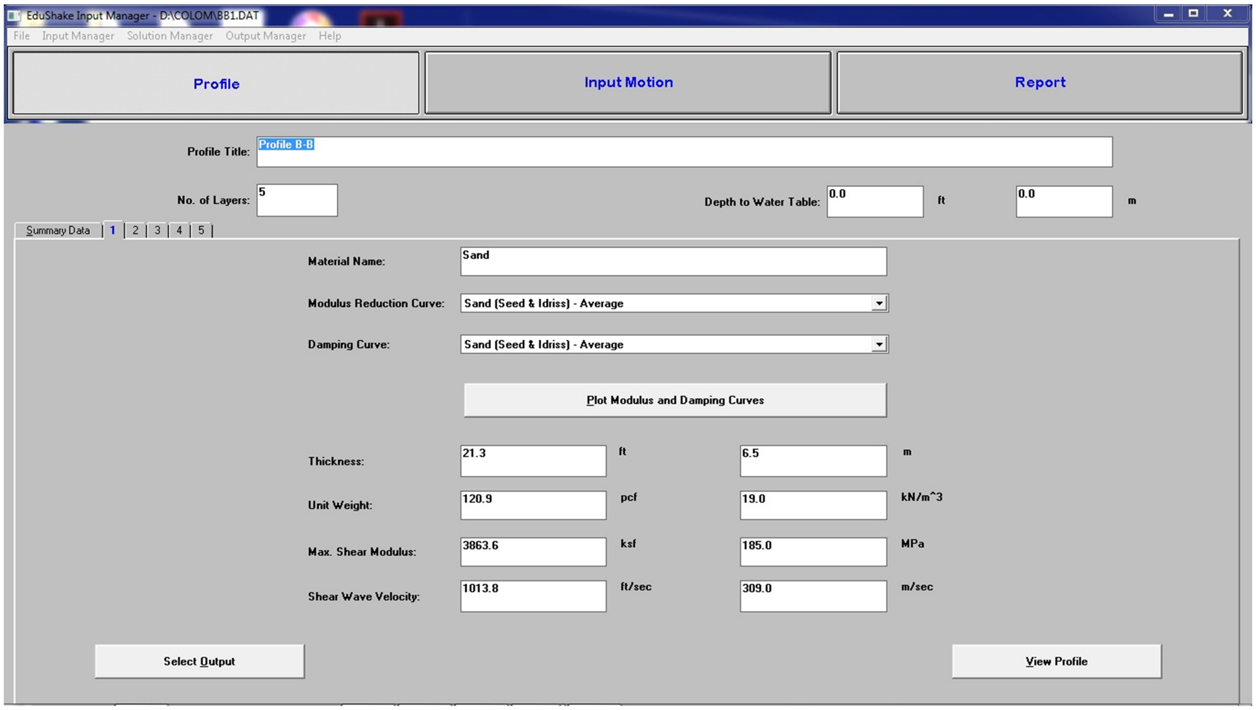
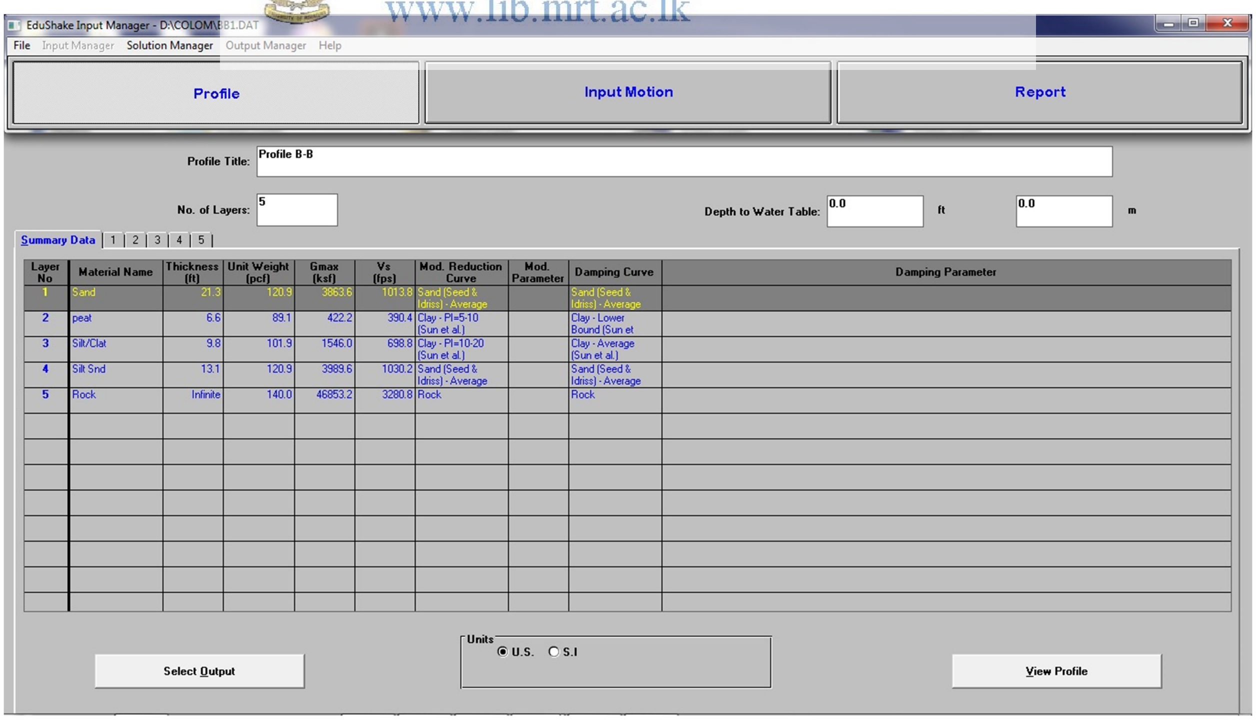



Figure 3.4 : Define of layer properties in EduShake






**Fugure3.5 : Define of layer properties in compact form**

velocity is shown in section 3.4. Now the layer has been defined. Figure 3.4 illustrates the screen of first layer.

In the same way other layers also can be defined. However, it will be faster for our example to enter subsequent data using. “Summary Data” tab. Click on that tab (Just to the left of the tab for Layer 1). The input data of ‘Layer 1’ can be displayed in a compact tabular form. Then the properties of other layer can be defined.  The layer properties in compact form is shown in Figure 3.5. After completion of the defining of all layers, in order to check for obvious errors (such as a misplaced decimal point) click the ‘View Profile’ button. The profile shows the variation of unit weight and shear wave velocity with depth as shown in Figure 3.6.

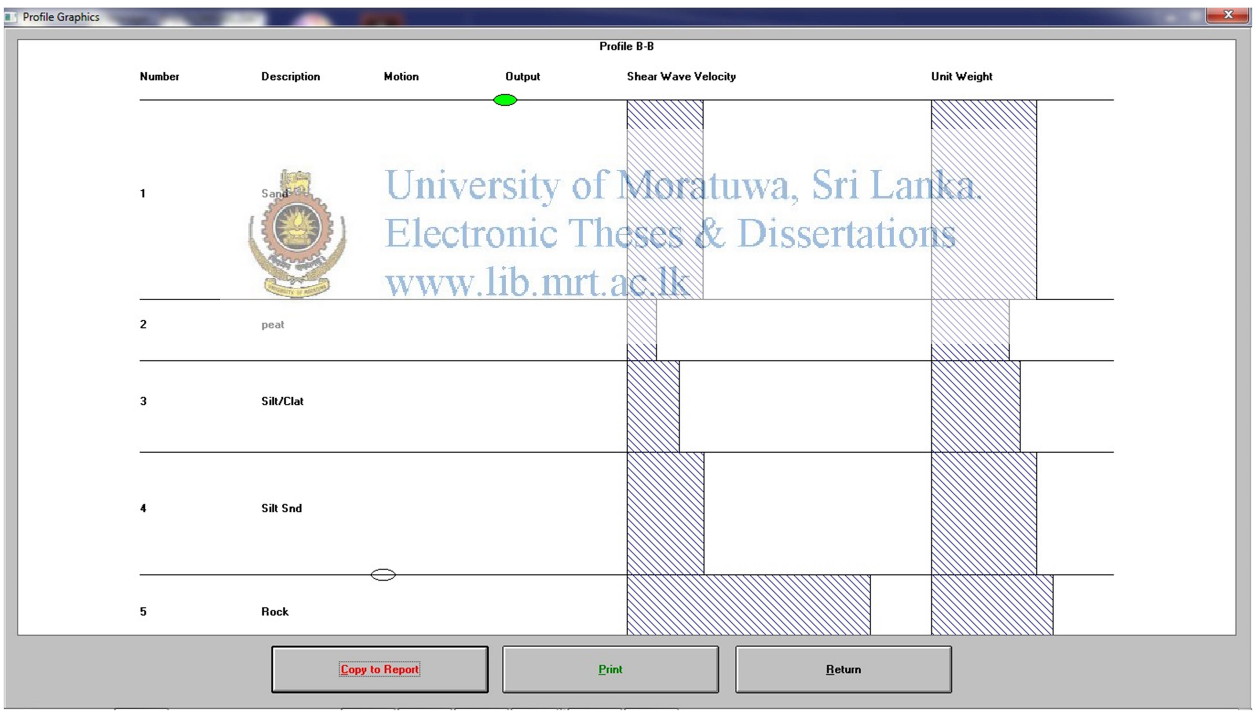




**Figure 3.6 :‘View Profile’ window**

Now it should be specified what information is to be computed during the ground response analysis. Click on tab for layer 1 and click on the ‘Select Output’ button. On the ‘Output

Location' window check the box for 'Acceleration' in 'Time History' and 'Response Spectrum' fields. Enter 'Damping %' of 5%. Figure 3.7 shows this screen.

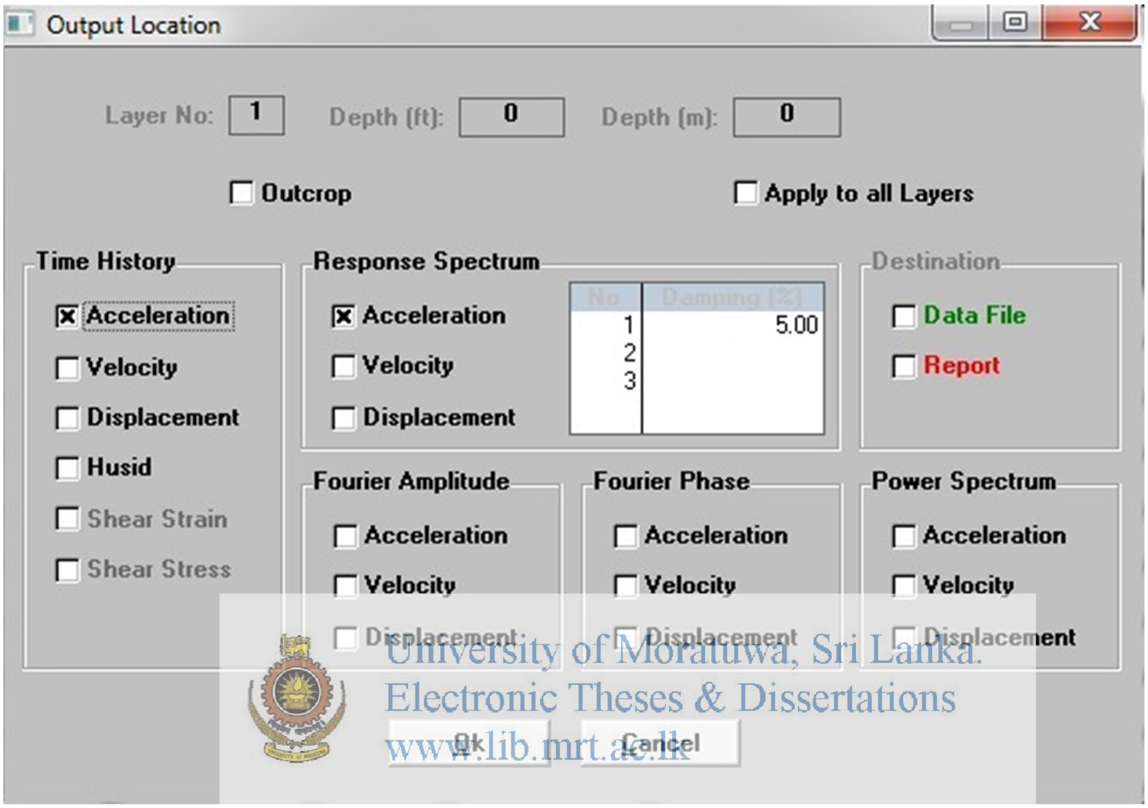




**Figure 3.7 : 'Output Location' window**

### 3.6.2 Specification of input motion

To be specified the input motion, click on the large 'Input Motion' button on the main 'Input Manager' form. This will bring up a form that allows to select an input motion, define its characteristics, view it graphically, and compute various ground motion parameters associated with the motion. According to the limitations of the software, only available spectral motions can be introduced. Software contains details of six motions. Hence enter 6 for 'Number of Motions'. Six tabs presents the six motions.

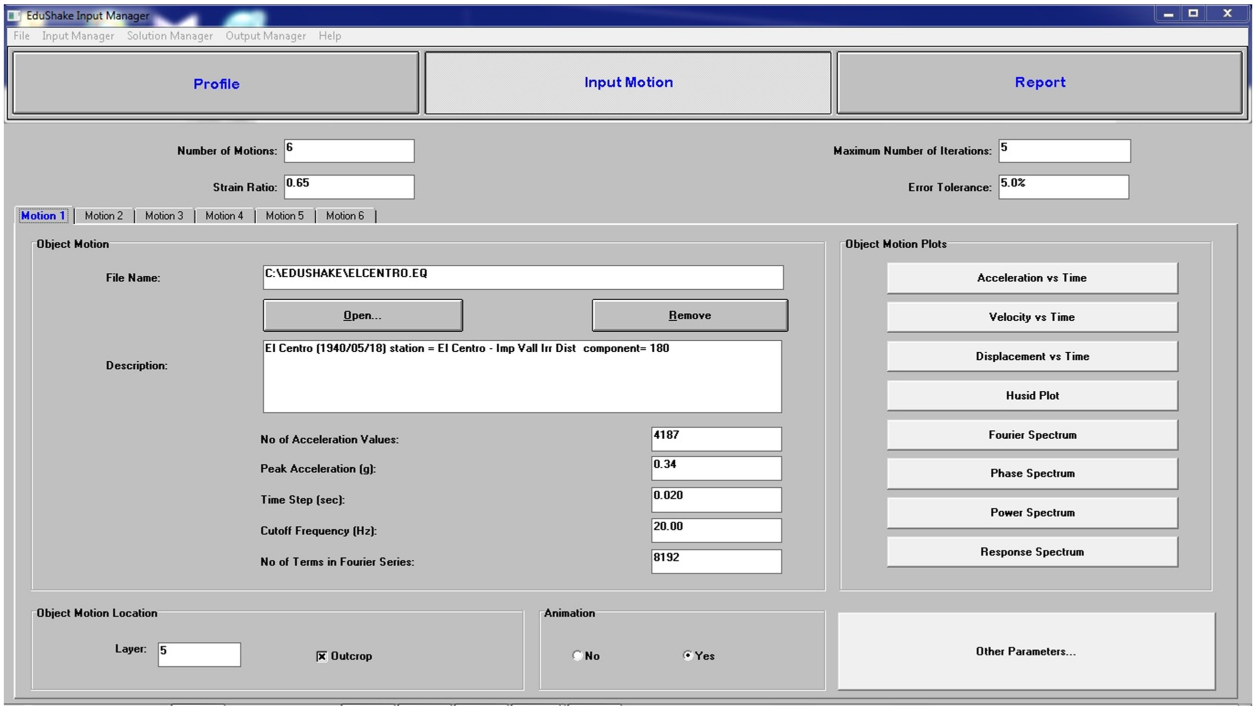



Figure 3.8 : Define of ground motion



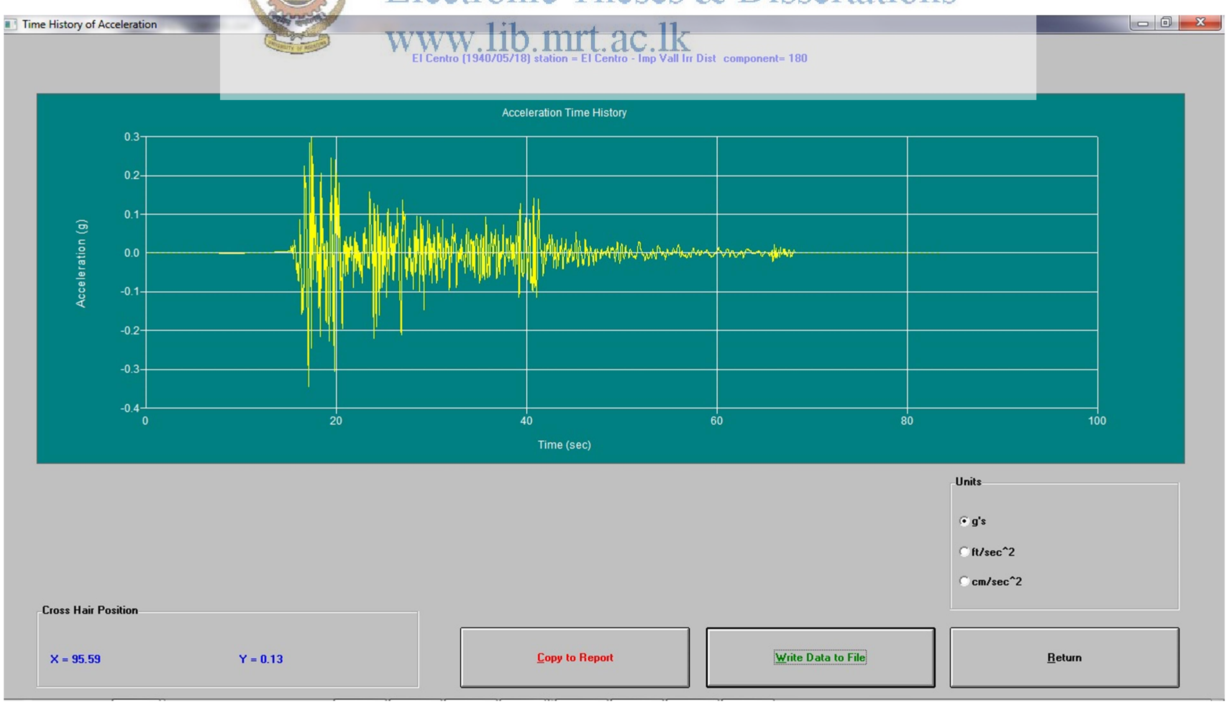



Figure 3.9 : Input horizontal acceleration of motion 1

Figure 3.8 shows the data of ‘Motion 1’. Figure 3.9 shows the accelerogram of ‘Motion 1’by clicking on the ‘Acceleration vs Time’ button. The details of all input motions are provided on Annexure 4. On this screen click on the ‘Response Spectrum’ button. The response spectrum for 5% damping can be seen. Figure 3.10 shows the spectral acceleration for ‘Motion 1’. On this window check the boxes for ‘All Motions’ and ‘Mean’ to obtain the all spectral acceleration and mean spectral acceleration. Then the all required input data has been entered. Then the input data file is saved as ‘BB.DAT’.



**Figure 3.10 :Spectral acceleration of ‘Motion 1’**

### 3.6.3. Analysis of data

Next step is to analyse the data. Select ‘Solution Manager’ from main menu. Then the software asks the ‘File Name’ from ‘Name of Input File to be Analysed, window. Select the ‘BB.DAT’ file from ‘Name of Input File to be Analyzed’. After hit on ‘OK’ button, programme will run. The word ‘Running’ will appear in the lower left corner of the screen and a dialog box will appear. When the analysis is completed, click ‘OK’ on the dialog box that appears to exit

'Solution Manager'. The results of the analysis performed by the 'Solution Manager' will automatically be written to a file with the same name as your data file, but with the extension .lyr – in this case BB.lyr.

### 3.6.4 Results of the analysis

To view the results of the analysis, select the 'Output Manager'. 'Output File Name' dialog box will appear and select the file 'BB.LYR'. Select 'Response Spectrum' and check the six boxes in 'Include' field to select all motions. The screen on that is shown in Figure 3.11. Then click on the button 'Plot'. Response spectra for all earthquakes (six numbers) will plot. Check on the 'Mean' in 'Option' field. Now click on 'Re-plot' to include the mean response spectra in above plot. Then the 'Response Spectra' graph contains 7 graphs (Six graphs for corresponding six earthquakes and the other for the mean). The screen of this is shown in Figure 3.12.

Click on 'Write Data to File' to save the output file as a .RAW file; in this case BB.RAW.Now open 'BB.RAW' file on 'Excel'. Select the 'BB.RAW' file and select'All Files' and then the file can be opened.



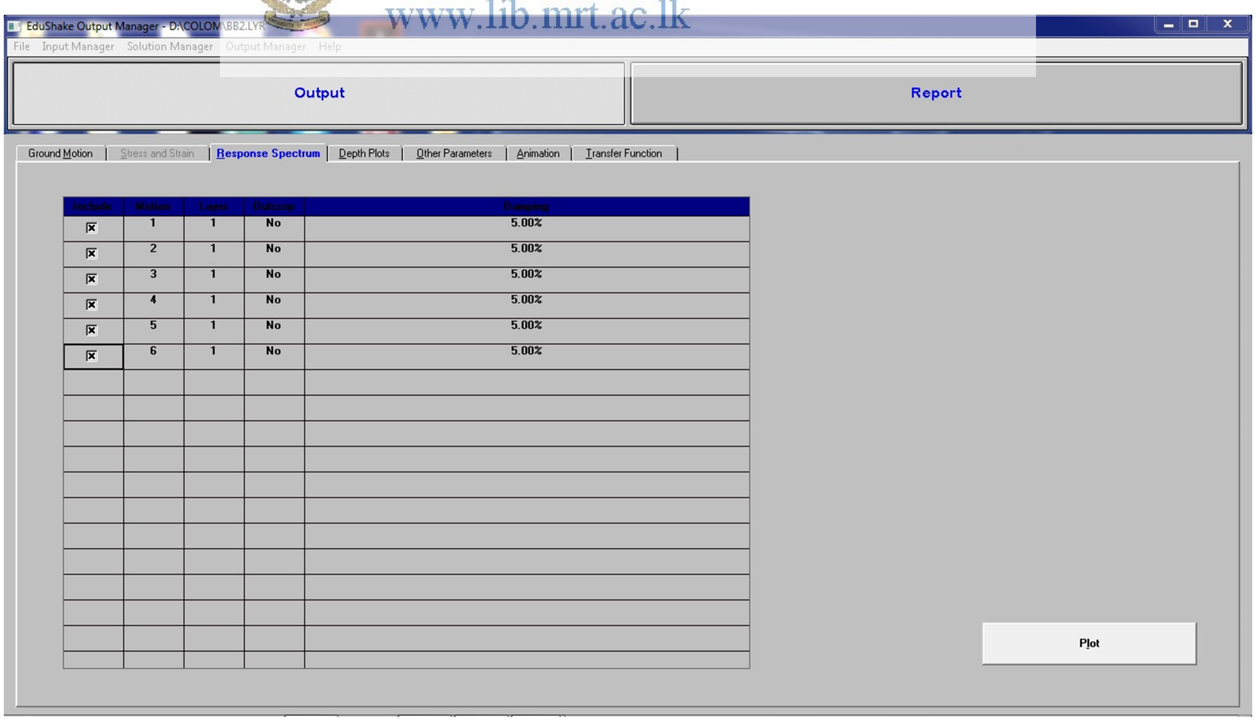



**Figure 3.11 : Required data for output file**

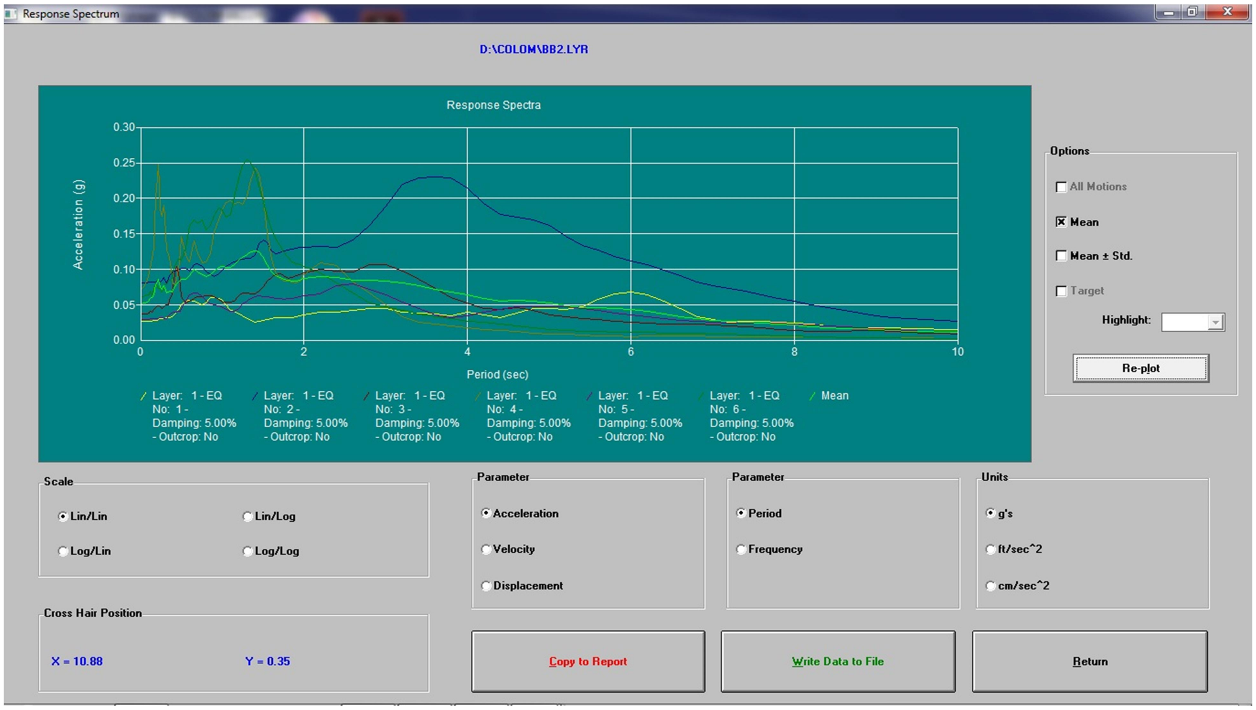



**Figure 3.12 : Ground response spectra for six earthquakes and mean value**



This sheet contains the following data.

1. Six input motions (spectral accelerations) related to the six earthquakes (Table 3.4)
2. Mean value of six input motions (Table 3.4)
3. Six output motions (ground level accelerations) related to six earthquakes (Table 3.5)
4. Mean value of six output motions (Table 3.5)

In the same way the input and output data for other profiles are obtained from the EduShake software.

# 4.0 ASSESSMENT OF LOCAL SITE EFFECTS IN COLOMBO, SRI LANKA

Under ideal conditions, the stress waves propagate at the source of an earthquake and spread in each direction through the bed rock. For a particular site which is on soil overlying the bedrock, the stress waves travel through the bed rock and come up to the surface through soil layers. When the wave travel through the soil layers, the soil plays a very important role.

One dimensional ground response analysis is based on the assumption that all soil layer boundaries are horizontal and the soil and bed rock are assumed to extend infinitely in the horizontal direction. There are two types of surface waves which are important in earthquake engineering called Rayleigh waves and Love waves. Rayleigh waves can be thought of as combinations of primary and shear waves. If there is a material with lower body wave velocity overlying the bedrock, Love waves can develop.



The ground motion records are a combination of those waves at the point where the ground motion recording instruments installed. The input data of this analysis are the six ground motion records which are available in the ground motion analysis software, EduShake.

The response spectrum at rock levels and the response spectrum with local effects are the output files. Those data are the average values from six earthquake data available in the EduShake software. The output file obtained from EduShake programme for profiles A-A, B-B, C-C, D-D, 1-1, 2-2, 3-3 and 4-4 are shown in Table 4-1 to 4-8. Figure 4-1 to 4-8 illustrates above data graphically.

Average value of response spectrums at rock level was taken as the average response spectrum at rock level and the average value of response spectrums with local site effects was taken as the average response spectrum with local site effects. Those data are shown in Table 4.9 and Figure 4.9 The difference between those profiles (d) is due to the local site effect. This difference is shown in Table 10. When spectral acceleration values of Colombo city is known, add those difference due to local site effect to obtain ground response spectrum.

The design response spectrum at rock level (Sa) is obtained from S.B. Uduweriya et.al. (2013). Those values also shown in Table 4.10. The addition of above two gives the RSLSE. Those values are also shown in Table 4.10.

**Table 4.1 : Mean acceleration of RSRL and RSLSE motions for profile A-A**

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 0.00 | 0.2501 | 0.4774 |
| 0.01 | 0.2498 | 0.4769 |
| 0.02 | 0.2417 | 0.4768 |
| 0.04 | 0.2531 | 0.5219 |
| 0.06 | 0.3110 | 0.5016 |
| 0.08 | 0.3394 | 0.5317 |
| 0.10 | 0.3895 | 0.5587 |
| 0.12 | 0.3939 | 0.5675 |
| 0.14 | 0.3882 | 0.6061 |
| 0.16 | 0.3838 | 0.6626 |
| 0.18 | 0.5037 | 0.7888 |
| 0.20 | 0.4707 | 0.7933 |
| 0.22 | 0.5402 | 0.8315 |
| 0.24 | 0.5548 | 0.8465 |
| 0.26 | 0.6193 | 0.9224 |
| 0.28 | 0.6390 | 1.0217 |
| 0.30 | 0.6198 | 1.0722 |
| 0.32 | 0.5650 | 1.0716 |
| 0.34 | 0.5313 | 1.0609 |
| 0.36 | 0.5006 | 0.9774 |
| 0.38 | 0.4572 | 0.9350 |
| 0.40 | 0.4256 | 1.0104 |
| 0.42 | 0.4483 | 1.1478 |
| 0.44 | 0.4991 | 1.2444 |
| 0.46 | 0.5267 | 1.2657 |
| 0.48 | 0.5222 | 1.2695 |
| 0.50 | 0.5284 | 1.2515 |
| 0.55 | 0.5666 | 1.1765 |
| 0.60 | 0.5833 | 1.1699 |
| 0.65 | 0.5369 | 1.0870 |
| 0.70 | 0.4645 | 0.9603 |
| 0.75 | 0.4061 | 0.8297 |
| 0.80 | 0.3697 | 0.7300 |
| 0.85 | 0.3611 | 0.7038 |
| 0.90 | 0.3355 | 0.6146 |
| 0.95 | 0.3166 | 0.5644 |
| 1.00 | 0.3004 | 0.5283 |
| 1.05 | 0.2857 | 0.4791 |
| 1.10 | 0.2634 | 0.4480 |
| 1.15 | 0.2586 | 0.4250 |
| 1.20 | 0.2571 | 0.4021 |
| 1.25 | 0.2514 | 0.3716 |
| 1.30 | 0.2456 | 0.3423 |
| 1.35 | 0.2426 | 0.3224 |
| 1.40 | 0.2387 | 0.3137 |
| 1.45 | 0.2334 | 0.3070 |
| 1.50 | 0.2289 | 0.2989 |
| 1.55 | 0.2232 | 0.2891 |
| 1.60 | 0.2169 | 0.2797 |
| 1.65 | 0.2090 | 0.2691 |
| 1.70 | 0.1998 | 0.2543 |
| 1.75 | 0.1917 | 0.2406 |
| 1.80 | 0.1828 | 0.2307 |
| 1.85 | 0.1762 | 0.2205 |
| 1.90 | 0.1709 | 0.2087 |
| 1.95 | 0.1657 | 0.2023 |
| 2.00 | 0.1622 | 0.1941 |
| 2.20 | 0.1476 | 0.1703 |
| 2.40 | 0.1352 | 0.1453 |
| 2.60 | 0.1253 | 0.1348 |
| 2.80 | 0.1093 | 0.1155 |
| 3.00 | 0.0915 | 0.0979 |
| 3.20 | 0.0825 | 0.0873 |
| 3.40 | 0.0760 | 0.0816 |
| 3.60 | 0.0654 | 0.0703 |
| 3.80 | 0.0543 | 0.0572 |
| 4.00 | 0.0479 | 0.0498 |
| 4.20 | 0.0421 | 0.0439 |
| 4.40 | 0.0380 | 0.0403 |
| 4.60 | 0.0344 | 0.0369 |
| 4.80 | 0.0308 | 0.0332 |
| 5.00 | 0.0282 | 0.0300 |
| 5.20 | | 0.0278 |
| 5.40 | | 0.0263 |
| 5.60 | | 0.0257 |
| 5.80 | | 0.0247 |
| 6.00 | | 0.0240 |
| 6.20 | | 0.0231 |
| 6.40 | | 0.0218 |
| 6.60 | | 0.0206 |
| 6.80 | | 0.0196 |
| 7.00 | | 0.0184 |
| 7.20 | | 0.0172 |
| 7.40 | | 0.0159 |
| 7.60 | | 0.0146 |
| 7.80 | | 0.0139 |
| 8.00 | | 0.0133 |
| 8.20 | | 0.0128 |
| 8.40 | | 0.0124 |
| 8.60 | | 0.0120 |
| 8.80 | | 0.0116 |
| 9.00 | | 0.0110 |
| 9.20 | | 0.0104 |
| 9.40 | | 0.0099 |
| 9.60 | | 0.0094 |
| 9.80 | | 0.0091 |
| 10.00 | | 0.0086 |

**Table 4.2 : Mean acceleration of RSRL and RSLSE motions for profile B-B**

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 0.00 | 0.2501 | 0.0881 |
| 0.01 | 0.2498 | 0.0880 |
| 0.02 | 0.2417 | 0.0880 |
| 0.04 | 0.2531 | 0.0884 |
| 0.06 | 0.3110 | 0.0907 |
| 0.08 | 0.3394 | 0.0918 |
| 0.10 | 0.3895 | 0.0975 |
| 0.12 | 0.3939 | 0.1014 |
| 0.14 | 0.3882 | 0.1053 |
| 0.16 | 0.3838 | 0.1099 |
| 0.18 | 0.5037 | 0.1176 |
| 0.20 | 0.4707 | 0.1168 |
| 0.22 | 0.5402 | 0.1154 |
| 0.24 | 0.5548 | 0.1039 |
| 0.26 | 0.6193 | 0.1155 |
| 0.28 | 0.6390 | 0.1308 |
| 0.30 | 0.6198 | 0.1332 |
| 0.32 | 0.5650 | 0.1289 |
| 0.34 | 0.5313 | 0.1299 |
| 0.36 | 0.5006 | 0.1352 |
| 0.38 | 0.4572 | 0.1361 |
| 0.40 | 0.4256 | 0.1358 |
| 0.42 | 0.4483 | 0.1416 |
| 0.44 | 0.4991 | 0.1509 |
| 0.46 | 0.5267 | 0.1637 |
| 0.48 | 0.5222 | 0.1716 |
| 0.50 | 0.5284 | 0.1764 |
| 0.55 | 0.5666 | 0.1953 |
| 0.60 | 0.5833 | 0.2135 |
| 0.65 | 0.5369 | 0.2295 |
| 0.70 | 0.4645 | 0.2161 |
| 0.75 | 0.4061 | 0.2021 |
| 0.80 | 0.3697 | 0.2191 |
| 0.85 | 0.3611 | 0.2147 |
| 0.90 | 0.3355 | 0.2211 |
| 0.95 | 0.3166 | 0.2015 |
| 1.00 | 0.3004 | 0.1878 |
| 1.05 | 0.2857 | 0.1826 |
| 1.10 | 0.2634 | 0.1759 |
| 1.15 | 0.2586 | 0.1713 |
| 1.20 | 0.2571 | 0.1710 |
| 1.25 | 0.2514 | 0.1704 |

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 1.30 | 0.2456 | 0.1694 |
| 1.35 | 0.2426 | 0.1663 |
| 1.40 | 0.2387 | 0.1624 |
| 1.45 | 0.2334 | 0.1603 |
| 1.50 | 0.2289 | 0.1597 |
| 1.55 | 0.2232 | 0.1608 |
| 1.60 | 0.2169 | 0.1624 |
| 1.65 | 0.2090 | 0.1610 |
| 1.70 | 0.1998 | 0.1567 |
| 1.75 | 0.1917 | 0.1497 |
| 1.80 | 0.1828 | 0.1441 |
| 1.85 | 0.1762 | 0.1393 |
| 1.90 | 0.1709 | 0.1365 |
| 1.95 | 0.1657 | 0.1339 |
| 2.00 | 0.1622 | 0.1309 |
| 2.20 | 0.1476 | 0.1246 |
| 2.40 | 0.1352 | 0.1313 |
| 2.60 | 0.1253 | 0.1295 |
| 2.80 | 0.1093 | 0.1318 |
| 3.00 | 0.0915 | 0.1321 |
| 3.20 | 0.0825 | 0.1263 |
| 3.40 | 0.0760 | 0.1167 |
| 3.60 | 0.0654 | 0.1072 |
| 3.80 | 0.0543 | 0.0971 |
| 4.00 | 0.0479 | 0.0847 |
| 4.20 | 0.0421 | 0.0733 |
| 4.40 | 0.0380 | 0.0642 |
| 4.60 | 0.0344 | 0.0578 |
| 4.80 | 0.0308 | 0.0532 |
| 5.00 | 0.0282 | 0.0490 |
| 5.20 | | 0.0449 |
| 5.40 | | 0.0422 |
| 5.60 | | 0.0404 |
| 5.80 | | 0.0393 |
| 6.00 | | 0.0372 |
| 6.20 | | 0.0340 |
| 6.40 | | 0.0304 |
| 6.60 | | 0.0285 |
| 6.80 | | 0.0266 |
| 7.00 | | 0.0254 |
| 7.20 | | 0.0242 |
| 7.40 | | 0.0229 |

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 7.60 | | 0.0214 |
| 7.80 | | 0.0198 |
| 8.00 | | 0.0182 |
| 8.20 | | 0.0168 |
| 8.40 | | 0.0156 |
| 8.60 | | 0.0146 |
| 8.80 | | 0.0139 |
| 9.00 | | 0.0133 |
| 9.20 | | 0.0126 |
| 9.40 | | 0.0119 |
| 9.60 | | 0.0113 |
| 9.80 | | 0.0106 |
| 10.00 | | 0.0101 |

**Table 4.3 : Mean acceleration of RSRL and RSLSE motions for profile C-C**

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 0.00 | 0.2501 | 0.4075 |
| 0.01 | 0.2498 | 0.4072 |
| 0.02 | 0.2417 | 0.4072 |
| 0.04 | 0.2531 | 0.4499 |
| 0.06 | 0.3110 | 0.4305 |
| 0.08 | 0.3394 | 0.4544 |
| 0.10 | 0.3895 | 0.4985 |
| 0.12 | 0.3939 | 0.5083 |
| 0.14 | 0.3882 | 0.4973 |
| 0.16 | 0.3838 | 0.5311 |
| 0.18 | 0.5037 | 0.5759 |
| 0.20 | 0.4707 | 0.5761 |
| 0.22 | 0.5402 | 0.6260 |
| 0.24 | 0.5548 | 0.6208 |
| 0.26 | 0.6193 | 0.7137 |
| 0.28 | 0.6390 | 0.7904 |
| 0.30 | 0.6198 | 0.8476 |
| 0.32 | 0.5650 | 0.8697 |
| 0.34 | 0.5313 | 0.8902 |
| 0.36 | 0.5006 | 0.8733 |
| 0.38 | 0.4572 | 0.8397 |
| 0.40 | 0.4256 | 0.9128 |
| 0.42 | 0.4483 | 1.0343 |
| 0.44 | 0.4991 | 1.1247 |
| 0.46 | 0.5267 | 1.1469 |
| 0.48 | 0.5222 | 1.1386 |
| 0.50 | 0.5284 | 1.1226 |
| 0.55 | 0.5666 | 1.0595 |
| 0.60 | 0.5833 | 1.0629 |
| 0.65 | 0.5369 | 0.9893 |
| 0.70 | 0.4645 | 0.8729 |
| 0.75 | 0.4061 | 0.7525 |
| 0.80 | 0.3697 | 0.6630 |
| 0.85 | 0.3611 | 0.6305 |
| 0.90 | 0.3355 | 0.5500 |
| 0.95 | 0.3166 | 0.5135 |
| 1.00 | 0.3004 | 0.4825 |
| 1.05 | 0.2857 | 0.4398 |
| 1.10 | 0.2634 | 0.4127 |
| 1.15 | 0.2586 | 0.3907 |
| 1.20 | 0.2571 | 0.3697 |
| 1.25 | 0.2514 | 0.3432 |

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 1.30 | 0.2456 | 0.3163 |
| 1.35 | 0.2426 | 0.3050 |
| 1.40 | 0.2387 | 0.2978 |
| 1.45 | 0.2334 | 0.2910 |
| 1.50 | 0.2289 | 0.2835 |
| 1.55 | 0.2232 | 0.2750 |
| 1.60 | 0.2169 | 0.2662 |
| 1.65 | 0.2090 | 0.2562 |
| 1.70 | 0.1998 | 0.2424 |
| 1.75 | 0.1917 | 0.2308 |
| 1.80 | 0.1828 | 0.2212 |
| 1.85 | 0.1762 | 0.2112 |
| 1.90 | 0.1709 | 0.1999 |
| 1.95 | 0.1657 | 0.1933 |
| 2.00 | 0.1622 | 0.1866 |
| 2.20 | 0.1476 | 0.1635 |
| 2.40 | 0.1352 | 0.1400 |
| 2.60 | 0.1253 | 0.1319 |
| 2.80 | 0.1093 | 0.1139 |
| 3.00 | 0.0915 | 0.0958 |
| 3.20 | 0.0825 | 0.0861 |
| 3.40 | 0.0760 | 0.0808 |
| 3.60 | 0.0654 | 0.0695 |
| 3.80 | 0.0543 | 0.0561 |
| 4.00 | 0.0479 | 0.0492 |
| 4.20 | 0.0421 | 0.0431 |
| 4.40 | 0.0380 | 0.0391 |
| 4.60 | 0.0344 | 0.0360 |
| 4.80 | 0.0308 | 0.0325 |
| 5.00 | 0.0282 | 0.0295 |
| 5.20 | | 0.0273 |
| 5.40 | | 0.0260 |
| 5.60 | | 0.0252 |
| 5.80 | | 0.0243 |
| 6.00 | | 0.0236 |
| 6.20 | | 0.0227 |
| 6.40 | | 0.0215 |
| 6.60 | | 0.0202 |
| 6.80 | | 0.0192 |
| 7.00 | | 0.0182 |
| 7.20 | | 0.0171 |
| 7.40 | | 0.0158 |

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 7.60 | | 0.0146 |
| 7.80 | | 0.0138 |
| 8.00 | | 0.0132 |
| 8.20 | | 0.0126 |
| 8.40 | | 0.0121 |
| 8.60 | | 0.0117 |
| 8.80 | | 0.0113 |
| 9.00 | | 0.0108 |
| 9.20 | | 0.0102 |
| 9.40 | | 0.0097 |
| 9.60 | | 0.0093 |
| 9.80 | | 0.0090 |
| 10.00 | | 0.0086 |

**Table 4.4 : Mean acceleration of RSRL and RSLSE motions for profile D-D**

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 0.00 | 0.2501 | 0.1917 |
| 0.01 | 0.2498 | 0.1916 |
| 0.02 | 0.2417 | 0.1916 |
| 0.04 | 0.2531 | 0.1924 |
| 0.06 | 0.3110 | 0.1957 |
| 0.08 | 0.3394 | 0.2003 |
| 0.10 | 0.3895 | 0.2003 |
| 0.12 | 0.3939 | 0.2047 |
| 0.14 | 0.3882 | 0.2071 |
| 0.16 | 0.3838 | 0.2211 |
| 0.18 | 0.5037 | 0.2487 |
| 0.20 | 0.4707 | 0.2519 |
| 0.22 | 0.5402 | 0.2737 |
| 0.24 | 0.5548 | 0.2586 |
| 0.26 | 0.6193 | 0.2856 |
| 0.28 | 0.6390 | 0.3222 |
| 0.30 | 0.6198 | 0.3405 |
| 0.32 | 0.5650 | 0.3357 |
| 0.34 | 0.5313 | 0.3364 |
| 0.36 | 0.5006 | 0.3389 |
| 0.38 | 0.4572 | 0.3325 |
| 0.40 | 0.4256 | 0.3461 |
| 0.42 | 0.4483 | 0.3748 |
| 0.44 | 0.4991 | 0.3986 |
| 0.46 | 0.5267 | 0.3958 |
| 0.48 | 0.5222 | 0.3886 |
| 0.50 | 0.5284 | 0.3960 |
| 0.55 | 0.5666 | 0.4749 |
| 0.60 | 0.5833 | 0.5166 |
| 0.65 | 0.5369 | 0.5299 |
| 0.70 | 0.4645 | 0.4811 |
| 0.75 | 0.4061 | 0.4374 |
| 0.80 | 0.3697 | 0.4031 |
| 0.85 | 0.3611 | 0.3878 |
| 0.90 | 0.3355 | 0.3720 |
| 0.95 | 0.3166 | 0.3440 |
| 1.00 | 0.3004 | 0.3235 |
| 1.05 | 0.2857 | 0.3131 |
| 1.10 | 0.2634 | 0.2984 |
| 1.15 | 0.2586 | 0.2911 |
| 1.20 | 0.2571 | 0.2973 |
| 1.25 | 0.2514 | 0.3073 |
| 1.30 | 0.2456 | 0.3155 |
| 1.35 | 0.2426 | 0.3259 |
| 1.40 | 0.2387 | 0.3322 |
| 1.45 | 0.2334 | 0.3337 |
| 1.50 | 0.2289 | 0.3322 |
| 1.55 | 0.2232 | 0.3285 |
| 1.60 | 0.2169 | 0.3239 |
| 1.65 | 0.2090 | 0.3178 |
| 1.70 | 0.1998 | 0.3095 |
| 1.75 | 0.1917 | 0.3022 |
| 1.80 | 0.1828 | 0.2967 |
| 1.85 | 0.1762 | 0.2903 |
| 1.90 | 0.1709 | 0.2838 |
| 1.95 | 0.1657 | 0.2762 |
| 2.00 | 0.1622 | 0.2718 |
| 2.20 | 0.1476 | 0.2519 |
| 2.40 | 0.1352 | 0.2243 |
| 2.60 | 0.1253 | 0.1966 |
| 2.80 | 0.1093 | 0.1732 |
| 3.00 | 0.0915 | 0.1450 |
| 3.20 | 0.0825 | 0.1175 |
| 3.40 | 0.0760 | 0.1076 |
| 3.60 | 0.0654 | 0.0942 |
| 3.80 | 0.0543 | 0.0789 |
| 4.00 | 0.0479 | 0.0647 |
| 4.20 | 0.0421 | 0.0547 |
| 4.40 | 0.0380 | 0.0479 |
| 4.60 | 0.0344 | 0.0430 |
| 4.80 | 0.0308 | 0.0386 |
| 5.00 | 0.0282 | 0.0351 |
| 5.20 | | 0.0327 |
| 5.40 | | 0.0303 |
| 5.60 | | 0.0283 |
| 5.80 | | 0.0275 |
| 6.00 | | 0.0265 |
| 6.20 | | 0.0255 |
| 6.40 | | 0.0240 |
| 6.60 | | 0.0226 |
| 6.80 | | 0.0216 |
| 7.00 | | 0.0207 |
| 7.20 | | 0.0196 |
| 7.40 | | 0.0184 |
| 7.60 | | 0.0171 |
| 7.80 | | 0.0157 |
| 8.00 | | 0.0144 |
| 8.20 | | 0.0138 |
| 8.40 | | 0.0133 |
| 8.60 | | 0.0128 |
| 8.80 | | 0.0122 |
| 9.00 | | 0.0117 |
| 9.20 | | 0.0110 |
| 9.40 | | 0.0104 |
| 9.60 | | 0.0099 |
| 9.80 | | 0.0094 |
| 10.00 | | 0.0089 |

**Table 4.5 : Mean acceleration of RSRL and RSLSE motions for profile 1-1**

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 0.00 | 0.2501 | 0.2885 |
| 0.01 | 0.2498 | 0.2884 |
| 0.02 | 0.2417 | 0.2882 |
| 0.04 | 0.2531 | 0.3084 |
| 0.06 | 0.3110 | 0.3025 |
| 0.08 | 0.3394 | 0.3217 |
| 0.10 | 0.3895 | 0.3283 |
| 0.12 | 0.3939 | 0.3270 |
| 0.14 | 0.3882 | 0.3348 |
| 0.16 | 0.3838 | 0.3518 |
| 0.18 | 0.5037 | 0.3691 |
| 0.20 | 0.4707 | 0.3662 |
| 0.22 | 0.5402 | 0.3925 |
| 0.24 | 0.5548 | 0.3916 |
| 0.26 | 0.6193 | 0.4121 |
| 0.28 | 0.6390 | 0.4463 |
| 0.30 | 0.6198 | 0.4625 |
| 0.32 | 0.5650 | 0.4808 |
| 0.34 | 0.5313 | 0.4815 |
| 0.36 | 0.5006 | 0.5014 |
| 0.38 | 0.4572 | 0.5033 |
| 0.40 | 0.4256 | 0.5291 |
| 0.42 | 0.4483 | 0.5846 |
| 0.44 | 0.4991 | 0.6335 |
| 0.46 | 0.5267 | 0.6650 |
| 0.48 | 0.5222 | 0.6856 |
| 0.50 | 0.5284 | 0.7063 |
| 0.55 | 0.5666 | 0.7859 |
| 0.60 | 0.5833 | 0.8350 |
| 0.65 | 0.5369 | 0.8020 |
| 0.70 | 0.4645 | 0.7181 |
| 0.75 | 0.4061 | 0.6360 |
| 0.80 | 0.3697 | 0.5781 |
| 0.85 | 0.3611 | 0.5891 |
| 0.90 | 0.3355 | 0.5489 |
| 0.95 | 0.3166 | 0.5226 |
| 1.00 | 0.3004 | 0.4867 |
| 1.05 | 0.2857 | 0.4551 |
| 1.10 | 0.2634 | 0.4198 |
| 1.15 | 0.2586 | 0.4021 |
| 1.20 | 0.2571 | 0.3886 |
| 1.25 | 0.2514 | 0.3782 |
| 1.30 | 0.2456 | 0.3685 |
| 1.35 | 0.2426 | 0.3639 |
| 1.40 | 0.2387 | 0.3554 |
| 1.45 | 0.2334 | 0.3597 |
| 1.50 | 0.2289 | 0.3559 |
| 1.55 | 0.2232 | 0.3349 |
| 1.60 | 0.2169 | 0.3154 |
| 1.65 | 0.2090 | 0.3037 |
| 1.70 | 0.1998 | 0.2885 |
| 1.75 | 0.1917 | 0.2738 |
| 1.80 | 0.1828 | 0.2623 |
| 1.85 | 0.1762 | 0.2499 |
| 1.90 | 0.1709 | 0.2364 |
| 1.95 | 0.1657 | 0.2241 |
| 2.00 | 0.1622 | 0.2158 |
| 2.20 | 0.1476 | 0.1888 |
| 2.40 | 0.1352 | 0.1668 |
| 2.60 | 0.1253 | 0.1461 |
| 2.80 | 0.1093 | 0.1271 |
| 3.00 | 0.0915 | 0.1066 |
| 3.20 | 0.0825 | 0.0919 |
| 3.40 | 0.0760 | 0.0831 |
| 3.60 | 0.0654 | 0.0743 |
| 3.80 | 0.0543 | 0.0628 |
| 4.00 | 0.0479 | 0.0528 |
| 4.20 | 0.0421 | 0.0462 |
| 4.40 | 0.0380 | 0.0419 |
| 4.60 | 0.0344 | 0.0377 |
| 4.80 | 0.0308 | 0.0336 |
| 5.00 | 0.0282 | 0.0312 |
| 5.20 | | 0.0294 |
| 5.40 | | 0.0279 |
| 5.60 | | 0.0267 |
| 5.80 | | 0.0263 |
| 6.00 | | 0.0252 |
| 6.20 | | 0.0243 |
| 6.40 | | 0.0229 |
| 6.60 | | 0.0216 |
| 6.80 | | 0.0208 |
| 7.00 | | 0.0197 |
| 7.20 | | 0.0186 |
| 7.40 | | 0.0174 |
| 7.60 | | 0.0161 |
| 7.80 | | 0.0148 |
| 8.00 | | 0.0141 |
| 8.20 | | 0.0136 |
| 8.40 | | 0.0133 |
| 8.60 | | 0.0129 |
| 8.80 | | 0.0125 |
| 9.00 | | 0.0120 |
| 9.20 | | 0.0113 |
| 9.40 | | 0.0106 |
| 9.60 | | 0.0102 |
| 9.80 | | 0.0100 |
| 10.00 | | 0.0097 |

**Table 4.6 : Mean acceleration of RSRL and RSLSE motions for profile 2-2**

| Time (s) | Mean Acceleration of motions (g) | | Time (s) | Mean Acceleration of motions (g) | | Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|---|---|---|---|---|---|
| | RSRL | RSLSE | | RSRL | RSLSE | | RSRL | RSLSE |
| 0.00 | 0.2501 | 0.3901 | 1.30 | 0.2456 | 0.4376 | 7.60 | | 0.0174 |
| 0.01 | 0.2498 | 0.3885 | 1.35 | 0.2426 | 0.4249 | 7.80 | | 0.0162 |
| 0.02 | 0.2417 | 0.3884 | 1.40 | 0.2387 | 0.4034 | 8.00 | | 0.0154 |
| 0.04 | 0.2531 | 0.4185 | 1.45 | 0.2334 | 0.3907 | 8.20 | | 0.0148 |
| 0.06 | 0.3110 | 0.4130 | 1.50 | 0.2289 | 0.3818 | 8.40 | | 0.0143 |
| 0.08 | 0.3394 | 0.4380 | 1.55 | 0.2232 | 0.3581 | 8.60 | | 0.0139 |
| 0.10 | 0.3895 | 0.4596 | 1.60 | 0.2169 | 0.3435 | 8.80 | | 0.0134 |
| 0.12 | 0.3939 | 0.4844 | 1.65 | 0.2090 | 0.3281 | 9.00 | | 0.0129 |
| 0.14 | 0.3882 | 0.5066 | 1.70 | 0.1998 | 0.3087 | 9.20 | | 0.0123 |
| 0.16 | 0.3838 | 0.5471 | 1.75 | 0.1917 | 0.2900 | 9.40 | | 0.0117 |
| 0.18 | 0.5037 | 0.6318 | 1.80 | 0.1828 | 0.2770 | 9.60 | | 0.0113 |
| 0.20 | 0.4707 | 0.7052 | 1.85 | 0.1762 | 0.2621 | 9.80 | | 0.0110 |
| 0.22 | 0.5402 | 0.7776 | 1.90 | 0.1709 | 0.2466 | 10.00 | | 0.0107 |
| 0.24 | 0.5548 | 0.7371 | 1.95 | 0.1657 | 0.2344 | | | |
| 0.26 | 0.6193 | 0.7522 | 2.00 | 0.1622 | 0.2266 | | | |
| 0.28 | 0.6390 | 0.7769 | 2.20 | 0.1476 | 0.1990 | | | |
| 0.30 | 0.6198 | 0.8087 | 2.40 | 0.1352 | 0.1739 | | | |
| 0.32 | 0.5650 | 0.7738 | 2.60 | 0.1253 | 0.1494 | | | |
| 0.34 | 0.5313 | 0.7337 | 2.80 | 0.1093 | 0.1283 | | | |
| 0.36 | 0.5006 | 0.7213 | 3.00 | 0.0915 | 0.1069 | | | |
| 0.38 | 0.4572 | 0.7128 | 3.20 | 0.0825 | 0.0937 | | | |
| 0.40 | 0.4256 | 0.7609 | 3.40 | 0.0760 | 0.0856 | | | |
| 0.42 | 0.4483 | 0.8489 | 3.60 | 0.0654 | 0.0754 | | | |
| 0.44 | 0.4991 | 0.9169 | 3.80 | 0.0543 | 0.0637 | | | |
| 0.46 | 0.5267 | 0.9615 | 4.00 | 0.0479 | 0.0535 | | | |
| 0.48 | 0.5222 | 0.9850 | 4.20 | 0.0421 | 0.0481 | | | |
| 0.50 | 0.5284 | 1.0067 | 4.40 | 0.0380 | 0.0446 | | | |
| 0.55 | 0.5666 | 1.1026 | 4.60 | 0.0344 | 0.0399 | | | |
| 0.60 | 0.5833 | 1.1444 | 4.80 | 0.0308 | 0.0369 | | | |
| 0.65 | 0.5369 | 1.0659 | 5.00 | 0.0282 | 0.0344 | | | |
| 0.70 | 0.4645 | 0.9669 | 5.20 | | 0.0324 | | | |
| 0.75 | 0.4061 | 0.8507 | 5.40 | | 0.0307 | | | |
| 0.80 | 0.3697 | 0.7679 | 5.60 | | 0.0288 | | | |
| 0.85 | 0.3611 | 0.7768 | 5.80 | | 0.0274 | | | |
| 0.90 | 0.3355 | 0.7071 | 6.00 | | 0.0265 | | | |
| 0.95 | 0.3166 | 0.6692 | 6.20 | | 0.0257 | | | |
| 1.00 | 0.3004 | 0.6236 | 6.40 | | 0.0244 | | | |
| 1.05 | 0.2857 | 0.5755 | 6.60 | | 0.0234 | | | |
| 1.10 | 0.2634 | 0.5289 | 6.80 | | 0.0225 | | | |
| 1.15 | 0.2586 | 0.5036 | 7.00 | | 0.0213 | | | |
| 1.20 | 0.2571 | 0.4773 | 7.20 | | 0.0201 | | | |
| 1.25 | 0.2514 | 0.4525 | 7.40 | | 0.0188 | | | |

**Table 4.7 : Mean acceleration of RSRL and RSLSE motions for profile 3-3**

| Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|
| | RSRL | RSLSE |
| 0.00 | 0.2501 | 0.2974 |
| 0.01 | 0.2498 | 0.2971 |
| 0.02 | 0.2417 | 0.2971 |
| 0.04 | 0.2531 | 0.3046 |
| 0.06 | 0.3110 | 0.3132 |
| 0.08 | 0.3394 | 0.3246 |
| 0.10 | 0.3895 | 0.3841 |
| 0.12 | 0.3939 | 0.3796 |
| 0.14 | 0.3882 | 0.3886 |
| 0.16 | 0.3838 | 0.4212 |
| 0.18 | 0.5037 | 0.4491 |
| 0.20 | 0.4707 | 0.4732 |
| 0.22 | 0.5402 | 0.4934 |
| 0.24 | 0.5548 | 0.5215 |
| 0.26 | 0.6193 | 0.5897 |
| 0.28 | 0.6390 | 0.6527 |
| 0.30 | 0.6198 | 0.6945 |
| 0.32 | 0.5650 | 0.6617 |
| 0.34 | 0.5313 | 0.6323 |
| 0.36 | 0.5006 | 0.6126 |
| 0.38 | 0.4572 | 0.6063 |
| 0.40 | 0.4256 | 0.6377 |
| 0.42 | 0.4483 | 0.6914 |
| 0.44 | 0.4991 | 0.7713 |
| 0.46 | 0.5267 | 0.8027 |
| 0.48 | 0.5222 | 0.7840 |
| 0.50 | 0.5284 | 0.7903 |
| 0.55 | 0.5666 | 0.7652 |
| 0.60 | 0.5833 | 0.7584 |
| 0.65 | 0.5369 | 0.7093 |
| 0.70 | 0.4645 | 0.6270 |
| 0.75 | 0.4061 | 0.5412 |
| 0.80 | 0.3697 | 0.4851 |
| 0.85 | 0.3611 | 0.4785 |
| 0.90 | 0.3355 | 0.4341 |
| 0.95 | 0.3166 | 0.4134 |
| 1.00 | 0.3004 | 0.3831 |
| 1.05 | 0.2857 | 0.3603 |
| 1.10 | 0.2634 | 0.3326 |
| 1.15 | 0.2586 | 0.3145 |
| 1.20 | 0.2571 | 0.3010 |
| 1.25 | 0.2514 | 0.2901 |
| 1.30 | 0.2456 | 0.2780 |
| 1.35 | 0.2426 | 0.2714 |
| 1.40 | 0.2387 | 0.2650 |
| 1.45 | 0.2334 | 0.2585 |
| 1.50 | 0.2289 | 0.2519 |
| 1.55 | 0.2232 | 0.2454 |
| 1.60 | 0.2169 | 0.2379 |
| 1.65 | 0.2090 | 0.2286 |
| 1.70 | 0.1998 | 0.2168 |
| 1.75 | 0.1917 | 0.2075 |
| 1.80 | 0.1828 | 0.1977 |
| 1.85 | 0.1762 | 0.1883 |
| 1.90 | 0.1709 | 0.1807 |
| 1.95 | 0.1657 | 0.1743 |
| 2.00 | 0.1622 | 0.1695 |
| 2.20 | 0.1476 | 0.1503 |
| 2.40 | 0.1352 | 0.1355 |
| 2.60 | 0.1253 | 0.1273 |
| 2.80 | 0.1093 | 0.1102 |
| 3.00 | 0.0915 | 0.0925 |
| 3.20 | 0.0825 | 0.0835 |
| 3.40 | 0.0760 | 0.0783 |
| 3.60 | 0.0654 | 0.0672 |
| 3.80 | 0.0543 | 0.0548 |
| 4.00 | 0.0479 | 0.0480 |
| 4.20 | 0.0421 | 0.0421 |
| 4.40 | 0.0380 | 0.0379 |
| 4.60 | 0.0344 | 0.0344 |
| 4.80 | 0.0308 | 0.0307 |
| 5.00 | 0.0282 | 0.0279 |
| 5.20 | | 0.0265 |
| 5.40 | | 0.0255 |
| 5.60 | | 0.0249 |
| 5.80 | | 0.0240 |
| 6.00 | | 0.0232 |
| 6.20 | | 0.0222 |
| 6.40 | | 0.0209 |
| 6.60 | | 0.0195 |
| 6.80 | | 0.0187 |
| 7.00 | | 0.0178 |
| 7.20 | | 0.0167 |
| 7.40 | | 0.0156 |
| 7.60 | | 0.0144 |
| 7.80 | | 0.0137 |
| 8.00 | | 0.0131 |
| 8.20 | | 0.0125 |
| 8.40 | | 0.0120 |
| 8.60 | | 0.0116 |
| 8.80 | | 0.0111 |
| 9.00 | | 0.0106 |
| 9.20 | | 0.0101 |
| 9.40 | | 0.0095 |
| 9.60 | | 0.0091 |
| 9.80 | | 0.0088 |
| 10.00 | | 0.0083 |

**Table 4.8 : Mean acceleration of RSRL and RSLSE motions for profile 4-4**

| Time (s) | Mean Acceleration of motions (g) | | Time (s) | Mean Acceleration of motions (g) | | Time (s) | Mean Acceleration of motions (g) | |
|---|---|---|---|---|---|---|---|---|
| | RSRL | RSLSE | | RSRL | RSLSE | | RSRL | RSLSE |
| 0.00 | 0.2501 | 0.1050 | 1.30 | 0.2456 | 0.1961 | 7.60 | | 0.0174 |
| 0.01 | 0.2498 | 0.1050 | 1.35 | 0.2426 | 0.1937 | 7.80 | | 0.0160 |
| 0.02 | 0.2417 | 0.1049 | 1.40 | 0.2387 | 0.1910 | 8.00 | | 0.0147 |
| 0.04 | 0.2531 | 0.1058 | 1.45 | 0.2334 | 0.1908 | 8.20 | | 0.0138 |
| 0.06 | 0.3110 | 0.1175 | 1.50 | 0.2289 | 0.1921 | 8.40 | | 0.0134 |
| 0.08 | 0.3394 | 0.1212 | 1.55 | 0.2232 | 0.1970 | 8.60 | | 0.0130 |
| 0.10 | 0.3895 | 0.1212 | 1.60 | 0.2169 | 0.2016 | 8.80 | | 0.0125 |
| 0.12 | 0.3939 | 0.1167 | 1.65 | 0.2090 | 0.2033 | 9.00 | | 0.0120 |
| 0.14 | 0.3882 | 0.1118 | 1.70 | 0.1998 | 0.2023 | 9.20 | | 0.0114 |
| 0.16 | 0.3838 | 0.1161 | 1.75 | 0.1917 | 0.1982 | 9.40 | | 0.0107 |
| 0.18 | 0.5037 | 0.1208 | 1.80 | 0.1828 | 0.1942 | 9.60 | | 0.0103 |
| 0.20 | 0.4707 | 0.1244 | 1.85 | 0.1762 | 0.1915 | 9.80 | | 0.0098 |
| 0.22 | 0.5402 | 0.1338 | 1.90 | 0.1709 | 0.1896 | 10.00 | | 0.0093 |
| 0.24 | 0.5548 | 0.1276 | 1.95 | 0.1657 | 0.1875 | | | |
| 0.26 | 0.6193 | 0.1375 | 2.00 | 0.1622 | 0.1861 | | | |
| 0.28 | 0.6390 | 0.1646 | 2.20 | 0.1476 | 0.1840 | | | |
| 0.30 | 0.6198 | 0.1758 | 2.40 | 0.1352 | 0.1849 | | | |
| 0.32 | 0.5650 | 0.1841 | 2.60 | 0.1253 | 0.1715 | | | |
| 0.34 | 0.5313 | 0.1864 | 2.80 | 0.1093 | 0.1539 | | | |
| 0.36 | 0.5006 | 0.1885 | 3.00 | 0.0915 | 0.1325 | | | |
| 0.38 | 0.4572 | 0.1894 | 3.20 | 0.0825 | 0.1095 | | | |
| 0.40 | 0.4256 | 0.2040 | 3.40 | 0.0760 | 0.1009 | | | |
| 0.42 | 0.4483 | 0.2146 | 3.60 | 0.0654 | 0.0890 | | | |
| 0.44 | 0.4991 | 0.2221 | 3.80 | 0.0543 | 0.0749 | | | |
| 0.46 | 0.5267 | 0.2283 | 4.00 | 0.0479 | 0.0610 | | | |
| 0.48 | 0.5222 | 0.2245 | 4.20 | 0.0421 | 0.0519 | | | |
| 0.50 | 0.5284 | 0.2178 | 4.40 | 0.0380 | 0.0455 | | | |
| 0.55 | 0.5666 | 0.2204 | 4.60 | 0.0344 | 0.0411 | | | |
| 0.60 | 0.5833 | 0.2193 | 4.80 | 0.0308 | 0.0371 | | | |
| 0.65 | 0.5369 | 0.2444 | 5.00 | 0.0282 | 0.0333 | | | |
| 0.70 | 0.4645 | 0.2293 | 5.20 | | 0.0310 | | | |
| 0.75 | 0.4061 | 0.2132 | 5.40 | | 0.0288 | | | |
| 0.80 | 0.3697 | 0.2267 | 5.60 | | 0.0275 | | | |
| 0.85 | 0.3611 | 0.2273 | 5.80 | | 0.0268 | | | |
| 0.90 | 0.3355 | 0.2278 | 6.00 | | 0.0260 | | | |
| 0.95 | 0.3166 | 0.2122 | 6.20 | | 0.0252 | | | |
| 1.00 | 0.3004 | 0.2017 | 6.40 | | 0.0239 | | | |
| 1.05 | 0.2857 | 0.2004 | 6.60 | | 0.0227 | | | |
| 1.10 | 0.2634 | 0.2070 | 6.80 | | 0.0220 | | | |
| 1.15 | 0.2586 | 0.2083 | 7.00 | | 0.0210 | | | |
| 1.20 | 0.2571 | 0.2044 | 7.20 | | 0.0199 | | | |
| 1.25 | 0.2514 | 0.1994 | 7.40 | | 0.0187 | | | |

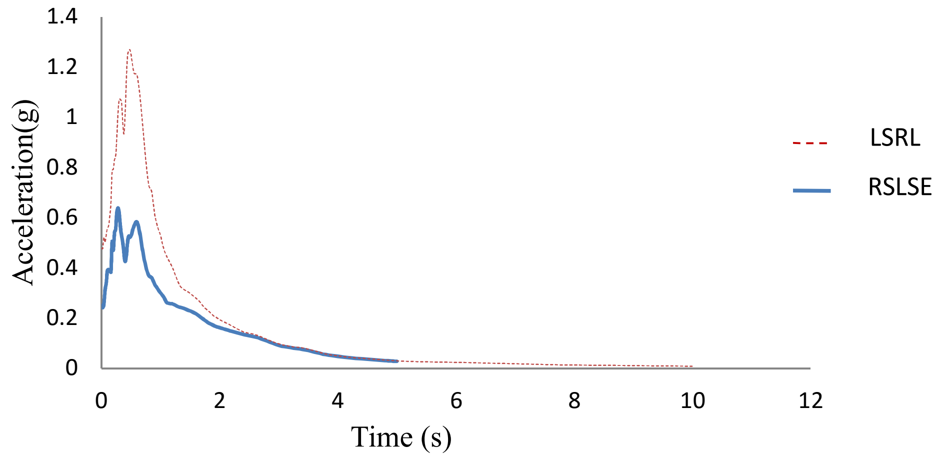



**Figure 4.1 : RSRL and RSLSE for profile A-A**

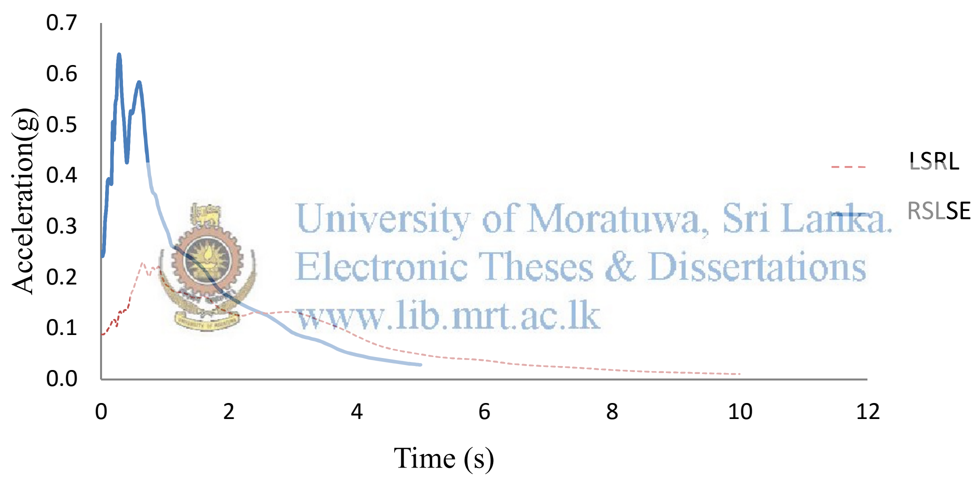





**Figure 4.2: RSRL and RSLSE for profile B-B**

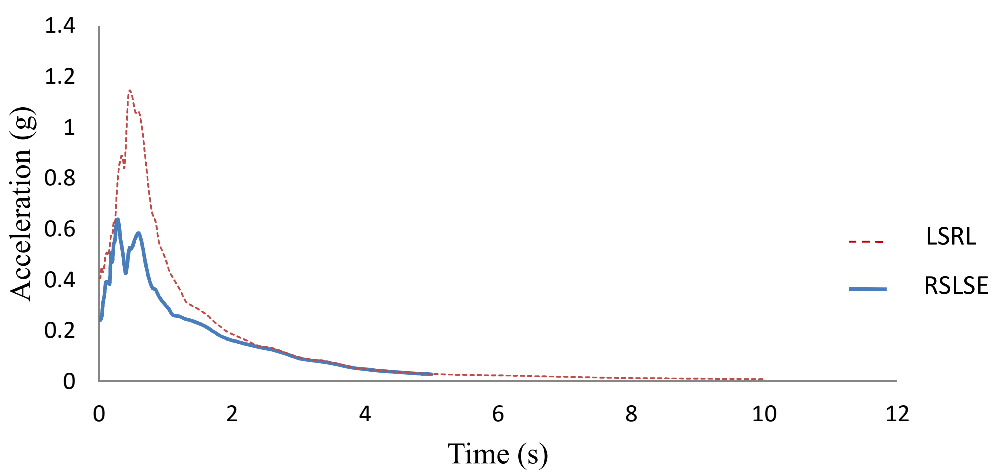



**Figure 4.3 : RSRLand RSLSE for profile C-C**

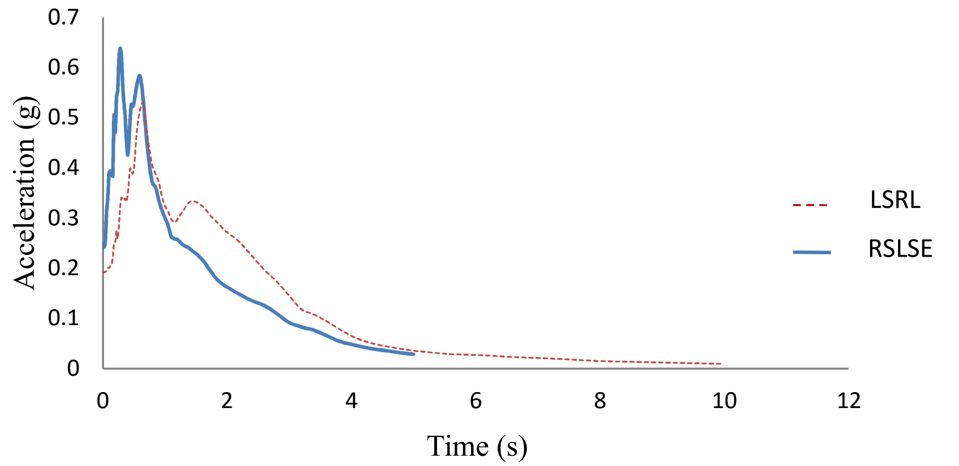



**Figure 4.4 : RSRL and RSLSE for profile D-D**

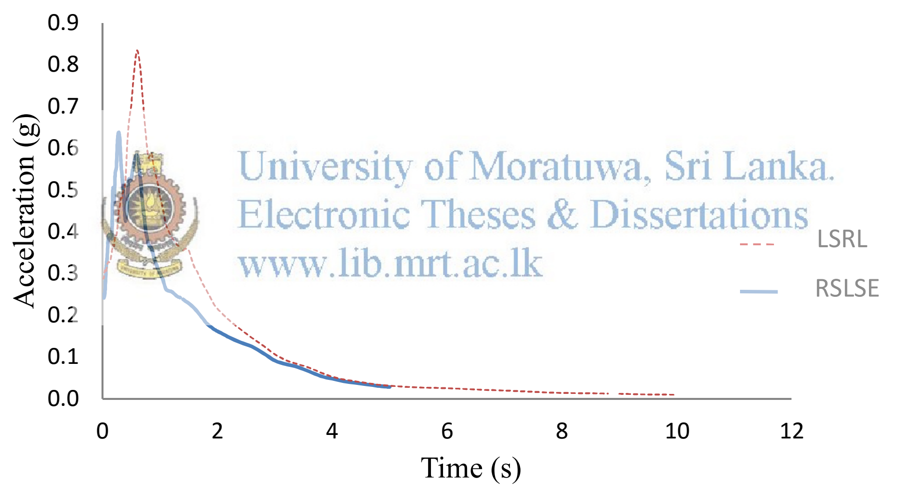





**Figure 4.5 : RSRL and RSLSE for profile 1-1**

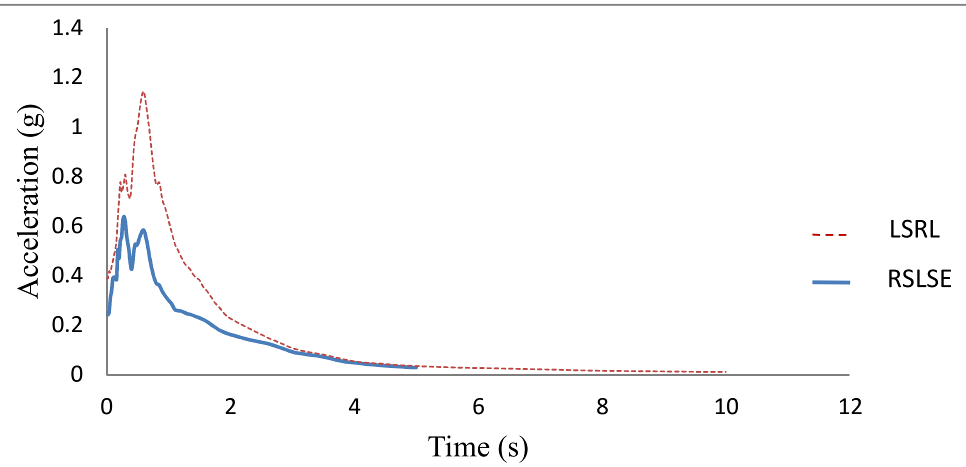



**Figure 4.6 : RSRL and RSLSE for profile 2-2**

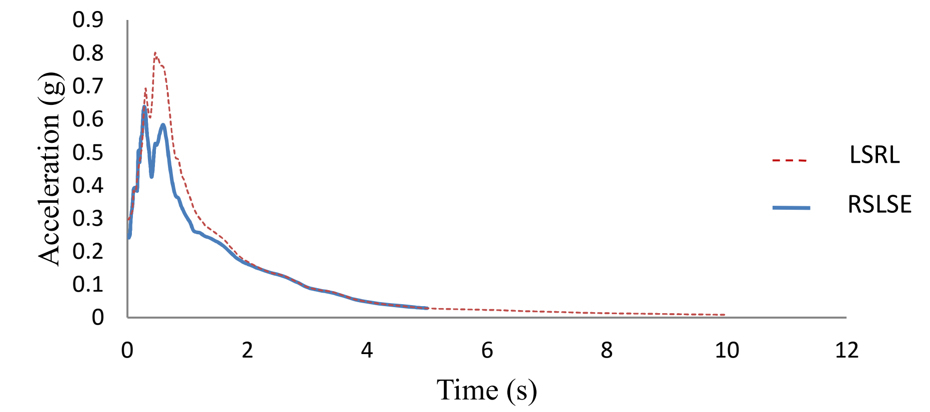



**Figure 4.7 : RSRL and RSLSE for profile 3-3**

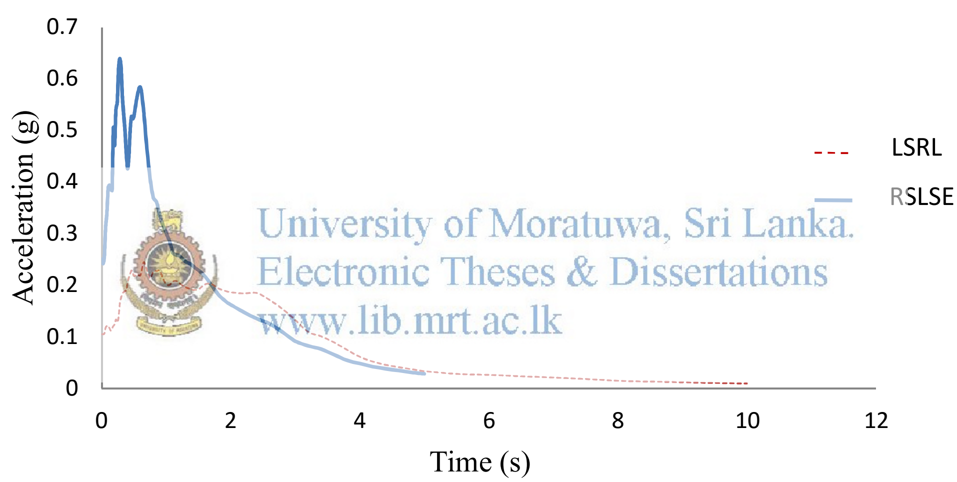





**Figure 4.8 : RSRL and RSLSE for profile 4-4**

**Table 4.9 :RSRL and RSLSE motion for mean value of all profile**

| Time (s) | RSRL | RSLSE |
|---|---|---|
| 0.00 | 0.2501 | 0.2807 |
| 0.01 | 0.2498 | 0.2803 |
| 0.02 | 0.2417 | 0.2803 |
| 0.04 | 0.2531 | 0.2987 |
| 0.06 | 0.3110 | 0.2956 |
| 0.08 | 0.3394 | 0.3105 |
| 0.10 | 0.3895 | 0.3310 |
| 0.12 | 0.3939 | 0.3362 |
| 0.14 | 0.3882 | 0.3447 |
| 0.16 | 0.3838 | 0.3701 |
| 0.18 | 0.5037 | 0.4127 |
| 0.20 | 0.4707 | 0.4259 |
| 0.22 | 0.5402 | 0.4555 |
| 0.24 | 0.5548 | 0.4509 |
| 0.26 | 0.6193 | 0.4911 |
| 0.28 | 0.6390 | 0.5382 |
| 0.30 | 0.6198 | 0.5669 |
| 0.32 | 0.5650 | 0.5633 |
| 0.34 | 0.5313 | 0.5564 |
| 0.36 | 0.5006 | 0.5436 |
| 0.38 | 0.4572 | 0.5319 |
| 0.40 | 0.4256 | 0.5671 |
| 0.42 | 0.4483 | 0.6298 |
| 0.44 | 0.4991 | 0.6828 |
| 0.46 | 0.5267 | 0.7037 |
| 0.48 | 0.5222 | 0.7059 |
| 0.50 | 0.5284 | 0.7085 |
| 0.55 | 0.5666 | 0.7226 |
| 0.60 | 0.5833 | 0.7400 |
| 0.65 | 0.5369 | 0.7072 |
| 0.70 | 0.4645 | 0.6340 |
| 0.75 | 0.4061 | 0.5578 |
| 0.80 | 0.3697 | 0.5091 |
| 0.85 | 0.3611 | 0.5011 |
| 0.90 | 0.3355 | 0.4595 |
| 0.95 | 0.3166 | 0.4301 |
| 1.00 | 0.3004 | 0.4021 |
| 1.05 | 0.2857 | 0.3757 |
| 1.10 | 0.2634 | 0.3529 |
| 1.15 | 0.2586 | 0.3383 |
| 1.20 | 0.2571 | 0.3141 |
| 1.25 | 0.2514 | 0.3030 |
| 1.30 | 0.2456 | 0.2967 |
| 1.35 | 0.2426 | 0.2901 |
| 1.40 | 0.2387 | 0.2864 |
| 1.45 | 0.2334 | 0.2820 |
| 1.50 | 0.2289 | 0.2736 |
| 1.55 | 0.2232 | 0.2663 |
| 1.60 | 0.2169 | 0.2585 |
| 1.65 | 0.2090 | 0.2474 |
| 1.70 | 0.1998 | 0.2366 |
| 1.75 | 0.1917 | 0.2280 |
| 1.80 | 0.1828 | 0.2191 |
| 1.85 | 0.1762 | 0.2103 |
| 1.90 | 0.1709 | 0.2032 |
| 1.95 | 0.1657 | 0.1977 |
| 2.00 | 0.1622 | 0.1791 |
| 2.20 | 0.1476 | 0.1627 |
| 2.40 | 0.1352 | 0.1484 |
| 2.60 | 0.1253 | 0.1317 |
| 2.80 | 0.1093 | 0.1137 |
| 3.00 | 0.0915 | 0.0995 |
| 3.20 | 0.0825 | 0.0918 |
| 3.40 | 0.0760 | 0.0809 |
| 3.60 | 0.0654 | 0.0682 |
| 3.80 | 0.0543 | 0.0580 |
| 4.00 | 0.0479 | 0.0504 |
| 4.20 | 0.0421 | 0.0452 |
| 4.40 | 0.0380 | 0.0409 |
| 4.60 | 0.0344 | 0.0370 |
| 4.80 | 0.0308 | 0.0338 |
| 5.00 | 0.0282 | 0.0315 |
| 5.20 | | 0.0297 |
| 5.40 | | 0.0284 |
| 5.60 | | 0.0275 |
| 5.80 | | 0.0265 |
| 6.00 | | 0.0254 |
| 6.20 | | 0.0237 |
| 6.40 | | 0.0224 |
| 6.60 | | 0.0214 |
| 6.80 | | 0.0214 |
| 7.00 | | 0.0203 |
| 7.20 | | 0.0192 |
| 7.40 | | 0.0179 |
| 7.60 | | 0.0166 |
| 7.80 | | 0.0155 |
| 8.00 | | 0.0145 |
| 8.20 | | 0.0139 |
| 8.40 | | 0.0133 |
| 8.60 | | 0.0128 |
| 8.80 | | 0.0123 |
| 9.00 | | 0.0118 |
| 9.20 | | 0.0112 |
| 9.40 | | 0.0106 |
| 9.60 | | 0.0101 |
| 9.80 | | 0.0097 |
| 10.00 | | 0.0093 |

**Table 4.10 : Sa, d and RSLSE with time**

| t/(s) | Sa | d | RSLSE |
|---|---|---|---|
| 0.001 | 0.100 | 0.031 | 0.131 |
| 0.010 | 0.115 | 0.031 | 0.146 |
| 0.020 | 0.130 | 0.039 | 0.169 |
| 0.040 | 0.160 | 0.046 | 0.206 |
| 0.060 | 0.190 | -0.015 | 0.175 |
| 0.080 | 0.220 | -0.029 | 0.191 |
| 0.100 | 0.250 | -0.059 | 0.191 |
| 0.120 | 0.250 | -0.058 | 0.192 |
| 0.140 | 0.250 | -0.044 | 0.206 |
| 0.160 | 0.250 | -0.014 | 0.236 |
| 0.180 | 0.250 | -0.091 | 0.159 |
| 0.200 | 0.250 | -0.045 | 0.205 |
| 0.220 | 0.250 | -0.085 | 0.165 |
| 0.240 | 0.250 | -0.104 | 0.146 |
| 0.260 | 0.250 | -0.128 | 0.122 |
| 0.280 | 0.250 | -0.101 | 0.149 |
| 0.300 | 0.250 | -0.053 | 0.197 |
| 0.320 | 0.250 | -0.002 | 0.248 |
| 0.340 | 0.250 | 0.025 | 0.275 |
| 0.360 | 0.250 | 0.043 | 0.293 |
| 0.380 | 0.250 | 0.075 | 0.325 |
| 0.400 | 0.250 | 0.141 | 0.391 |
| 0.420 | 0.198 | 0.181 | 0.380 |
| 0.440 | 0.189 | 0.184 | 0.373 |
| 0.460 | 0.181 | 0.177 | 0.358 |
| 0.480 | 0.174 | 0.184 | 0.357 |
| 0.500 | 0.167 | 0.180 | 0.347 |
| 0.550 | 0.152 | 0.156 | 0.307 |
| 0.600 | 0.139 | 0.157 | 0.296 |
| 0.650 | 0.128 | 0.170 | 0.298 |
| 0.700 | 0.119 | 0.169 | 0.289 |
| 0.750 | 0.111 | 0.152 | 0.263 |
| 0.800 | 0.104 | 0.139 | 0.244 |
| 0.850 | 0.098 | 0.140 | 0.238 |
| 0.900 | 0.093 | 0.124 | 0.217 |
| 0.950 | 0.088 | 0.114 | 0.201 |
| 1.000 | 0.083 | 0.102 | 0.185 |
| 1.050 | 0.079 | 0.090 | 0.169 |
| 1.100 | 0.076 | 0.089 | 0.165 |
| 1.150 | 0.072 | 0.080 | 0.152 |
| 1.200 | 0.069 | 0.069 | 0.139 |
| 1.250 | 0.067 | 0.063 | 0.129 |
| 1.300 | 0.064 | 0.057 | 0.121 |
| 1.350 | 0.062 | 0.054 | 0.116 |
| 1.400 | 0.060 | 0.051 | 0.111 |
| 1.450 | 0.057 | 0.053 | 0.110 |
| 1.500 | 0.056 | 0.053 | 0.109 |
| 1.550 | 0.054 | 0.050 | 0.104 |
| 1.600 | 0.052 | 0.049 | 0.102 |
| 1.650 | 0.051 | 0.049 | 0.100 |
| 1.700 | 0.049 | 0.048 | 0.097 |
| 1.750 | 0.048 | 0.045 | 0.092 |
| 1.800 | 0.046 | 0.045 | 0.091 |
| 1.850 | 0.045 | 0.043 | 0.088 |
| 1.900 | 0.044 | 0.039 | 0.083 |
| 1.950 | 0.043 | 0.038 | 0.080 |
| 2.000 | 0.042 | 0.036 | 0.077 |
| 2.200 | 0.038 | 0.031 | 0.069 |
| 2.400 | 0.035 | 0.028 | 0.062 |
| 2.600 | 0.032 | 0.023 | 0.055 |
| 2.800 | 0.030 | 0.022 | 0.052 |
| 3.000 | 0.028 | 0.022 | 0.050 |
| 3.200 | 0.026 | 0.017 | 0.043 |
| 3.400 | 0.025 | 0.016 | 0.040 |
| 3.600 | 0.023 | 0.015 | 0.039 |
| 3.800 | 0.022 | 0.014 | 0.036 |
| 4.000 | 0.021 | 0.010 | 0.031 |

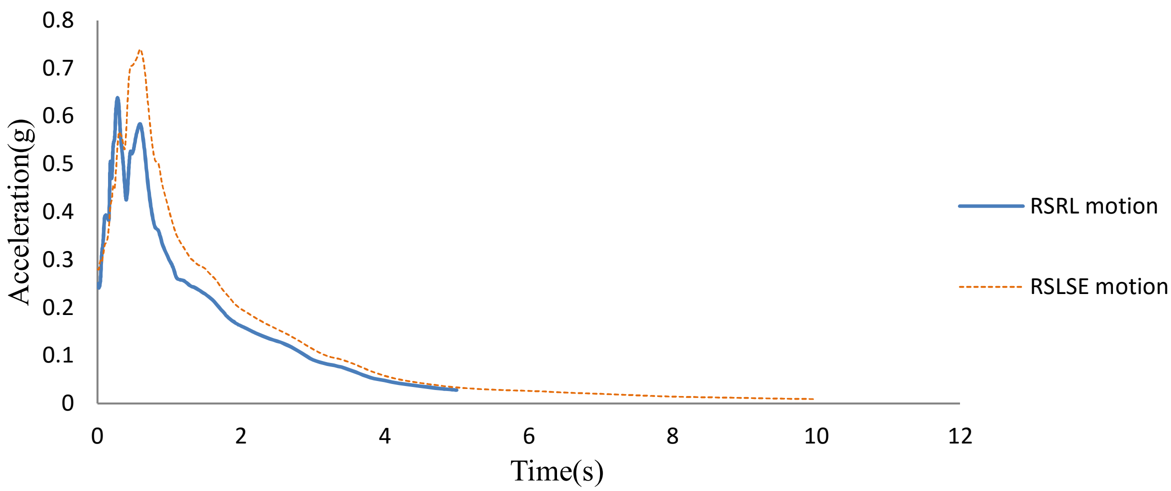



**Figure 4.9 : RSRL and RSLSL for mean value of all profiles**



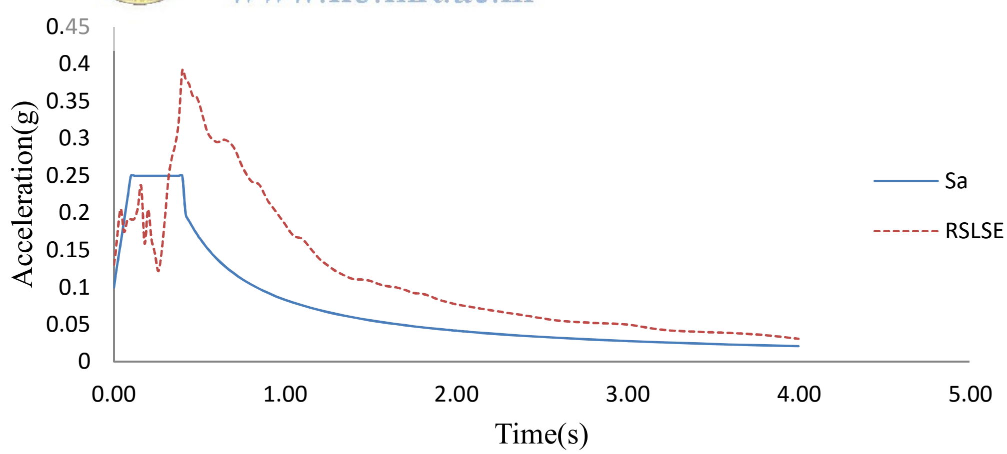



**Figure 4.10 : Sa and RSLSL with time**

# 05. CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion and Recommendations

Eight soil profiles were developed in the Colombo city area based on the available borehole data. The computer software (EduShake) was used to ground response analysis and it is limited to 1-D analysis. For this purpose, the soil layers must be horizontal. According to those soil profiles, the overburden soil layer thickness is varied from about 15m to 25m. Commonly a Silt and/or Clay layer is found everywhere in study area between topmost and bottommost fine Sand layers. In some low lying areas, in addition to Silt and/or Clay layers, a Peat or Organic Clay layer can be observed. A generalized soil profile for study area is shown in Figure 5.1. The generalized shear wave velocity of study area is also shown in Figure 5.1. The shear wave velocity of basement rock was selected as 1000 m/s.



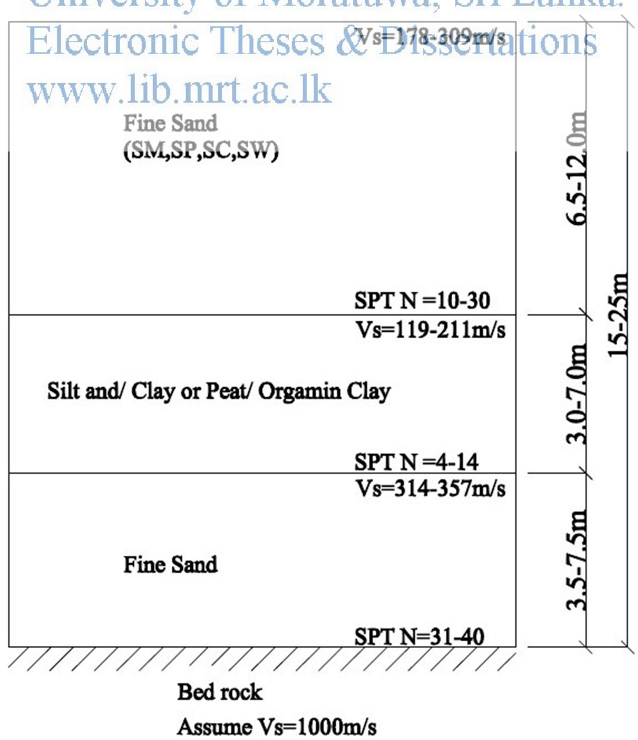



**Figure 5.1: Generalized soil profile for Colombo city area**

According to this research study, the PGA (Peak Ground Acceleration) is 0.13g for Colombo city area with local site effects. Following formulae, given in IS 1893.1:2002 are used to obtain the design response spectrum for Colombo city area.

$$s_a = \begin{cases} (1+15T)a_{max} & 0.00 \leq T \leq 0.10s \\ 2.50a_{max} & 0.10s \leq T \leq 0.55s \\ \dfrac{1.36}{T}a_{max} & 0.55s \leq T \leq 4.00s \end{cases}$$

The proposed design response spectrum for Colombo city with local site effects (RSLSE) is given in Figure 5.2.

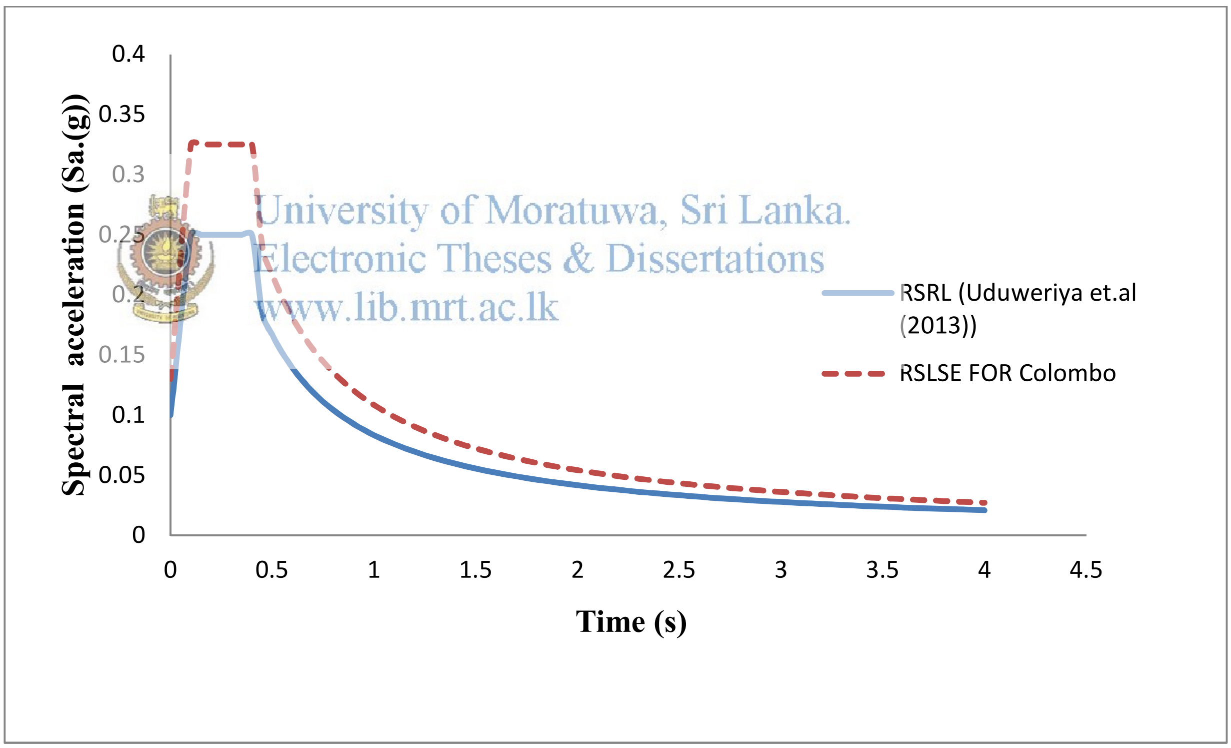




**Figure 5.2: RSRL (Uduweriya et.al (2013)) with RSLSE for Colombo city area**

## 5.2 Further Study

1. In this study, details of only 77 boreholes were used and only eight soil profiles were developed. By increasing number of boreholes and number of profiles, more accurate results can be obtained.

2. In this study the shear wave velocity of basement rock was assumed. But if it can be obtained in a proper way, more accurate results can be obtained.

3. Due to the limitations of software used, only one dimensional analysis was carried out. Presence of tunnel, dams, retaining walls, earth cut etc. cannot be model using 1-D analysis. 2-D and 3-D analysis are required in such a cases.

4. This study was limited to Colombo city. But other cities are also developing rapidly. Hence development of response spectrums with local site effects for other cities also required.

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Annexure 1: A sample of borehole log

# LOG OF BOREHOLE

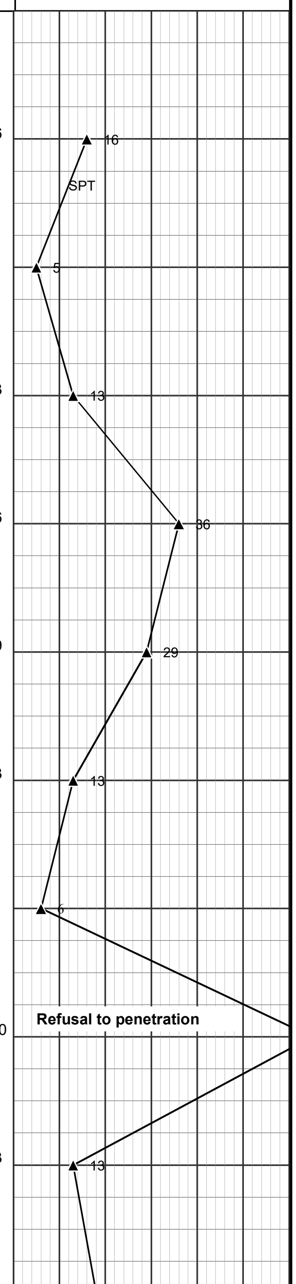
**NATIONAL BUILDING RESEARCH ORGANISATION**
**GEOTECHNICAL ENGINEERING DIVISION**
**99/1, Jawatta Road, Colombo 05.**



| | | | | | |
|---|---|---|---|---|---|
| PROJECT | SOIL INVESTIGATION FOR THE CONSTRUCTION OF FIVE STORIED OFFICERS MARRIED QUARTERS AT SLAF BASE | CLIENT | SRI LANKA AIR FORCE | BOREHOLE NO | BH1 |
| LOCATION | RATMALANA | PROJECT NO | 30/23052 | DEPTH OF HOLE (m) | 32.25 |
| DRILING METHOD | CORE DRILLING | ELEVATION (m RL) | 100.000 | CHAINAGE / OFFSET | |
| CORE SIZE [mm] | CASING SIZE | CO-ORDINATES | N | DATE COMMENCED | 29/2/2007 |
| VANE SIZE [mm*mm] | UDS SAMPLER SIZE [mm] | | E | DATE COMPLETED | 20/3/2007 |

| DEPTH [m] | ELEVATION [m RL] | LAYER THICKNESS(m) | SAMPLE TYPE | SAMPLE NO. | SOIL DESCRIPTION | STRATA | LEGEND | GWL | Y - [g/cm³] OTHER TESTS | DEPTH TESTED [m] | SPT blows per 15cm: 1 | 2 | 3 | FOR 30cm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 100.000 | | | | GROUND LEVEL | | | | | | | | | |
| 0.50 | 99.500 | 0.50 | | | GRAVELLY SILT, reddish brown with sand, dry (laterite fill) | MG | | | | | | | | |
| 1.00 | | | X | | SILTY SAND, brown and black, medium to coarse sand grains with organic matters, MEDIUM DENSE, moist | SM | | 1.85m GL, 20/3/2007 | | 1.00 | 3 | 10 | 6 | 16 |
| 2.00 | 98.000 | 1.50 | X | | | | | | | 2.00 | 2 | 2 | 3 | 5 |
| | | | | | CLAYEY SAND, brownish grey, fine to medium sand grains with low plastic clay fines, LOOSE, moist | SC | | | | | | | | |
| 3.00 | | | X | | | | | | | 3.00 | 1 | 2 | 11 | 13 |
| 3.30 | 96.700 | 1.30 | | | | | | | | | | | | |
| 4.00 | 96.000 | 0.70 | X | | SILTY SAND, dark brown black to brown grey, fine to medium sand grains with traces of mica, MEDIUM DENSE, moist | SM | | | | 4.00 | 5 | 14 | 22 | 36 |
| 5.00 | | | X | | SANDY SILT, brown, very fine sand grains with traces of mica, DENSE to MEDIUM DENSE, moist | MS | | | | 5.00 | 11 | 14 | 15 | 29 |
| 5.80 | 94.200 | 1.80 | | | | | | | | | | | | |
| 6.00 | | | X | | SANDY SILT, bluish grey, fine sand grains with traces of mica, MDEIUM DENSE, moist | MS | | | | 6.00 | 4 | 4 | 9 | 13 |
| 6.80 | 93.200 | 1.00 | | | | | | | | | | | | |
| 7.00 | | | X | | SILTY SAND, brownish grey, fine to coarse sand grains with low plastic clay fines, LOOSE, moist | SM | | | | 7.00 | 7 | 2 | 4 | 6 |
| 8.00 | 92.000 | 1.20 | X | | SILTY SAND, bluish grey, fine to medium sand grains with traces of mica, VERY DENSE, moist | SM | | | | 8.00 | 35 | 42/15 | - | >50 |
| 8.80 | 91.200 | 0.80 | | | | | | | | | | | | |
| 9.00 | | | X | | CLAYEY SAND, whitish grey, fine to medium sand grains, intermediate plastic, MEDIUM DENSE, moist | SC | | | | 9.00 | 4 | 5 | 8 | 13 |
| 10.00 | | | | | | | | | | | | | | |

MOISTURE CONTENT - % (10 20 30 40 50 60)
UNDRAINED SHEAR STRENGTH - kN/m²
SPT RESISTANCE - Blows/30 cm (10 20 30 40 50 60)




| | | | | | |
|---|---|---|---|---|---|
| I-----I | Natural moisture content, Atterberg Limits (LL, PL) | γ –Wet unit weight | W - Wash sample | Drilled By | PSN |
| ▲——▲ | SPT 'N', blows/ft | G -Grainsize Analysis | SPT - SPT Sample | Date | 29/2/2007 |
| +——+ | Vane shear strength, peak | U - Unconfined compression | Undisturbed sample | Logged By | JU |
| ×— — —× | Vane shear strength, residual | CU - Consolidated undrained triaxial | Disturbed Sample | Date | 9/3/2007 |

# LOG OF BOREHOLE

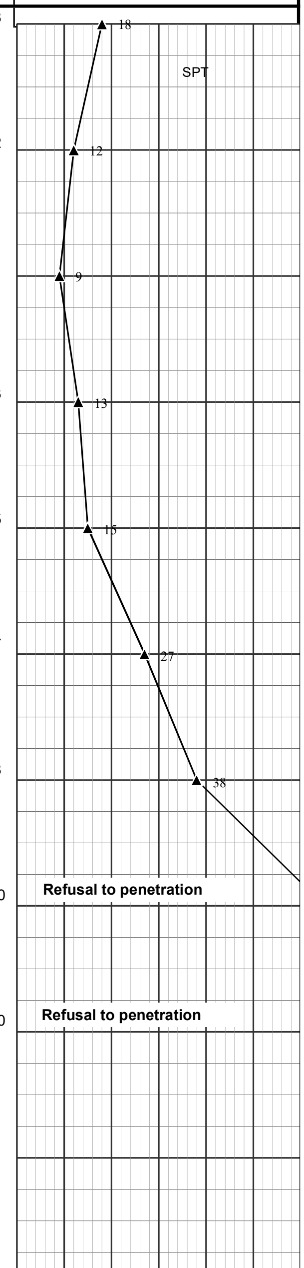
**NATIONAL BUILDING RESEARCH ORGANISATION**
GEOTECHNICAL ENGINEERING DIVISION
99/1, Jawatta Road, Colombo 05.



| | | | | | |
|---|---|---|---|---|---|
| PROJECT | SOIL INVESTIGATION FOR THE CONSTRUCTION OF FIVE STORIED OFFICERS MARRIED QUARTERS AT SLAF BASE | CLIENT | SRI LANKA AIR FORCE | BOREHOLE NO | BH1 |
| LOCATION | RATMALANA | PROJECT NO | 30/23052 | DEPTH OF HOLE (m) | 32.25 |
| DRILING METHOD | CORE DRILLING | ELEVATION (m RL) | 100.000 | CHAINAGE / OFFSET | |
| CORE SIZE [mm] | CASING SIZE | CO-ORDINATES | N | DATE COMMENCED | 29/2/2007 |
| VANE SIZE [mm*mm] | UDS SAMPLER SIZE [mm] | | E | DATE COMPLETED | 20/3/2007 |

| DEPTH [m] | ELEVATION [m RL] | LAYER THICKNESS(m) | SOIL DESCRIPTION | STRATA | GWL | DEPTH TESTED [m] | Blows 1 | Blows 2 | Blows 3 | FOR 30cm |
|---|---|---|---|---|---|---|---|---|---|---|
| 10.00 | 90.000 | 1.20 | | SC | | 10.00 | 9 | 9 | 9 | 18 |
| 11.00 | | | CLAYEY SILT, dull white, traces of sand, high plastic, MEDIUM DENSE, moist | MH | 1.85m GL, 20/3/2007 | 11.00 | 5 | 7 | 5 | 12 |
| 12.00 | | | | | | 12.00 | 3 | 4 | 5 | 9 |
| 13.00 | | | | | | 13.00 | 3 | 5 | 8 | 13 |
| 14.00 | 86.000 | 4.00 | | | | 14.00 | 3 | 6 | 9 | 15 |
| 15.00 | 85.000 | 1.00 | CLAYEY SILT, grey mottled with white, traces of sand with mica, low plastic, MEDIUM DENSE, moist | ML | | 15.00 | 11 | 12 | 15 | 27 |
| 16.00 | 84.000 | 1.00 | SILTY SAND, blueish grey, fine to medium sand grains with mica and low plastic clay fines, MEDIUM DENSE, moist | SM | | 16.00 | 7 | 14 | 24 | 38 |
| 17.00 | | | SILTY SAND, blueish grey mottled with white, fine to medium sand grains with traces of mica, DENSE to VERY DENSE, moist | SM | | 17.00 | 23 | 37 | 15/5 | >50 |
| 18.00 | | | | | | 18.00 | 14 | 53 | 10/2 | >50 |
| 18.32 | 81.680 | 2.32 | | | | | | | | |
| 19.00 | | | SILTY SAND, light grey mottled with brown, fine to medium sand grains with mica, VERY DENSE, moist (completely weathered rock) | SM | | | | | | |
| 20.00 | | | | | | | | | | |

MOISTURE CONTENT - % / UNDRAINED SHEAR STRENGTH - kN/m² / SPT RESISTANCE - Blows/30 cm (10 20 30 40 50 60)




Natural moisture content, Atterberg Limits (LL, PL) · SPT 'N', blows/ft · Vane shear strength, peak · Vane shear strength, residual

γ –Wet unit weight · G -Grainsize Analysis · U - Unconfined compression · CU - Consolidated undrained triaxial

W - Wash sample · SPT - SPT Sample · Undisturbed sample · Disturbed Sample

| | |
|---|---|
| Drilled By | PSN |
| Date | 29/2/2007 |
| Logged By | JU |
| Date | 9/3/2007 |

# LOG OF BOREHOLE

NATIONAL BUILDING RESEARCH ORGANISATION
GEOTECHNICAL ENGINEERING DIVISION
99/1, Jawatta Road, Colombo 05.

SHEET NO. 3 of 4

| | | | | | |
|---|---|---|---|---|---|
| PROJECT | SOIL INVESTIGATION FOR THE CONSTRUCTION OF FIVE STORIED OFFICERS MARRIED QUARTERS AT SLAF BASE | CLIENT | SRI LANKA AIR FORCE | BOREHOLE NO | BH1 |
| LOCATION | RATMALANA | PROJECT NO | 30/23052 | DEPTH OF HOLE (m) | 32.25 |
| DRILING METHOD | CORE DRILLING | ELEVATION (m RL) | 100.000 | CHAINAGE / OFFSET | |
| CORE SIZE [mm] | CASING SIZE | CO-ORDINATES | N | DATE COMMENCED | 29/2/2007 |
| VANE SIZE [mm*mm] | UDS SAMPLER SIZE [mm] | | E | DATE COMPLETED | 20/3/2007 |

| DEPTH [m] | ELEVATION [m RL] | LAYER THICKNESS(m) | SAMPLE TYPE | SAMPLE NO. | SOIL DESCRIPTION | STRATA | LEGEND | GWL | Y - [g/cm³] OTHER TESTS | DEPTH TESTED [m] | Core Recovery % | RQD % | Return of Water % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20.00 | | | | | | SM | | | | | | | |
| 21.20 | 78.800 | 2.88 | | | | | | 1.85m GL, 20/3/2007 | | 21.20 25.50 | NIL | NIL | NIL |
| | | | | | SAND, grey, fine to medium sand grains, traces of mica, poorly graded (washed sample-completely weathered rock) | SP | | | | | | | |
| 25.50 | 74.500 | 4.30 | | | | | | | | 25.50 28.20 | 9 | NIL | NIL |
| 25.60 | 74.400 | 0.10 | | | Highly weathered rock, whitish yellow, medium to fine grained, weak | | | | | | | | |
| | | | | | Metazomatism biotite granitic gniess, pinkish grey, medium to very coarse grained, slightly weathered, highly fractured, strong | | | | | 28.20 29.75 | 39 | NIL | 90 |
| 30.00 | | | | | | | | | | 29.75 30.75 | 40 | NIL | 80 |

STANDARD PENETRATION TEST DATA — NUMBER OF BLOWS PER 15cm (1, 2, 3), FOR 30cm

MOISTURE CONTENT - % (10 20 30 40 50 60); UNDRAINED SHEAR STRENGTH - kN/m²; SPT RESISTANCE - Blows/30 cm (10 20 30 40 50 60)

Natural moisture content, Atterberg Limits (LL, PL) — γ -Wet unit weight — W - Wash sample
SPT 'N', blows/ft — G -Grainsize Analysis — SPT - SPT Sample
Vane shear strength, peak — U - Unconfined compression — Undisturbed sample
Vane shear strength, residual — CU - Consolidated undrained triaxial — Disturbed Sample

| | |
|---|---|
| Drilled By | PSN |
| Date | 29/2/2007 |
| Logged By | JU |
| Date | 9/3/2007 |

| LOG OF BOREHOLE | NATIONAL BUILDING RESEARCH ORGANISATION<br>GEOTECHNICAL ENGINEERING DIVISION<br>99/1, Jawatta Road, Colombo 05. | SHEET NO.<br>4 of 4 |
|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| PROJECT | SOIL INVESTIGATION FOR THE CONSTRUCTION OF FIVE STORIED OFFICERS MARRIED QUARTERS AT SLAF BASE | CLIENT | SRI LANKA AIR FORCE | BOREHOLE NO | BH1 |
| LOCATION | RATMALANA | PROJECT NO | 30/23052 | DEPTH OF HOLE (m) | 32.25 |
| DRILING METHOD | CORE DRILLING | ELEVATION (m RL) | 100 | CHAINAGE / OFFSET | |
| CORE SIZE [mm] | CASING SIZE | CO-ORDINATES | N | DATE COMMENCED | 29/2/2007 |
| VANE SIZE [mm*mm] | UDS SAMPLER SIZE [mm] | | E | DATE COMPLETED | 20/3/2007 |

| DEPTH [m] | ELEVATION [m RL] | LAYER THICKNESS(m) | SAMPLE TYPE | SAMPLE NO. | SOIL DESCRIPTION | STRATA | LEGEND | GWL | Y - [g/cm³] OTHER TESTS | DEPTH TESTED [m] | Core Recovery % | RQD % | Return of Water % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30.00 | | | | | | | | | | | | | |
| | | | | | | | | | | 30.75<br>32.25 | 19 | NIL | 50 |
| 31.00 | | | | | | | | 1.85m GL, 20/3/2007 | | | | | |
| 32.00 | | | | | | | | | | | | | |
| 32.25 | 67.750 | | | | Borehole terminated at 32.25m depth | | | | | | | | |
| 33.00 | | | | | | | | | | | | | |
| 34.00 | | | | | | | | | | | | | |
| 35.00 | | | | | | | | | | | | | |
| 36.00 | | | | | | | | | | | | | |
| 37.00 | | | | | | | | | | | | | |
| 38.00 | | | | | | | | | | | | | |

STANDARD PENETRATION TEST DATA — NUMBER OF BLOWS PER 15cm (1, 2, 3), FOR 30cm

MOISTURE CONTENT - % (10 20 30 40 50 60); UNDRAINED SHEAR STRENGTH - kN/m²; SPT RESISTANCE - Blows/30 cm (10 20 30 40 50 60)



| | | | |
|---|---|---|---|
| Natural moisture content, Atterberg Limits (LL, PL) | γ –Wet unit weight | W - Wash sample | Drilled By: PSN |
| SPT 'N', blows/ft | G -Grainsize Analysis | SPT - SPT Sample | Date: 29/2/2007 |
| Vane shear strength, peak | U - Unconfined compression | - Undisturbed sample | Logged By: JU |
| Vane shear strength, residual | CU - Consolidated undrained triaxial | - Disturbed Sample | Date: 9/3/2007 |

Figure A1: Sample log of a borehole.

# Annexure 2: Summary of borehole log

| Total_dept | Date | Proj_No | Location | Borehole No | X1/(m) | Y1/(m) | RASTERVALU | Dem_ Height/(m) |
|---|---|---|---|---|---|---|---|---|
| 24.200000 | 5.6.2006 | 30/22898 | Kirulapana-18 storried build-edmonton road | BH001 | 100932 | 186871 | 0.0 | 19.3 |
| 24.000000 | 14.6.2006 | 30/22898 | Kirulapana-18 storried build-edmonton road | BH002 | 100934 | 186877 | 0.0 | 18.4 |
| 24.000000 | 17.6.2006 | 30/22898 | Kirulapana-18 storried build-edmonton road | BH003 | 100933 | 186882 | 0.0 | 17.0 |
| 25.400000 | 27.6.2006 | 30/22898 | Kirulapana-18 storried build-edmonton road | BH004 | 100934 | 186893 | 0.0 | 16.3 |
| 15.400000 | 16.10.2005 | 30/22759 | Maradana - attorney generals dept | BH005 | 99516 | 192951 | 4.7 | 4.7 |
| 8.450000 | 7.2.2006 | 30/22854 | SLAVE ISLANG-GALLE FACE-TAJ SAMUDRA | BH006 | 97809 | 191490 | 4.2 | 4.2 |
| 12.300000 | 7.5.2006 | 30/22904 | ISIPATHANA MAWATHA | BH007 | 100060 | 187683 | 0.0 | 4.0 |
| 15.400000 | 25.1..2006 | 30/23007 | HARBOUR-DOCK YARD | BH008 | 98973 | 195290 | 7.2 | 7.2 |
| 13.450000 | 9.3.2006 | 30/22886 | COLOMBO 10 , 18 STORIED BMC HEAD QUARTERS | BH009 | 99934 | 191474 | 7.0 | 7.0 |
| 10.700000 | 22.4.2006 | 30/22834 | COLOMBO 12 -MINISTRY OF JUSICE BUILD - 6 SORIES | BH010 | 99464 | 192885 | 5.1 | 5.1 |
| 10.450000 | 26.6.2005 | 30/22650 | Air force HEAD QUARTERS | BH011 | 98271 | 192128 | 2.9 | 2.9 |
| 11.150000 | 4.8.2005 | 30/22650 | Air force HEAD QUARTERS | BH012 | 98268 | 192097 | 2.9 | 2.9 |
| 5.800000 | 27.2.2005 | 30/22627 | NARAHENPITA - CARETAKERS QUARTERS -WATER BOARD | BH013 | 100779 | 188338 | 0.0 | 3.6 |
| 11.900000 | 22.10.2005 | 30/22818 | COLOMBO 06 -42ND LANE | BH015 | 99304 | 185359 | 0.0 | 8.1 |
| 22.300000 | 10.06.2005 | 30/22702 | MATTAKKULIYA GVT HOUSINH SCHEME | BH016 | 101577 | 196887 | 2.1 | 2.1 |
| 10.450000 | 10.04.2005 | 30/22661 | COLOMBO 1- STAFF QUARTERS AT PRESIDENT HOUSE | BH017 | 97377 | 193040 | 3.1 | 3.1 |
| 33.740000 | 26.12.2004 | 30/22561 | COLOMBO 03 - 10TH LANE | BH018 | 98368 | 188899 | 0.0 | 8.0 |
| 5.900000 | 20.7.2005 | 30/22748 | COLOMBO 01- PRESIDENE HOUSE | BH019 | 97331 | 193020 | 3.9 | 3.9 |
| 20.370000 | 08.10.2004 | 30/22443 | MAITLAND PLACE-SR ARMY | BH020 | 100163 | 189643 | 0.0 | 6.0 |
| 18.700000 | 29.07.2004 | 30/22443-1 | ARMI HEAD QUARTERS BALADAKSHA MAWATHA | BH021 | 97741 | 191979 | 4.6 | 4.6 |
| 16.860000 | 09.04.2004 | 30/22419 | Buddhist research center wijerama mw | BH023 | 100772 | 189621 | 0.0 | 2.0 |
| 10.330000 | 27.08.2004 | 30/22460 | PERAHERA MW | BH024 | 98706 | 190724 | 4.3 | 4.3 |
| 12.050000 | 07.10.2003 | 30/22319 | SANASA FEDEARTION BUILDING -KIRULAPANA | BH025 | 101085 | 186710 | 0.0 | 19.6 |
| 16.050000 | 27.2.2003 | 30/22200 | MINISTRY OF BUDDASASANA DARMAPALAMW CO 07 | BH026 | 99125 | 190595 | 5.6 | 5.6 |
| 11.500000 | 20.08.2004 | 30/22473 | COMMUNITY CENTER CWW KANNANGARA MW CO 07 | BH027 | 99791 | 190589 | 7.0 | 7.0 |
| 20.000000 | 06.08.2004 | 30/22461 | NARAHENPIA RMV OFFICE PREMISSES | BH028 | 101629 | 188726 | 0.0 | 1.0 |
| 15.600000 | 11.03.2003 | 30/22182F | BORELLA PALANGASTHUDUWA LAND | BH031 | 101209 | 190612 | 6.7 | 6.7 |
| 19.600000 | 2.05.2003 | | COLOMBO 7 AGRO & FOOD TECHNOLOGY DDIVISION FOR ITI | BH032 | 100778 | 189665 | 0.0 | 2.3 |
| 12.160000 | 27.02.2003 | 30/22182A | PROJECT, NEAR RAIL WAY TRACK(PRAMUKA BANK) | BH033 | 98031 | 190173 | 6.4 | 6.4 |
| 16.300000 | 15.01.2002 | 30/22166 | SURPENTINE RD, COLOMBO 09 | BH034 | 101635 | 190990 | 2.4 | 2.4 |
| 17.000000 | 23.05.2002 | 30/21993 | BORELLA GOVERNMENT SERVANTS AT GOTHAMI RD | BH037 | 102015 | 190265 | 3.2 | 3.2 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 29.550000 | 11.08.2002 | 30/22098 | NARAHENPITA, NATIONAL BLOOD TRANSFUTION CENTER | BH039 | 101169 | 188031 | 0.0 | 3.4 |
| 22.440000 | 16.05.2002 | 30/21654 | BAMBALAPITIYA, WPCC, POLICE STATION | BH040 | 98780 | 188131 | 0.0 | 7.2 |
| 8.450000 | 27.06.2002 | 30/ | HAVELOCK RD. PAMANKADA JUNCTION | BH041 | 100291 | 186690 | 0.0 | 4.1 |
| 18.220000 | 21.02.2002 | 30/ | THUN MULLA GYMNASIUM SLAF | BH043 | 99548 | 188335 | 0.0 | 7.0 |
| 21.220000 | 17.02.2002 | 30/22015 | FAMILY HEALTH BUEAU, COLOMBO 10 | BH044 | 100201 | 191344 | 7.1 | 7.1 |
| 4.010000 | 03.05.2001 | 30/21830 | HOLY FAMILY CONVENT BUMBALAPITIYA | BH046 | 98806 | 187617 | 0.0 | 8.0 |
| 12.500000 | 06.12.200 | 30/21823 | KOTAHENA, 256 RAMANATHAN MAWATHA, COLO 13 | BH047 | 98949 | 194513 | 4.8 | 4.8 |
| 14.650000 | 15.06.1992 | 30/20567 | YORK STREET CO 01 | BH049 | 97319 | 192713 | 5.7 | 5.7 |
| 13.450000 | 3.12.1990 | 30/20403 | MINISTRY OF FOREIGN AFFAIRS CO1 | BH051 | 97459 | 193105 | 1.6 | 1.6 |
| 12.130000 | 15.12.1993 | 30/20786 | ASIAN DEVELOPMENT BANK TRAINING CENTER CO1 | BH052 | 97460 | 193173 | 0.9 | 0.9 |
| 18.450000 | 10.10.1989 | 30/20313 | MEDICAL RECEPTION CENTER NEAVY HEAD QUARTERS CO1 | BH053 | 97273 | 193086 | 3.6 | 3.6 |
| 11.150000 | 26.04.1990 | 30/20353 | ADDITIONAL OFFICE FOR PRESIDENTIAL SECRETARY CO1 | BH054 | 97463 | 192713 | 4.2 | 4.2 |
| 13.000000 | 11.09.1990 | 30/20316 | KLM BUILDING CO 1 JANADIPATHI MAWATHA | BH055 | 97156 | 192688 | 6.2 | 6.2 |
| 16.110000 | 9.05.1991 | 30/20454 | CHATHAM STREET CO1 | BH056 | 97405 | 192800 | 4.7 | 4.7 |
| 11.810000 | 12.03.1991 | 30/20348 | UPPER CHATHAM STREET CO1 | BH057 | 97225 | 192813 | 6.7 | 6.7 |
| 17.750000 | 22.08.1990 | 30/20347 | PORTS AUTHORITY CO1 | BH058 | 97194 | 193288 | 0.5 | 0.5 |
| 10.650000 | 20.08.1990 | 30/20373 | DEFENCE MINISTRY GALLE FACE | BH059 | 97413 | 192238 | 3.4 | 3.4 |
| 19.500000 | 22.07.1993 | 30/20674 | POLLICE HEAD QUATRES FORT CHURCH STREET | BH060 | 97338 | 193075 | 3.1 | 3.1 |
| 26.100000 | 6.08.1993 | 30/20716 | LAKE HOUSE CO1 | BH061 | 97625 | 192588 | 3.6 | 3.6 |
| 15.100000 | 4.01.1998 | 30/20342 | COLOMBO FORT | BH062 | 97740 | 193120 | 1.4 | 1.4 |
| 5.250000 | 05.09.1992 | 30/20454 | 125 CHATHAM STREET | BH063 | 97400 | 192794 | 4.8 | 4.8 |
| 18.050000 | 10.09.1992 | 30/20454 | 125 CHATHAM STREET | BH064 | 97400 | 192794 | 4.8 | 4.8 |
| 24.210000 | 26.12.1993 | 30/20736 | 266, VAUXHALL STREET CO 2 | BH065 | 98998 | 191504 | 3.7 | 3.7 |
| 24.900000 | 26.04.1994 | 30/20803 | NAWAM MAWATHA NDB BANK CO 2 | BH066 | 98265 | 191071 | 2.7 | 2.7 |
| 14.450000 | 29.01.1994 | 30/20618 | MORGAN ROAD CUSTOM QUARTERS SLAVE ISLAND | BH067 | 98325 | 192056 | 3.1 | 3.1 |
| 12.450000 | 16.06.1986 | 30/20 | KUMARAN RATHNAM MAWATHA ARMY WORK SHOP CO2 | BH068 | 97956 | 192025 | 3.6 | 3.6 |
| 10.400000 | 26.08.1983 | 30/ | NEAR RAILWAY STATION SLAVE ISLAND CO 2 | BH069 | 97800 | 191550 | 4.3 | 4.3 |
| 15.300000 | 13.01.1988 | 30/20090 | SLAVE ISLANG-CHURCH STREET | BH070 | 98020 | 191530 | 4.6 | 4.6 |
| 18.020000 | 07.02.1986 | | RAMADA RENAISSANCE HOTEL CO 2 | BH071 | 97815 | 192115 | 4.2 | 4.2 |
| 20.180000 | 20.08.1986 | | SIR JAMES PIERIS MAWATHA SLAVE ISLAND CO 3 | BH072 | 98169 | 191231 | 4.0 | 4.0 |
| 10.450000 | 29.03.1995 | 30/20870 | SIR JAMES PIERIS MAWATHA NAWAM MAWATHA | BH073 | 98250 | 191330 | 5.0 | 5.0 |
| 16.570000 | 11.04.1995 | 30/20870 | ANANDA KUMARSWAMO/SIR JAMES PERIS MW | BH074 | 98500 | 190770 | 3.2 | 3.2 |
| 10.450000 | 24.03.1995 | 30/20870 | HYDE PARK CONER/ UNION PLACE | BH075 | 99510 | 190840 | 7.5 | 7.5 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 10.450000 | 18.04.1995 | 30/20870 | DARLY RD TB JAYA MAWATHA | BH076 | 99090 | 191430 | 4.6 | 4.6 |
| 16.300000 | 16.06.1988 | 30/20152 | BALADAKSHA MAWATHA CO 2 | BH077 | 97500 | 192025 | 3.3 | 3.3 |
| 25.100000 | 04.01.1994 | 30/20736 | VAUXHALL STREET CO 2 | BH078 | 98794 | 191469 | 4.3 | 4.3 |
| 30.620000 | 27.01.1994 | 30/20796 | UNION PLACE CO 2 | BH079 | 98225 | 191506 | 5.7 | 5.7 |
| 26.100000 | 18.09.1991 | 30/20470 | KEW ROAD CO2 | BH080 | 98250 | 191500 | 5.9 | 5.9 |
| 28.000000 | 21.02.1994 | 30/20803 | NAWAM MAWATHA | BH081 | 98244 | 191094 | 3.0 | 3.0 |
| 15.300000 | 13.01.1988 | 30/20197 | CHURCH STREET SLAVE ISLAND | BH082 | 97938 | 191550 | 4.3 | 4.3 |
| 15.450000 | 01.02.1986 | | RAMADA HOTEL CO 2 | BH083 | 97813 | 192113 | 4.2 | 4.2 |
| 13.200000 | 15.10.1988 | 30/20199 | W A D RAMANAYAKA MW CO2 | BH084 | 98681 | 190606 | 4.7 | 4.7 |
| 23.050000 | 15.05.1986 | | D MEL MAWATHA CO 3 | BH085 | 98607 | 189441 | 0.0 | 6.6 |

# Annexure 3: Earthquake data in and around Sri Lanka

**Table A3-1: Earthquake in and around srilanka**

| No. | Yr | M | D | Long. | Lat. | Magnitude (Mw) |
|---|---|---|---|---|---|---|
| 1 | 1615 | 4 | 14 | 79.8 | 6.9 | 6.4 |
| 2 | 1819 | 6 | 20 | 79.6 | 12 | 4.3 |
| 3 | 1822 | 1 | 29 | 79 | 12 | 5 |
| 4 | 1823 | 3 | 2 | 76.6 | 9.5 | 4.3 |
| 5 | 1823 | 11 | 26 | 80 | 7 | 4.3 |
| 6 | 1823 | 3 | 9 | 80 | 7 | 5 |
| 7 | 1823 | 2 | 9 | 85 | 12 | 5.5 |
| 8 | 1823 | 2 | 9 | 80 | 7 | 5.7 |
| 9 | 1829 | 3 | 12 | 77.6 | 13 | 4.3 |
| 10 | 1856 | 8 | 25 | 77 | 8.7 | 4.3 |
| 11 | 1856 | 9 | 1 | 76 | 9.5 | 4.3 |
| 12 | 1858 | 12 | 30 | 78.4 | 12.4 | 4.3 |
| 13 | 1858 | 8 | 13 | 76 | 11.4 | 4.7 |
| 14 | 1859 | 1 | 3 | 79 | 12.5 | 4.3 |
| 15 | 1859 | 12 | 17 | 78.1 | 11.6 | 4.3 |
| 16 | 1860 | 1 | 17 | 78.2 | 11.9 | 4.3 |
| 17 | 1861 | 3 | 4 | 78.2 | 11.9 | 4.2 |
| 18 | 1864 | 1 | 5 | 78.7 | 10.8 | 4.3 |
| 19 | 1865 | 8 | 2 | 78.7 | 12.7 | 4.3 |
| 20 | 1867 | 7 | 3 | 79.6 | 12 | 5.7 |
| 21 | 1882 | 2 | 28 | 76.7 | 11.5 | 5.6 |
| 22 | 1882 | 1 | 0 | 81.2 | 8.6 | 6 |
| 23 | 1900 | 2 | 8 | 76.7 | 10.7 | 6 |
| 24 | 1916 | 1 | 7 | 77 | 13 | 5 |
| 25 | 1919 | 10 | 14 | 83 | 2 | 5 |
| 26 | 1938 | 8 | 7 | 77.5 | 4 | 5.6 |
| 27 | 1938 | 9 | 10 | 79.2 | 7.7 | 6 |
| 28 | 1939 | 8 | 7 | 77.5 | 4 | 5.8 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 29 | 1952 | 5 | 9 | 78 | 11 | 4.7 |
| 30 | 1953 | 1 | 29 | 82.5 | 6.7 | 5 |
| 31 | 1953 | 7 | 26 | 76.3 | 9.9 | 5 |
| 32 | 1955 | 7 | 11 | 76.5 | 12.4 | 4.6 |
| 33 | 1956 | 12 | 15 | 78 | 6.5 | 5 |
| 34 | 1959 | 12 | 17 | 78.1 | 11.7 | 4.2 |
| 35 | 1961 | 6 | 13 | 83.2 | 8.7 | 4 |
| 36 | 1962 | 2 | 7 | 76.9 | 11.4 | 4.2 |
| 37 | 1966 | 4 | 10 | 80.2 | 13 | 4.8 |
| 38 | 1966 | 1 | 8 | 84.93 | 11.6 | 5.2 |
| 39 | 1968 | 8 | 13 | 79.1 | 12.9 | 4 |
| 40 | 1969 | 6 | 4 | 78.2 | 12.1 | 4 |
| 41 | 1969 | 9 | 21 | 77.5 | 13 | 4 |
| 42 | 1971 | 8 | 4 | 79.9 | 11.9 | 4 |
| 43 | 1971 | 11 | 12 | 78.2 | 12.5 | 4 |
| 44 | 1971 | 1 | 17 | 77 | 12.4 | 4.1 |
| 45 | 1972 | 5 | 16 | 77 | 12.4 | 4.6 |
| 46 | 1972 | 7 | 29 | 77 | 11 | 4.7 |
| 47 | 1973 | 5 | 1 | 77.4 | 12.5 | 4.1 |
| 48 | 1973 | 8 | 30 | 84.33 | 7.15 | 5.9 |
| 49 | 1974 | 7 | 31 | 78.3 | 12.8 | 4.1 |
| 50 | 1984 | 3 | 20 | 77.8 | 12.7 | 4.5 |
| 51 | 1984 | 11 | 27 | 78.6 | 12.4 | 4.5 |
| 52 | 1986 | 10 | 12 | 85 | 3.97 | 5 |
| 53 | 1987 | 10 | 31 | 84 | 6.8 | 4.3 |
| 54 | 1987 | 10 | 30 | 84.8 | 2.54 | 5.3 |
| 55 | 1988 | 6 | 7 | 77.21 | 9.81 | 4.4 |
| 56 | 1993 | 12 | 6 | 78.3 | 6.8 | 5.4 |
| 57 | 1995 | 12 | 10 | 83.3 | 4.1 | 4.1 |
| 58 | 1996 | 3 | 19 | 76.8 | 9.9 | 4 |
| 59 | 1998 | 2 | 4 | 76.84 | 12.67 | 4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 60 | 1998 | 8 | 25 | 77.98 | 12.27 | 4.1 |
| 61 | 1998 | 9 | 1 | 78.24 | 5.49 | 4.2 |
| 62 | 1998 | 11 | 17 | 77.78 | 5.51 | 4.4 |
| 63 | 2000 | 12 | 12 | 76.79 | 9.69 | 4.9 |
| 64 | 2001 | 1 | 29 | 77.36 | 12.44 | 4.2 |
| 65 | 2001 | 10 | 28 | 76.32 | 7.15 | 4.3 |
| 66 | 2001 | 1 | 7 | 76.8 | 9.69 | 4.7 |
| 67 | 2001 | 9 | 25 | 80.31 | 11.79 | 5.6 |
| 68 | 2003 | 3 | 22 | 83.96 | 2.19 | 4.1 |
| 69 | 2004 | 8 | 5 | 76.86 | 2.02 | 5 |
| 70 | 2005 | 1 | 3 | 83.29 | 7.54 | 4.7 |
| 71 | 2005 | 7 | 7 | 84.94 | 4.47 | 4.9 |
| 72 | 2007 | 7 | 18 | 84.4 | 6.47 | 5.1 |
| 73 | 2009 | 4 | 15 | 82.43 | 6.62 | 4.1 |
| 74 | 2009 | 5 | 9 | 77.52 | 7.37 | 5 |
| 75 | 2010 | 7 | 25 | 76.83 | 6.53 | 4 |
| 76 | 2011 | 11 | 19 | 79.05 | 4.02 | 4.6 |
| 77 | 2012 | 7 | 6 | 77.1 | 5.18 | 4.3 |

# Annexure 4: Section through of borehole

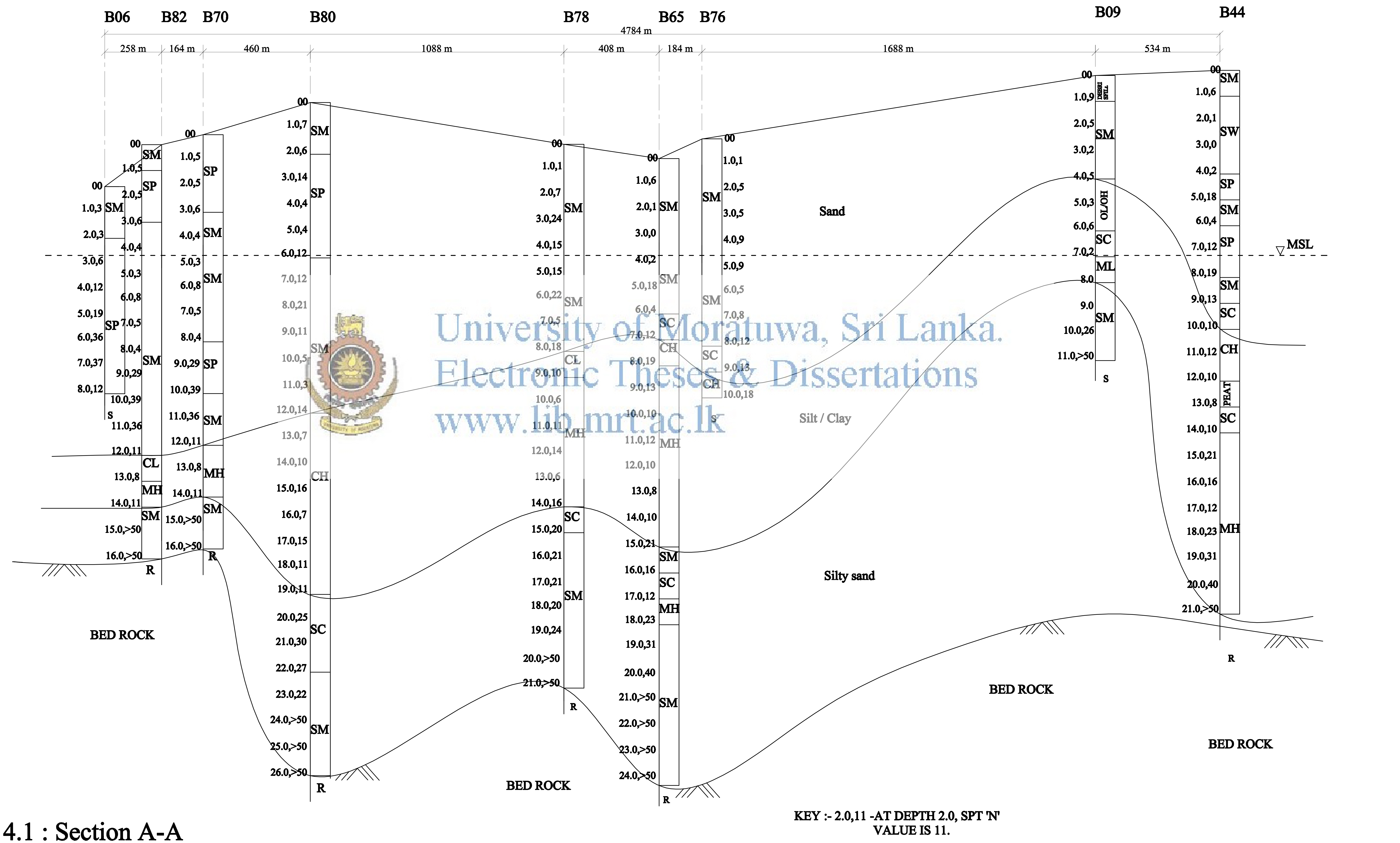



Figure A 4.1 : Section A-A

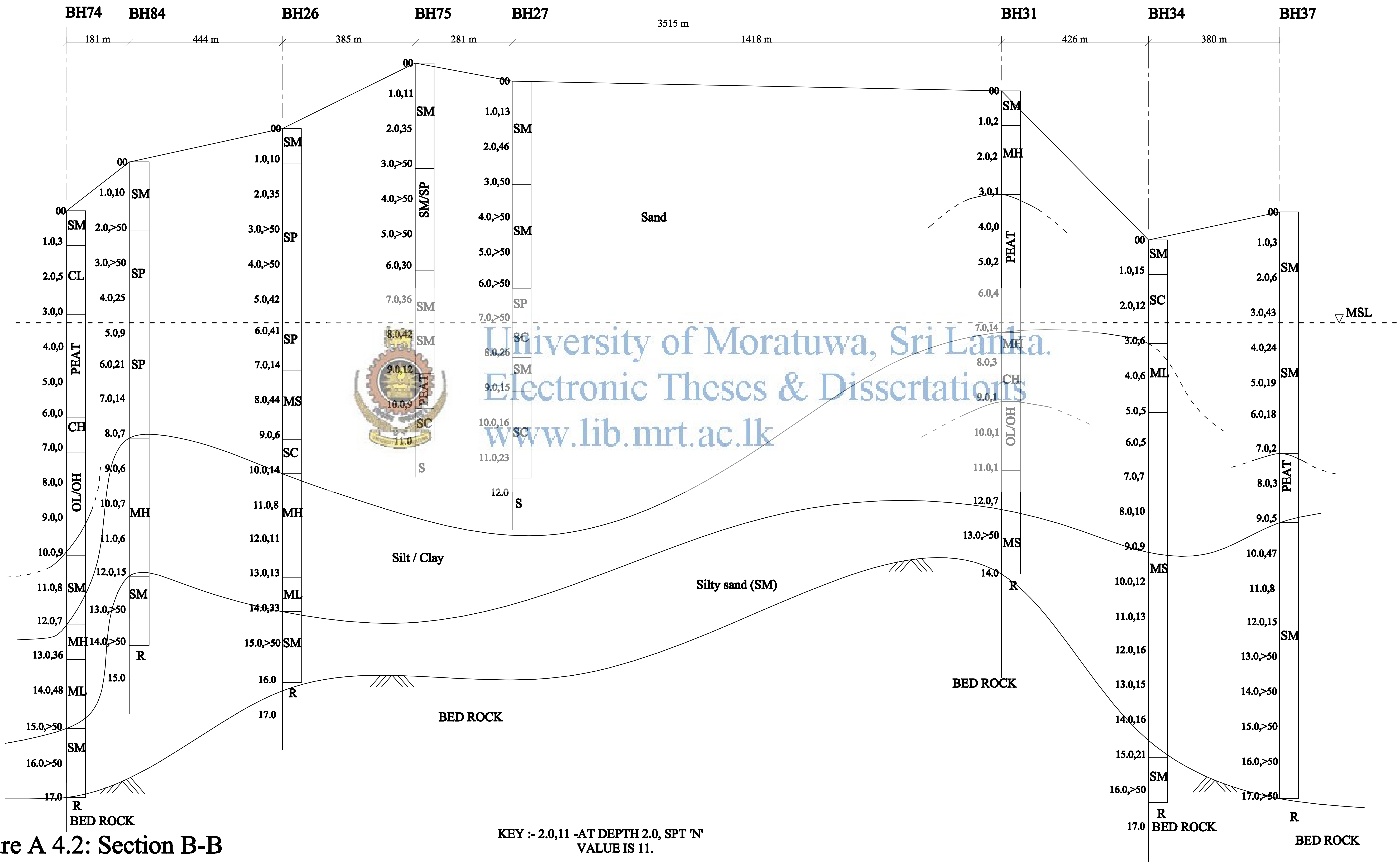



Figure A 4.2: Section B-B

KEY :- 2.0,11 -AT DEPTH 2.0, SPT 'N' VALUE IS 11.

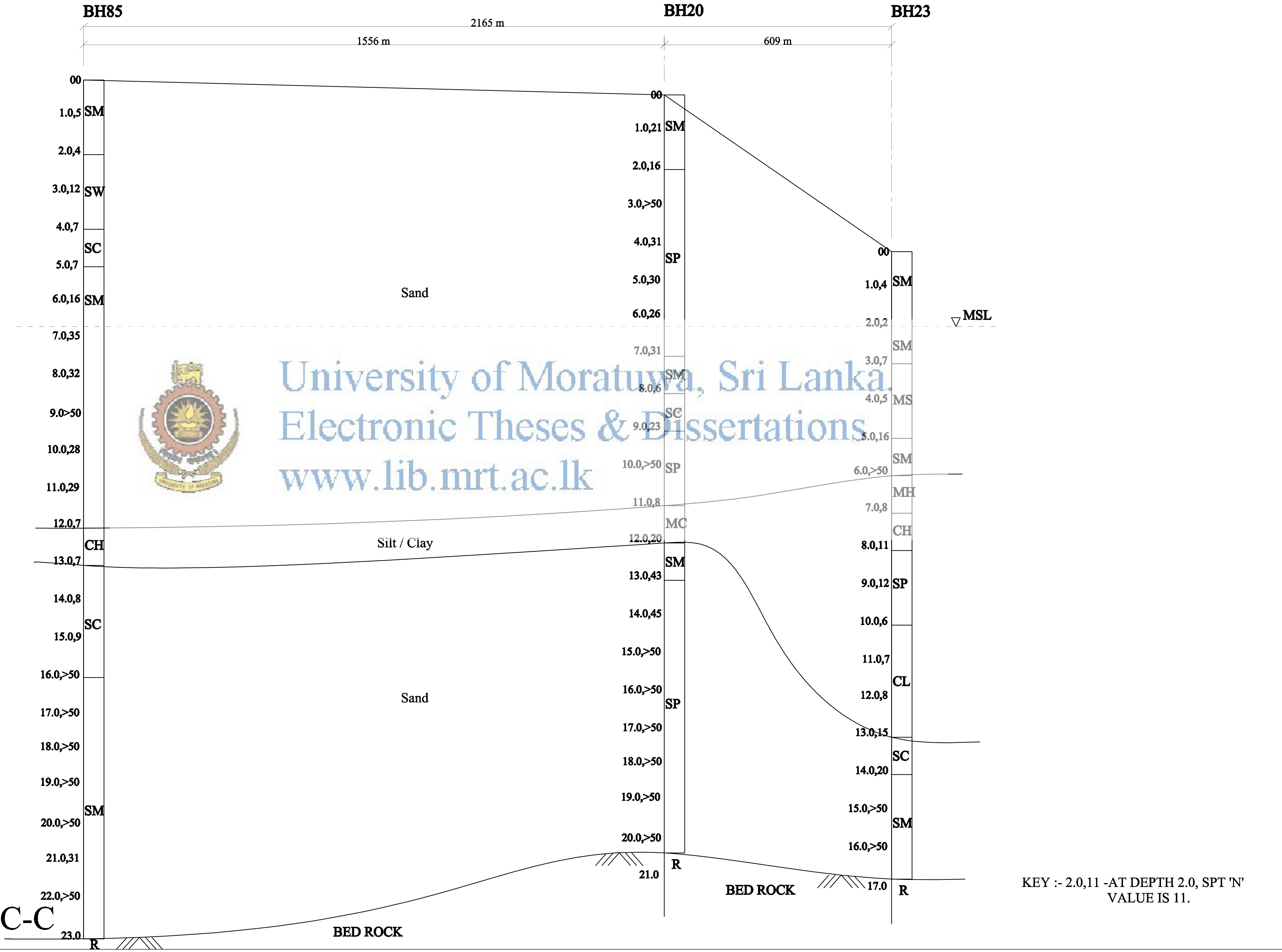



Figure A 4.3: Section C-C

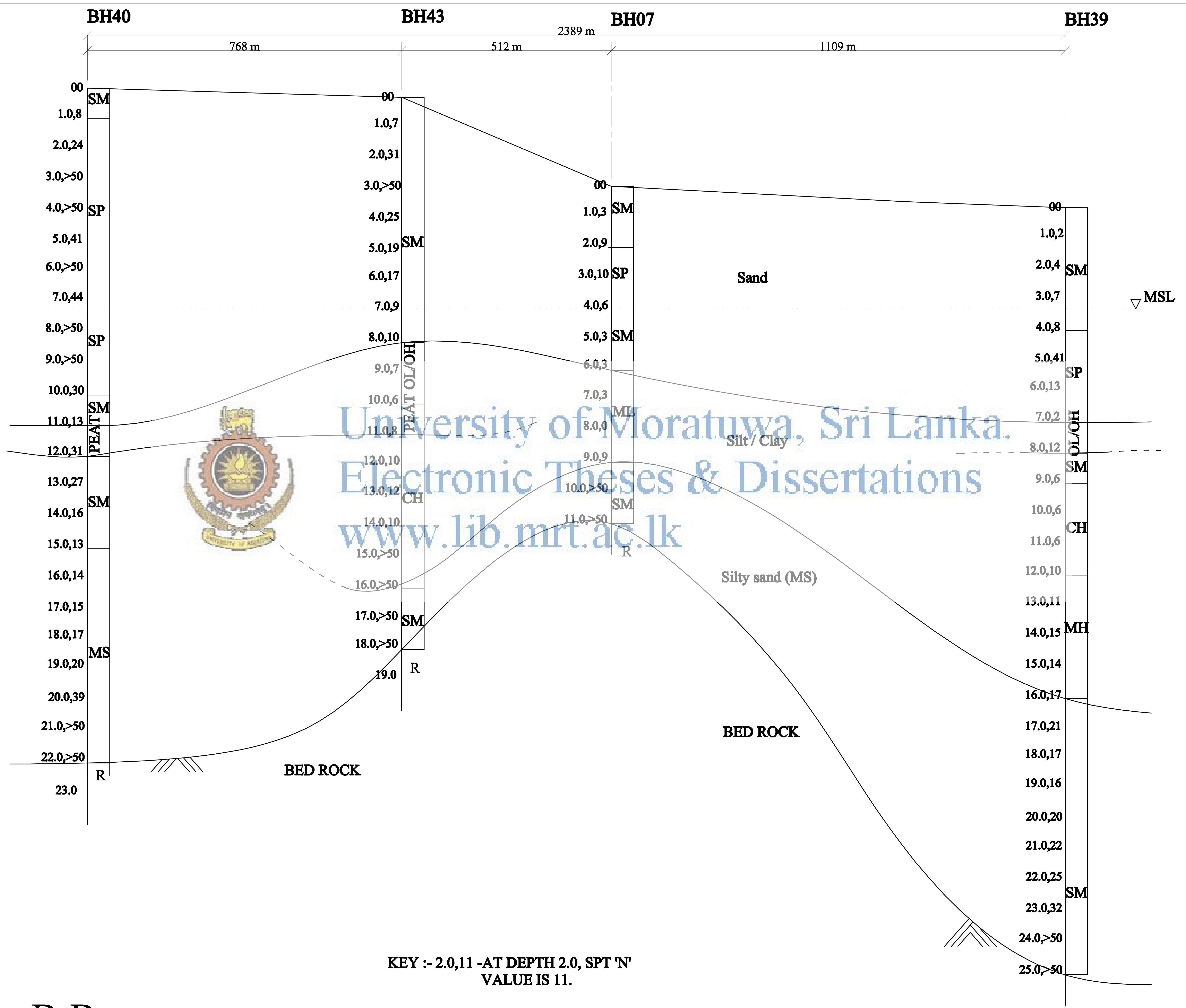





Figure A 4.4: Section D-D

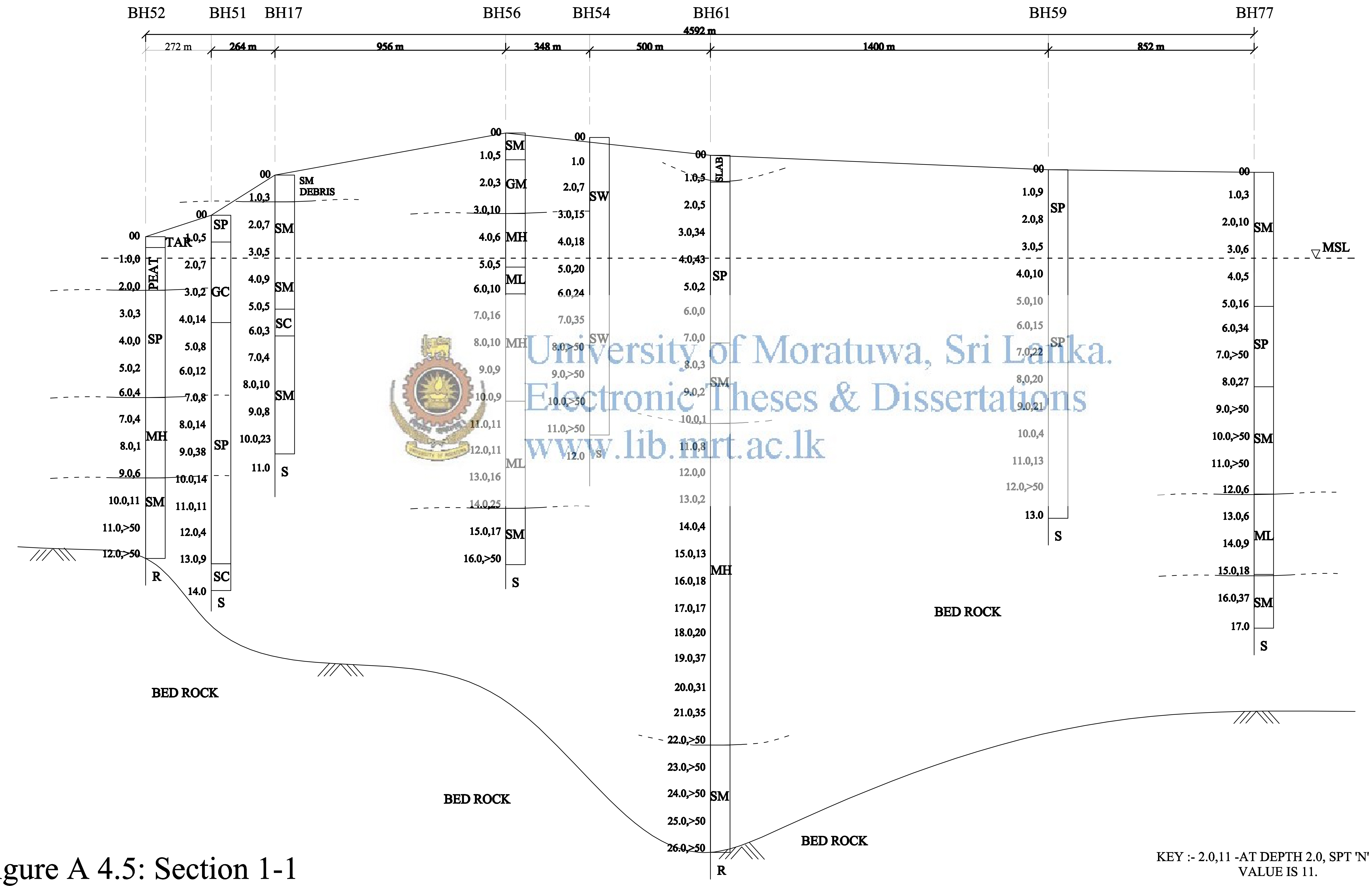




Figure A 4.5: Section 1-1

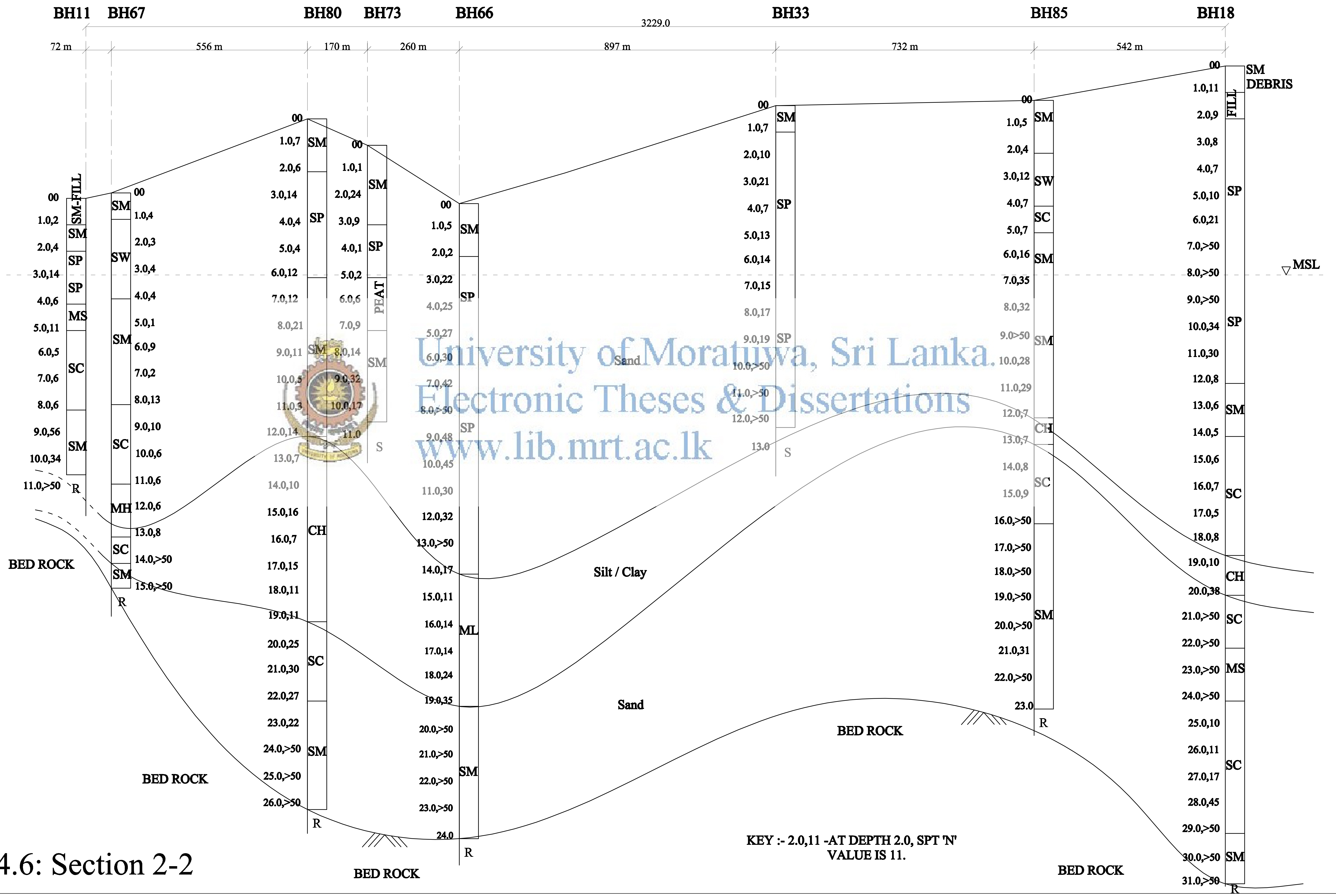



Figure A 4.6: Section 2-2

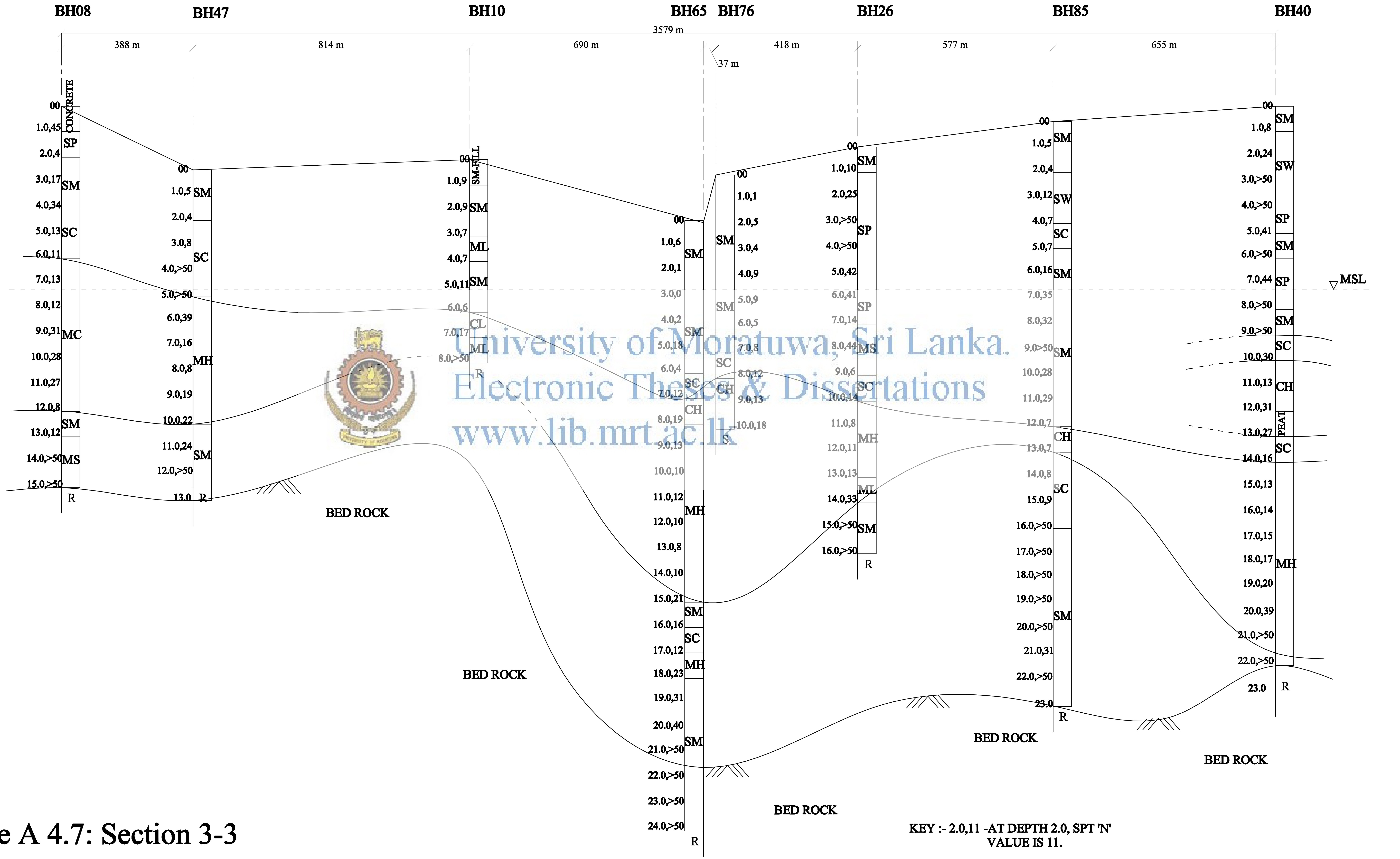



Figure A 4.7: Section 3-3

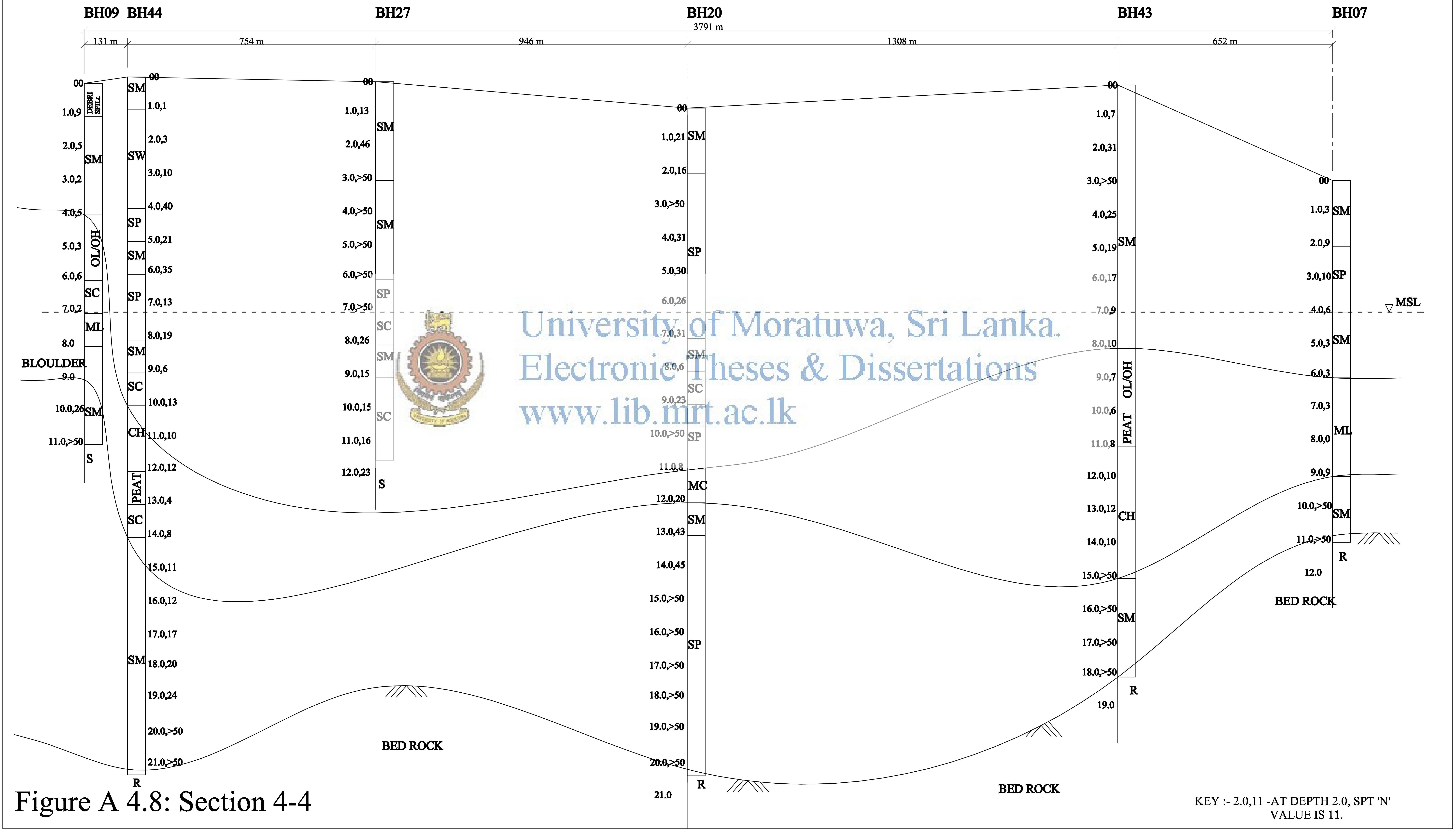



Figure A 4.8: Section 4-4

# Annexure 5: Input earthquake motion

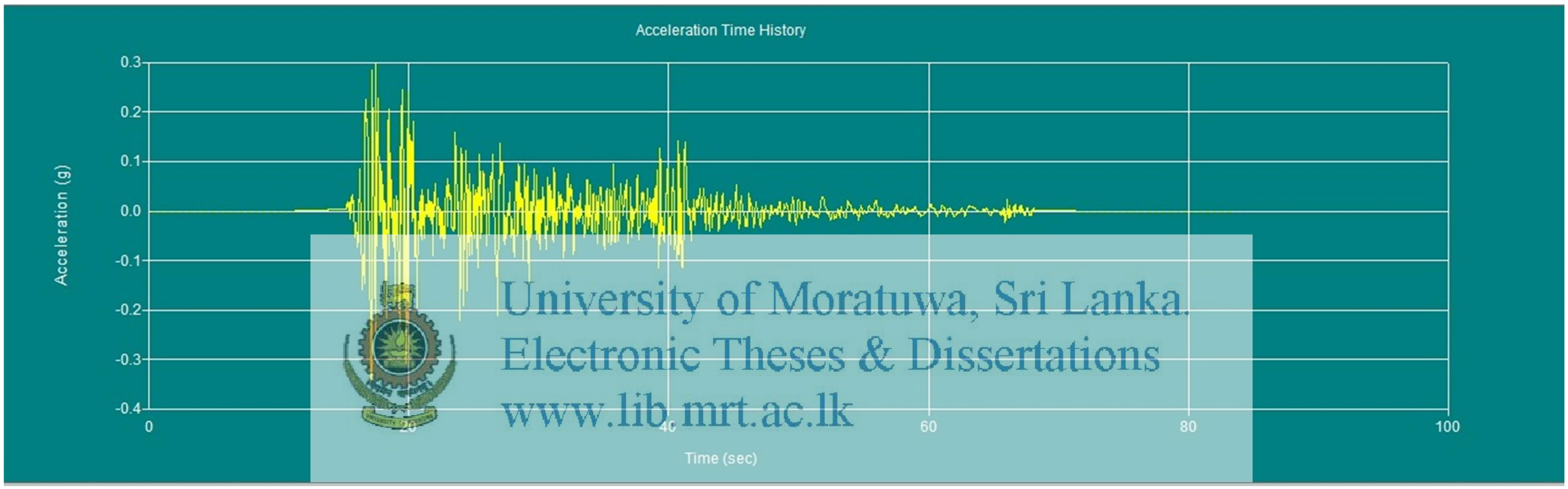




Figure. A4.1 Time history of El Centro Earthquake (1940/05/18) station = El Centro - Imp Vall Irr Dist component= 180

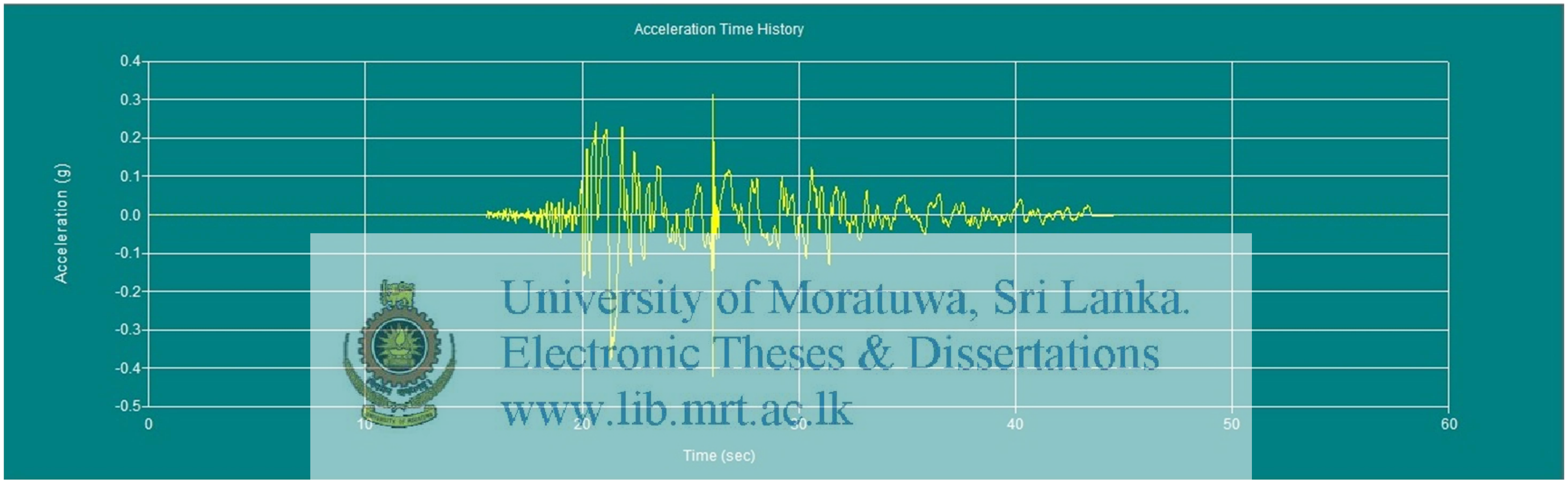




Figure . A4.2 Time history of Petrolia/Cape Mendocino Earthquake (1992/04/25) Station = 1023 Component= 270

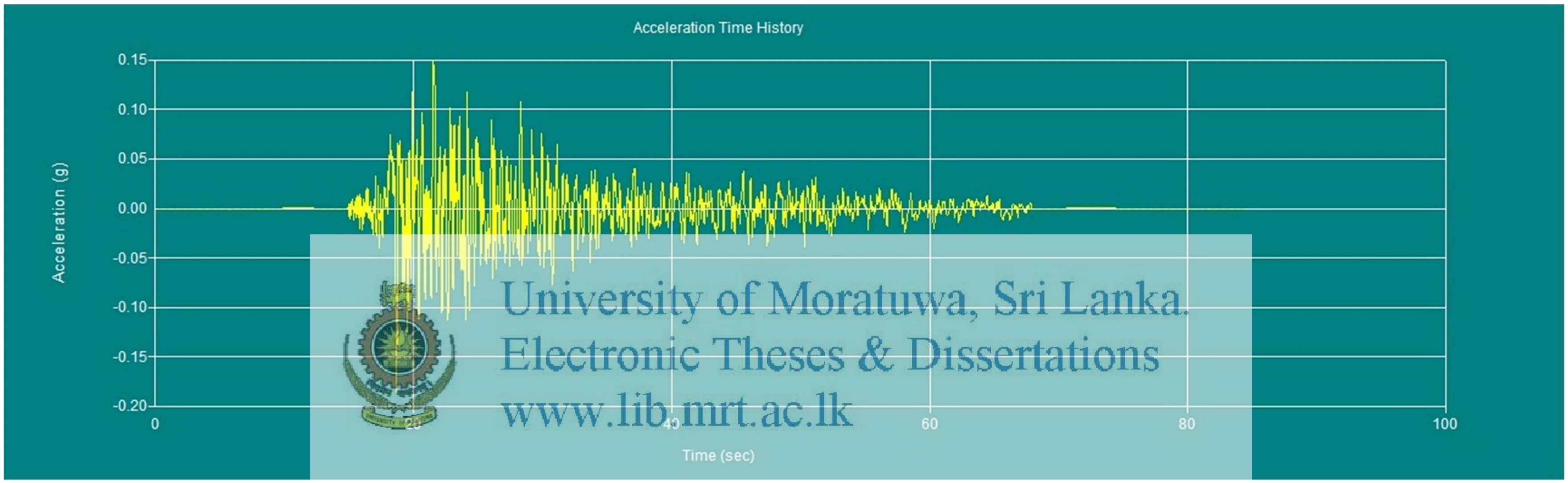





Figure .A4.3 Time history of TAFT Kern County Earthquake (1952/07/21) station = Taft component = 111

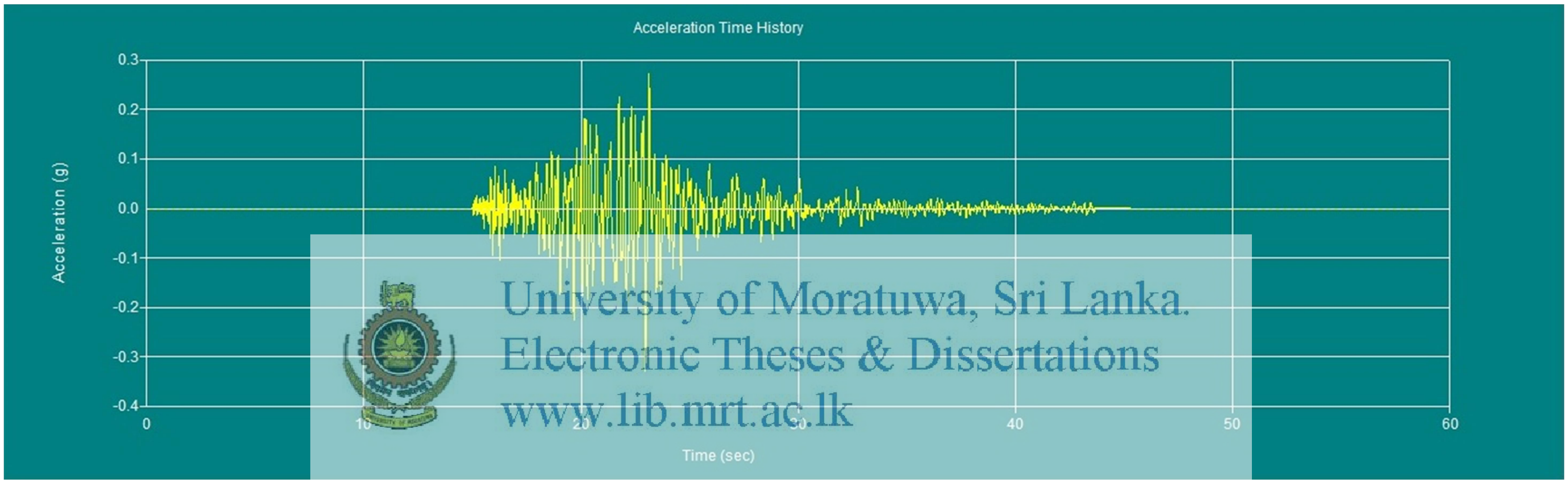




Figure . A4.4 Time history of Northridge Earthquake (1994/01/17) station = Topanga

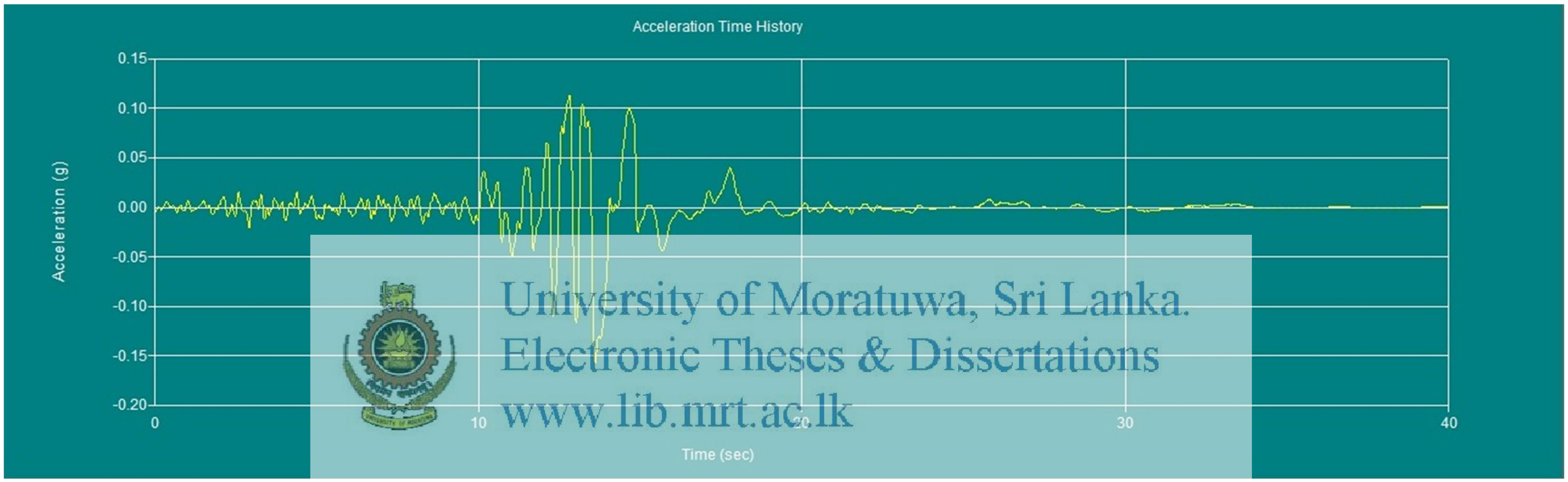




Figure .A.5 Time history of Treasure Island - Santa Cruz Mtns (Loma Prieta) Earthquake

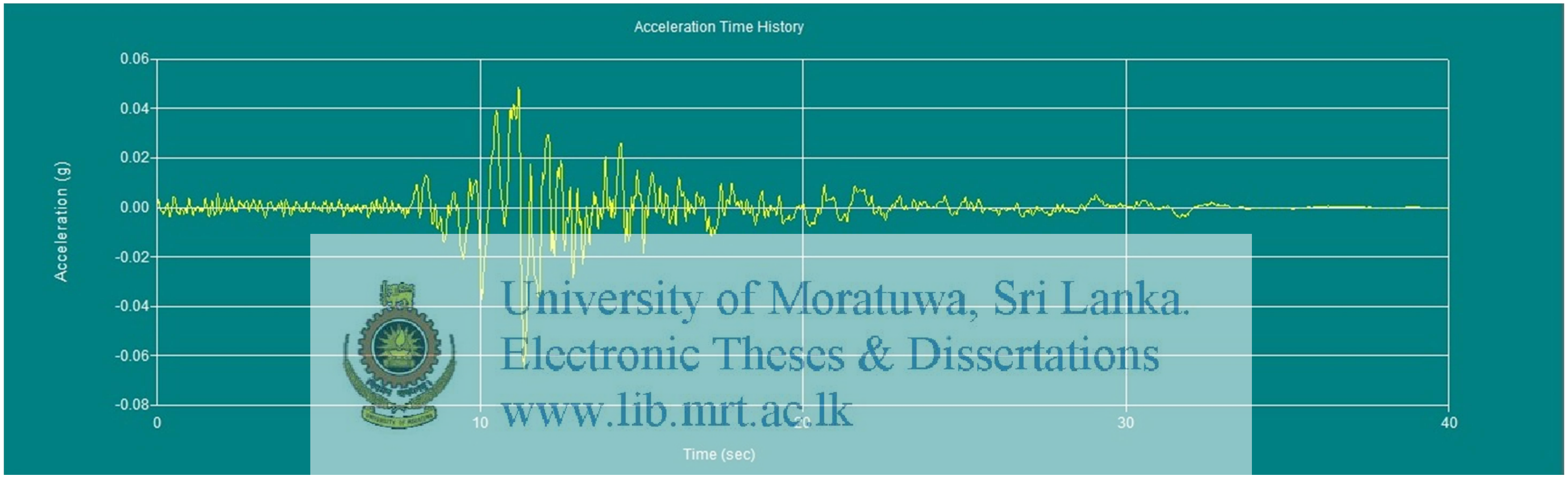





Figure A.4.6 Time history of Yerba Buena Island - Santa Cruz Mtns (Loma Prieta) Earthquake