2.1 INTRODUCTION

A site response analysis which is sometimes referred to as a ground response analysis or soil amplification analysis involves the determination of components of ground motion for design or seismic evaluation. Typically, as in this study, that determination is made for a “free-field” response at the ground surface of an assumed ideal soil deposit (with horizontal layers which extends to infinity) to a spatially-uniform motion applied at the base. The seismic motions at these defined three points, as well as at any other point in the vertical profile, are unique. Design earthquakes are frequently specified as corresponding to a motion of a rock outcrop. Mathematical expressions (transfer functions) are then used to find the equivalent motion for the base rock (bedrock), after that the seismic waves are propagated through the soil column for determination of the free-field motion.

Site-specific evaluation of earthquake ground motions includes a number of contributors such as soil stratiography, basin effects, regional geology, topographic relief, and soil-foundation-structure interaction (SFSI). The study of basin effects, regional geology and topographic relief impacts on ground motions are primarily in the domain of engineering seismology and remains primarily in the realm of research. This study focuses on the evaluation of local soil deposit related site effects most importantly soil deposit with horizontal soil layers.

Site response is primarily influenced by properties that influence wave propagation, particularly stiff and damping. Ground failure is influenced by the shear
strength of soil. Site response has been studied in a large number of earthquakes since late 1950’s. The soil is the most nonlinear material dealt by engineers, and its behaviour during strong shaking is very complex. Seismologists have traditionally treated soil as linear material and rarely considered soil nonlinearity in the assessment of site conditions (Finn, W.D.L., 1991). Soil nonlinearity is prevalent even at low strain values (strains less than $10^{-2}$). The pioneering work of Seed, H.B., and Idriss, I.M. (1969) brought attention to the nonlinear behaviour of soils during seismic shaking. Observations during 1964 Alaska, Niigata earthquakes, and the 1967 Caracas Earthquake formed the basis of the work. Since then, site response has become an integral part of geotechnical earthquake engineering.

2.2 SITE RESPONSE EVALUATION APPROACHES

Three general approaches can be used to evaluate soil effects on ground motions:

(1) The attenuation relationship approach

(2) The code-factor approach, and

(3) The site-response analysis approach.

The attenuation relationship approach uses attenuation relationships or Ground Motion Prediction Equations (GMPE) that consider local site effects, including soil conditions. While older attenuation equations distinguish only between soil and rock, recently published Next Generation Attenuation (NGA) relationships (Abrahamson et al. 2008) can provide ground motion prediction as a function of shear wave velocity ($V_s$). In this approach, a response spectrum is developed and can be used directly in spectral analysis.
The code-factor approach for assessing soil effects on ground motions computes a rock outcrop (surface rock) response spectrum using a rock attenuation equation and then modifies the rock spectrum by generic soil amplification factors such as $F_{PGA}$ (used in AASHTO, 2010a) or Rodriguez-Marek et al. (2001) or Stewart et al. (2003). Similar to the attenuation relationship approach, a response spectrum is developed and can be used directly in spectral analysis (Matasovic and Hashash, 2012).

The third approach, i.e., the site response analysis approach calls for evaluation of local site effects by conducting a detailed site response analysis using various numerical codes available. The site response analysis approach is widely used and is favoured by Geotechnical Earthquake Engineers as it takes into account the unique geotechnical characteristic (i.e., “seismic signature”) of a site.

2.3 SITE RESPONSE ANALYSIS METHODS

Site response analysis methods can be classified by the domain in which calculations are performed (frequency domain or time domain), the sophistication of the constitutive model employed (linear, equivalent linear and nonlinear), whether effects of pore water pressure generation are neglected or not (total-stress or effective-stress analyses, respectively), and the dimensionality of the space in which analysis is performed (1-D, quasi 2-D, 2-D and 3-D). Other considerations in classifying site response analysis methods include modelling of cyclic reduction and degradation in a total-stress mode.

The various techniques used widely to quantify site response includes the following-
(1) Experimental methods

a. Standard Spectral Ratio (SSR)

b. Microtremor Measurements
   i. Horizontal to Vertical Noise Ratio (Nogoshi-Nakamura Technique)
   ii. Horizontal to Vertical Noise Ratio of weak motion

c. Earthquake Records
   i. Horizontal to Vertical Spectral Ratio (HVSR) Technique
   ii. Sediment to Bedrock Spectral Ratio (SBSR) Technique

(2) Numerical Methods

a. One Dimensional (1-D) Site Response Analysis
   i. 1-D Linear Site Response Analysis
   ii. 1-D Equivalent Linear Site Response Analysis
   iii. 1-D Nonlinear Site-Response Analysis

b. Two-Dimensional (2-D) Site Response Analysis

c. Three-Dimensional (3-D) Site Response Analysis

(3) Empirical and Semi-empirical methods

Of the above techniques the SSR, HVSR and 1-D Equivalent Linear Site Response Analysis are adopted in this study for amplification studies.

2.3.1 Standard Spectral Ratio (SSR)

One of the most popular and widely used technique to characterize site amplification is standard spectral ratio (SSR) technique (Mittal et al., 2013). The SSR is a technique where the site response is defined as the ratio of the Fourier amplitude
spectra of a soil-site record to that of a nearby rock-site record from the same earthquake and component of motion (Borcherdt, 1970). In this method it is assumed that earthquake records obtained from the reference site (an earthquake recording station located on a hard rock outcrop) are free from site effects and contains the same source properties and when the two sites are closely located, the path or propagation effects are also same for the pair of records. Hence, the ratio of the Fourier amplitude spectra of the sedimentary site to reference site expresses the local site effects or in other term amplification at the sedimentary site.

A usual option for the selection of the reference station is a site of outcropping rock, while less frequently, a bedrock site having a downhole accelerometer installed in a borehole is used for this purpose. The basic conditions for the application of this particular technique in the case of a surface reference station are:

a) the existence of simultaneous recordings at a soil site and at the reference site,

b) the reference site has to be free of any site effects (sediment and topography),

c) the distance between the soil and the reference site ought to be small (i.e. smaller than the epicentral distance) to consider that the effect of the propagating path of the seismic energy is the same for the two sites.

Since the pioneering work of Borcherdt (1970) the site response analysis method capable of estimating site amplification, the SSR technique has been used in many studies under a wide variety of geological environments (e.g., Borcherdt and Gibbs, 1976; Tucker and King, 1984; Jarpe et al., 1988; Lermo et al., 1988; Singh et al., 1988a; Borcherdt et al., 1989; Chavez-Garcia et al., 1990; Lermo and Chavez,
Detailed comparison between SSR and other reference station techniques (Field et al., 1992; Stiedl, 1993; Field and Jacob, 1995) and other studies (Lachet et al., 1996; Ergin et al., 2004; Pilz et al., 2009) have led to few basic qualitative conclusions such as:

a) the estimation of site effects with the use of SSR technique is relatively stable even if records are quite noisy,

b) the process should be based on a significant number of earthquake recordings (the use of limited number of records should be avoided),

c) the amplification level determined with SSR technique is quite similar with that determined from other techniques,

d) there is general agreement between the methods regarding the frequency band of amplification.

Difficulties in the application of SSR are discussed by Safak (1991) and Steidl et al., (1996). Safak (1991) pointed out to problems in the application of the spectral ratio method to real records because the spectral ratios could be significantly influenced by their processing procedure. This pre-processing allows for a more stable calculation of the frequency spectrum and is typical in all seismic data processing (Yilmaz, 2001) Applicability of SSR becomes a constraint when proper rock site or an adequate reference site motions are not available for the same earthquake. The critical assumption in the SSR technique is that the surface rock site record (reference) is equivalent to the input motion at the base of the soil layers (Steidl et al., 1996). Steidl
et al. (1996) had reported that surface rock sites (locations, where earthquake recorded are considered as reference site motion, and where a flat response behavior is assumed, i.e., close to unity or no amplification) can have a site response of their own. Hence careful selection of reference site motion was necessary.

Table 2.1 gives a general view of the various types of data recordings used in SSR study by various authors.

Table 2.1: Types of Applied Data used by Various Authors Applying SSR Method and their Comparison to other Methods (modified from Lang, 2004)

<table>
<thead>
<tr>
<th>Sl.</th>
<th>Author, reference</th>
<th>Data</th>
<th>Comparison to other method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lermo et al., 1988</td>
<td>A</td>
<td>Frequency Amplitude Spectrum</td>
</tr>
<tr>
<td>2</td>
<td>Borcherdt et al., 1989</td>
<td>V, A</td>
<td>Transfer function of P, SV and SH</td>
</tr>
<tr>
<td>3</td>
<td>Chavez-Garcia et al., 1990</td>
<td>V **</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Rovelli et al., 1991</td>
<td>V</td>
<td>SSR of Noise Readings (SSRNR),</td>
</tr>
<tr>
<td>5</td>
<td>Field et al., 1992</td>
<td>V</td>
<td>1-D transfer function</td>
</tr>
<tr>
<td>6</td>
<td>Gutierrez &amp; Singh, 1992</td>
<td>A</td>
<td>FAS</td>
</tr>
<tr>
<td>7</td>
<td>Yamanaka et al., 1993</td>
<td>V</td>
<td>SSRNR</td>
</tr>
<tr>
<td>8</td>
<td>Lermo &amp; Chavez Garcia, 1993; 1994</td>
<td>A, V</td>
<td>HVSR, HVNR</td>
</tr>
<tr>
<td>9</td>
<td>Duval et al., 1994</td>
<td>**</td>
<td>HVNR</td>
</tr>
<tr>
<td>10</td>
<td>Field et al., 1995</td>
<td>A</td>
<td>HVNR</td>
</tr>
<tr>
<td>11</td>
<td>Theodulis &amp; Bard, 1995</td>
<td>A</td>
<td>HVSR</td>
</tr>
<tr>
<td>12</td>
<td>Steidl et al., 1996</td>
<td>A</td>
<td>FAS</td>
</tr>
<tr>
<td>13</td>
<td>Beresnev and Wen, 1996</td>
<td>A **</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Riepl et al., 1998</td>
<td>A</td>
<td>General Inversion Technique (GIT)</td>
</tr>
<tr>
<td>15</td>
<td>Chavez-Garcia &amp; Cuenca, 1998</td>
<td>A, V</td>
<td>HVSR, HVNR</td>
</tr>
<tr>
<td>16</td>
<td>Raptakis et al., 1998</td>
<td>A</td>
<td>HVSR</td>
</tr>
<tr>
<td>17</td>
<td>Zaslavsky et al., 1998</td>
<td>V</td>
<td>HVSR, HVNR</td>
</tr>
<tr>
<td>18</td>
<td>Rodriguez &amp; Midorikawa, 2000</td>
<td>A</td>
<td>HVNR</td>
</tr>
<tr>
<td>19</td>
<td>Cruz et al., 2000</td>
<td>A</td>
<td>HVNR</td>
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<tr>
<td>20</td>
<td>Sakajiri, 2000</td>
<td>V</td>
<td>FAS</td>
</tr>
<tr>
<td>21</td>
<td>Taber, 2000</td>
<td>V</td>
<td>HVSR, HVNR</td>
</tr>
<tr>
<td>22</td>
<td>Satoh et al., 2001b</td>
<td>V</td>
<td>HVSR, HVNR</td>
</tr>
<tr>
<td>23</td>
<td>Özel et al., 2002</td>
<td>A, V</td>
<td>HVSR</td>
</tr>
<tr>
<td>24</td>
<td>Nath et al., 2003</td>
<td>A</td>
<td>HVSR, GIT</td>
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<tr>
<td>25</td>
<td>Molnar et al., 2004</td>
<td>A</td>
<td>HVSR, FAS</td>
</tr>
<tr>
<td>26</td>
<td>Ergin et al., 2004</td>
<td>A</td>
<td>HVSR</td>
</tr>
<tr>
<td>27</td>
<td>Pilz et al., 2009</td>
<td>A</td>
<td>HVSR, HVNR</td>
</tr>
<tr>
<td>28</td>
<td>Mittal et al. 2013</td>
<td>A **</td>
<td></td>
</tr>
</tbody>
</table>

A = Acceleration, V = Velocity, ** = data not available
The SSR method has been applied to earthquake data by scientific groups with varying success. Lang (2004) pointed out that the different quality of investigation results (stability and plausibility of spectral curves) may depend on the following factors:

- the type of recording instruments.
- the recorded data type (acceleration, velocity, displacement)
- the types of applied earthquake records (source distance, magnitude range),
- the local site conditions at the recording stations.

2.3.1.1 Case studies (SSR)

Notwithstanding the various difficulties, the SSR technique remains an accurate method (Beresnev and Wen, 1996) to determine site amplification characteristics. A brief review of a few studies related to SSR technique is included here.

Jarpe et al. (1988) determined the response of an unsaturated soil in Coalinga, California, which indicated that the response was linear within the limits of random error, for frequencies below 10 Hz and accelerations up to 0.7 g. The response of the soil site relative to a bedrock site was determined by dividing the Fourier amplitude spectrum of the soil site ground motion for a given event by the amplitude spectrum of the bedrock site ground motion for the same event.

Borcherdt et al. (1989) performed the reference station technique for determining the effect of site conditions on ground motions in Leninakan, Armenia S.S.R. Fourier spectra for each corresponding pair of recordings were computed for the time interval corresponding to the record of shortest length. It was also mentioned...
that the most stable estimate of the site response is generally provided by spectra computed from the entire seismogram as opposed to some portion. Prior to computing the ratios the Fourier spectra were corrected for leakage using 10 percent cosine taper on each end of the time series. The Fourier spectra were also smoother with a triangular Hanning window of half-width 0.1 Hz prior to the computation of the ratios.

Lermo and Chavez (1993) performed a comparison between the SSR and Horizontal the Vertical Spectral Ratio (HVSR) and found good agreement between results obtained from both the techniques if the geology of the sites investigated are simple. It is also reported that Lermo (1992) had applied earthquake velocity records for both SSR and HVSR and obtained very good agreement with results.

Wen et al., (1994) applied the SSR technique to strong ground motion records and concluded that nonlinear soil response characteristics are experimentally detectable from available records.

Lachet et al. (1996) carried out a detailed comparative study of three site response analysis techniques (SSR, HVSR, and Receiver function technique) in terms of predominant frequency and amplification levels. The study was carried out for the city of Thessaloniki, Greece. A total of 40 local earthquakes were used for the analysis. It was found that there was a satisfactory agreement between the three techniques regarding the amplified frequency band. On the other hand in was found that regarding amplification levels the other two methods gave underestimated amplification levels.
It is an inherent assumption in SSR analysis that the surface-rock-site record is equivalent to the input motion at the base of the soil layers. Steidl et al. (1996) in their study stated that surface-rock-sites could have a site amplification of their own, which could lead to underestimation of the seismic hazard when these sites are used as reference sites.

Beresnev and Wen (1996) carried out a study on the accuracy of the SSR method analyzing data obtained from the SMART1 array in Taiwan. They compared the soil to rock spectra ratios to the surface and downhole spectral ratios. They concluded that the soil-to-rock spectral ratios could be considered as the reliable estimates of the real site response.

Riepl et al., (1998) carried out a comparison study of SSR method with General Inversion Technique, HVSR, and Coda Technique. They studied 13 records from the EURO-SEISTEST area near Thessaloniki (Greece) (by a dense array of 31 stations, with a minimum inter-station distance of 250 meters) for the amplification effects of a sedimentary valley.

Taber (2000) compared SSR method with HVSR method by using macroseismic and micro-earthquakes data from short-period and broadband seismograph in the Hutt Valley, Wellington, New Zealand for an alluvial valley with sediment depth up to 300 m. It was reported that the HVSR method underestimated the amplitude of amplification. However, both the methods agreed with the predominant frequencies of the sediment valley.

Nath et al.(2003) carried out a site response study of Delhi region using the SSR, HVSR, GIT for nine local and nine regional earthquakes. The SSR method
shows good resemblance with GIT method. They reported that the fluvial deposits of the newer alluvium of the east Yamuna sector show steeper site amplification gradient at lower frequencies, while the greater Delhi experiences moderate site amplification.

Rodriguez and Midorikawa (2003) applied site response techniques employing accelerograms of fifteen earthquakes as well as micro tremor of 150 sites. They found that the reference site method provides more accurate soil response estimations.

Avcilar is the suburb of Istanbul that was most heavily damaged during the August 17, 1999, Mw 7.4 Izmit Earthquake and has different local site response as compared to other location in Istanbul. Ergin et al. (2004) conducted an SSR and HVSR study of earthquakes and microtremors of the area and found that the results of both the method agreed for the frequency band.

Molnar et al. (2004) compared results obtained from SSR and HVSR method for the 28th Feb, 201, Mw 6.8 earthquake at Cascadia subduction zone. They reported that both the method provided similar period and amplitude.

Pilz et al., (2009) conducted a comparison of site response techniques (SSR and HVSR) of the earthquake as well as microtremor data of urban area Santiago de Chile. They agreed that both methods provided reasonable agreement of fundamental frequency.

Mittal et al. (2013) carried out a detailed study of Delhi region in an attempt to characterize the site and study the seismic hazard analysis considering local site effects and to develop contour maps for Delhi. SSR method was adopted to estimate the site effect.
2.3.2 Horizontal to Vertical Spectral Ratio (HVSR)

Damages caused by earthquakes are a direct result of local geological conditions affecting the ground motion. The best approach for understanding the effect of ground conditions is through direct observation of seismic ground motion, but such studies are restricted to areas with a relatively high rate of seismicity (Nakamura, 2000). Because of restrictions in other methods, such as high rates of seismicity, availability of proper reference site (as in SSR method), non-reference site methods, have been applied to site response studies. One such non-reference site technique is Horizontal to Vertical Spectral Ratio (HVSR) technique proposed by Nakamura (1989). This technique has received much attention in connection with soft-soil site effects, investigated using microtremor measurements.

Nakamura (1989) proposed to use HVSR to interpret records of microtremors. He reported that HVSR not only allowed to identify the dominant period of soft-soil sediments but also to estimate amplification level. Since then, HVSR has been extensively used at various sites (e.g., Lermo and Chavez-Garcia, 1993; Duval, 1994; Field, 1994; Field et al., 1995; Chavez-Garcia and Cuenca, 1995; Lachet et al., 1996; Seekins et al., 1996; Riepl et al. 1998). In addition to experimental studies, some authors have investigated the hypothesis of HVSR method using simple (Lermo and Chavez-Garcia, 1994) or elaborate numerical models (Field and Jacob, 1993; Lachet and Bard, 1994). These theoretical efforts have concentrated on HVSR applied to microtremor records in the context of soft-soil amplification problem. A wonderful review of this application of HVSR was presented by Kudo (1995) and Claudet et al. (2006). Kudo (1995) concluded that HVSR allows identifying the dominant period of the soil column of a site under observation. Kudo (1995) strongly disagrees with the
interpretation of HVSR proposed by Nakamura (1989) and suggested that amplitude of HVSR shows a poor correlation with other more standards methods. Following Kudo (1995), Mucciarelli & Gallipolli (2001) provides a critical review of the HVSR method and where they discuss various issues related to the method. Mucciarelli & Gallipolli (2001) however agreed that the method is well capable of determining the fundamental soil frequency.

The applicability of HVSR method to obtain site effects using weak and strong motion earthquake records in the frequency domain was investigated initially by Lermo and Chavez-Garcia (1993). The authors were of the conclusion that very good results were obtained regarding the resonance characteristics of soft soil sites having simple geology using HVSR with the intense S-wave part of earthquake records. Following Lermo and Chavez-Garcia (1993) many authors (e.g.; Theodulidis and Bard, 1995; Theodulidis et al., 1996; Lachet et al., 1996; Bonilla et al., 1997; Yamazaki et al., 1997; Raptakis et al., 1998; Taber, 2000; Mucciarelli et al., 2003; Pilz et al., 2009; Arash and Sahram, 2011; Upadhayay and Mori, 2013; Wen et al., 2014) have used this technique to study amplification behavior and determine the fundamental frequency of sites for weak and strong ground motions of single station. Site response estimations analyzed by the HVSR method and other methods were compared and evaluated by Field and Jacob(1995), Bonilla et al. (1997), Riepl et al. (1998) and Huang and Teng (1999).

The HVSR technique also has its share of criticism because it does not have any sound theoretical background. Nakamura (2000, 2008) tried to address the confusion behind the theoretical background of the HVSR method. In these publications, the author tried to explain the theoretical aspects of the HVSR method.
and defends the explanation of the method as given in Nakamura (1989). The HVSR method from its origin was overviewed, and its practical applications in the various aspects of disaster prevention were evaluated.

The HVSR method has also been utilized in site classification (Lee et al., 2001; Zhao et al., 2006; Ghasemi et al., 2009; Wen et al., 2010; Wen et al., 2014), liquefaction vulnerability (Salazar et al., 2013). This method also has been proposed as an alternative tool to classical geophysical exploration for characterizing sediment thickness, if shear wave velocity profile in the sediment does not change significantly over large areas (Ibs-Vohn Seht and Wolhenderg, 1999; Parolai et al., 2002).

Despite the lack of clear theoretical background and various unaddressed issues as has been identified by Mucciarelli & Gallipolli (2001), HVSR remains a adopted method for initial estimation of various dynamic characteristics of soil and also of buildings because of its relatively simple and low cost of application.

2.3.2.1 Case studies (HVSR)

Brief reviews of some HVSR studies are discussed below.

Lermo and Chavez-Garcia (1993) discussed certain important limitations of the reference site method i.e. SSR method as pointed out by Safak (1991). As an alternative, they pointed out that spectral ratios between horizontal and vertical components of motion without a reference station i.e. the HVSR method, originally proposed by Nakamura(1989) to analyze Rayleigh waves in the microtremor records is applicable to study the intense S-wave part in the earthquake records. They concluded that the cases considered for study by them showed good agreement
between results from HVSR method and those from SSR method. However, they cited that further study was required to evaluate the limitations of the method.

Field and Jacob (1993) examined an estimate of site response proposed by HVSR. They found that Nakamura's estimate applied to both observed, and predicted noise spectra were successful in identifying the fundamental frequency, with a slight (<10%) shift toward lower frequencies. They also added that future work was required determine the generality of their results.

Lermo and Chavez-Garcia (1994) had reviewed the applicability of microtremor measurements in evaluating the site response of soft soils. They evaluated three different techniques used in estimating site effects from microtremor measurements: interpretation of Fourier amplitude spectra, comparing the spectral ratios relative to a reference station, and, finally, computation of spectral ratios of horizontal components relative to the vertical component of ground motion (Nakamura's technique). These techniques were applied to microtremor records obtained in three cities in Mexico: Mexico City, Oaxaca, and Acapulco. These cities differ in their local geological conditions and their seismo-tectonic environment. To evaluate the results obtained from microtremor measurements, they compared them with standard spectral ratios of the intense, S-wave part of weak or strong motion records obtained at the same sites. Their results showed that microtremor measurements could be used to estimate the dominant period of a site with very acceptable reliability in the range 0.3 to 5 Hz. The best results were obtained with Nakamura's technique, which also gives a rough estimate of amplification of seismic waves when the local geology is relatively simple. Simple numerical simulations indicated that the underlying assumptions of Nakamura's technique are consistent
with the propagation of Rayleigh waves. These simple numerical simulations also explained why different researchers have been able to successfully characterize 1D site effects using microtremor records, regardless of whether they consider microtremors to consist of surface or body waves. Their results strongly suggested that the technique by Nakamura effectively compensates for source effects in microtremor measurements, which eliminates a major limitation to their application in earthquake engineering.

Field and Jacob (1995) using the data from 18 aftershock events of Loma Prieta Earthquake recorded at 4 sediment sites and 1 bedrock site. The paper compares 2 reference site dependent methods: standard spectral ratios (SSR) method, generalized inversion method (GIT), parameterized source and path effects inversion method and 2 non-reference-site dependent techniques: receiver function technique and Nakamura’s technique. The study pays particular attention to the uncertainties involved in each method. It was found that site amplification estimates are very similar between SSR and GIT approaches. The uncertainty estimates can be significantly different depending on the data weighting procedure. If all data were weighted equally, the uncertainties obtained from GIT could be up to a factor of 0.7 less than those of SSR. All of the three non-reference-site-dependent techniques are found to reveal useful information regarding the site response estimate. The parameterized inversion and receiver function techniques were found to be successful in identifying the frequency dependence of site response, and the Nakamura’s technique was found to be successful in identifying the fundamental resonant frequency. However, it was observed that there are discrepancies exists among all of the site response estimation methods when the frequency independent amplitude
values are considered. If the SSR estimates are taken as the most reliable then all others under predict the site response (at this stage the results from an earlier work of one-dimensional model predictions were also compared and found to lower by a factor of 2). The authors conclude that the frequency dependence of site response estimated from any of these methods is promising and if corroborated with other studies these estimations will be useful in areas that lack an adequate reference site.

Chavez-Garcia et al. (1996) presented a complementary study to microzonation of Mexico City where the authors studied the site effects at two counties that are located in the north of the city and that have been recently incorporated into the Mexico City conurbation. Measurements of microtremors at 67 points and weak motion recordings from a temporary digital seismograph network were analyzed according to HVSR technique to extend the existing predominant period map of Mexico City. Additionally, a map of maximum relative amplification was proposed. Both maps were found to be consistent with local geology and suggested to be useful for a detailed microzonation study of the region.

Chavez-Garcia & Cuenca (1998) presented a study to improve microzonation of Acapulco, Mexico. Two maps that reflect the fundamental characteristics of the site effects in the area were proposed: dominant period and maximum relative amplification. The microzonation was based on three basic sources of data: strong motion records obtained from 7 permanent stations, weak motion data obtained from a temporary digital seismograph network of 6 stations, and measurements of microtremors at 35 sites. The strong motion data included recordings from 24 events with magnitudes of 3.5 to 6.9. The data was analyzed using both SSR and HVSR techniques. The weak motion data included recordings from 8 events in more than 4
stations, 3 events in more than 3 stations and a large number of events in 1 or 2 stations. They were analyzed using three techniques: SSR, HVSR and the computation of response spectral ratios (RSR). In the third method, the velocity response spectra ratios at 5% damping were computed. Finally, microtremor recordings obtained at 35 sites were analyzed by Nakamura’s technique. The resulting transfer functions obtained from weak and strong motion data using HVSR method are very similar to those obtained using SSR technique. This good agreement was observed both for the dominant period and for the average value of maximum relative amplification. RSR technique applied to weak motion data also revealed similar values of the dominant period. Amplification factors obtained from this method were in general half of those determined from SSR. Comparing the results with those obtained from microtremor data showed that microtremors could provide a good estimation of the dominant period. The maximum relative amplification factors obtained with this method were also good within an uncertainty factor of 2. Relying on the results obtained in this study the authors concluded that microtremors were useful tools to interpolate sparse earthquake data. The resulting microzonation maps of dominant period and maximum relative amplification factor were presented as based on the integration of all data obtained in the study.

Theodulidis et al. (1996) checked the use of the HVSR, with the help of data which consisted of 110, three-component, high sensitivity accelerograms, recorded at five different depths by the Garner Valley Downhole Array (GVDA), in southern California, with peak ground accelerations 0.0002g - 0.04 g, magnitudes 3.0 - 4.6 M_L, and hypocentral distances 16 km - 107 km. They found a good stability of the HVSR by computing the mean for the whole data set in different depths. They reported that
most prominent difference between the HVSR and the SSR was in their absolute levels, with the latter being 2 to about 6 times higher.

Lachet et al. (1996) analyzed 40 local earthquakes which were recorded with a good signal-to-noise ratio with three different techniques: (a) the classical SSR to a reference station, (b) the receiver functions, and (c) the HVSR on noise recordings. The results were compared in terms of predominant frequencies and amplification levels. The three methods were found equally able to reveal the fundamental frequency. Regarding local site amplification, they provided significantly different results with a general trend of the two H/V ratio methods (b and c) to underestimate the amplification levels compared to that inferred from the classical SSR technique. They found a good correlation between the local site amplification and the type and age of the local geological formation as well as with the depth of bedrock.

Seekins et al. (1996) compared that site amplifications of microtremors, derived from both the traditional soil-bedrock station-pair spectral ratio method and Nakamuara’s single station method, to results derived from Loma Prieta aftershock S-waves and codas. They found that the site response (SSR method) derived from microtremors are consistently higher than those derived from S-waves and do not always show amplification of the same frequencies, although the fundamental resonant frequency is generally the same. They found that HVSR method when applied to earthquake waves results in spectral ratios that are similar in shape near the fundamental frequency to those from earthquake S-wave station pairs, but with higher amplitudes. They reported that Nakamura’s method, applied to microtremors recorded at soil sites, adequately predicts the fundamental frequency observed from aftershock S waves at soil-rock station pairs.
Chavez-Garcia et al. (1997) carried out an experimental study of topographic site effects. A total of 68 earthquakes recorded in 10 digital stations were considered for the study. The recordings were analyzed using HVSR method and Generalized Inversion Scheme (GIS) (as presented by Boatwright et al. 1991). They on the basis of the study concluded that HVSR method, as well as the GIS method, can be used to determine topographic site effects.

Yamazaki et al. (1997) studied the strong motion data recorded by JMA-87-accelerometers using the HVSR method. From the analysis of these accelerograms, they reported that horizontal to vertical Fourier spectrum ratios of a site for different earthquakes were stable irrespective of magnitude, distance, and depth.

Raptakis et al. (1998) described a study in which the effectiveness of SSR and HVSR techniques on site response estimation were evaluated. For this purpose, both techniques were applied to an acceleration data set recorded at the Euroseistest array during 1994-1996. The data set consisted of 495-time history records triggered by 36 events (2.7≤M≤6.6 and 12≤R≤160km). It was observed that both techniques show similar spectral ratio shapes with comparable fundamental resonance frequencies, which were also well correlated with the well known geotechnical-geological conditions. A good stability of the HVSR in comparison with that of the SSR was observed. The results from these empirical analyzes were also found to be consistent with theoretical 1D equivalent linear response analyzes (SHAKE) and 1D elastic response analysis performed at the centre of the Euroseistest Valley using the detailed geophysical and geotechnical data collected. It was observed that the amplitudes obtained from HVSR were systematically lower than those of the SSR. This was attributed to the relative enrichment of the vertical component. The authors suggest
that the difference in amplitude between two methods could also be useful as an indication of 2-D or 3-D site effects due to near-surface geology.

Riepl et al. (1998) studied empirically the site amplification effects of a sedimentary valley. One of the main advantages of this site was the very detailed knowledge of the near subsurface structure due to exhaustive geophysical and geotechnical measurements and data analyses, which was carried out by Jongmans et al., 1998. Besides there were 31 stations installed perpendicular and parallel to the valley axis, with 250 m minimum interstation distances. The records of 13 local events were analyzed using SSR, GIS, HVSR technique. It was found from the analysis that HVSR technique failed to estimate the amplification level due to the complex near-subsurface structure of the valley.

Ibs-Vohn Seht and Wolhenderg (1999) successfully applied the HVSR method to determine the thickness of soft cover layers. They found that the frequency of the main peak in these spectral ratios correlated well with the sediment thickness at the site. They derived a simple formula which could calculate the cover thickness from the frequency of the main peak in the H/V spectrum and was applicable to a wide range of thickness, namely, from tens of meters to more than 1000 m. They also reported that SSR is strongly influenced by the noise level and are therefore less reliable in determining the resonant frequency of the subsoil.

Taber (2000) compared the site response by SSR and the HVSR method for micro-seismic / micro-earthquake data obtained from short-period and broadband seismographs. They reported that HVSR and SSR agreed on the frequency band but differed on the amplification level with the SSR method giving higher amplification.
It was also concluded that HVSR would not be effective in determining the ground shaking hazard over a region of varying geology.

Nakamura (2000) comes back with an explanation of the fundamental idea of HVSR method. It is claimed that the peak of H/V ratio, either for micro-tremor or earthquakes cannot be explained with Rayleigh waves since Rayleigh wave energy is very small for the peak frequency but high on the trough of H/V ratio. The author concludes that explanation in Nakamura (1989) is correct for explaining this peak with SH waves.

Mucciarelli & Gallipolli (2001) gave a critical review of the HVSR method since its inception. The authors were skeptical about the soundness of the method since it had no clear theoretical explanation and the available literature provided contradictory statements of the method. For example, some suggested that it gave better results when the impedance contrast is high (Trifunac and Todorovska, 2000) while others invoked it just for low-impedance contrast (Al-Yuncha and Luzòn, 2000). However, the author reports that the method remains popular because of its ease of implementation and simplicity.

Nath, S.K. et al. (2002) studied the site response in the Garhwal Himalaya using digital seismograms recorded by a five-station 24-bit digital micro-earthquake network. 15 aftershocks were chosen to determine the site response using HVSR and GIS. The authors concluded that the site response computed by both the techniques showed good resemblance.

Mucciarelli et al. (2003) analyzed the stability of the amplification function obtained by the HVSR method for a sedimentary site with a simple geomorphological situation for triggered noise as well as earthquake recordings. A total
of 674 triggered noise and 132 earthquakes recordings were considered during the study. The analysis was performed in four phases. First, the stability of the HVSR function was evaluated. Second, verification of the existence of periodicity patterns in the time sequences of the fundamental frequency and its relevant amplification using noise and earthquakes separately was studied. Third, investigation of the correlation among the fundamental frequency and its relevant amplification sequences and maximum amplitude of the recording and magnitude of earthquakes was studied. Finally, the HVSR transfer function was compared with the one obtained with a linear-equivalent 1D model based on a Vs profile derived from noise analysis (NASW) measurements. The authors concluded that HVSR was a remarkably stable site-dependent feature. Furthermore, they also reported that there was a good agreement between the observed HVSR and the 1D model used in the study carried out using Equivalent Earthquake Response Analysis (EERA) as proposed by Bardet et al., 2000.

“Site EffectS assessment using AMbient Excitations”, SESAME (2004) was a European research project which was based on a comprehensive and very detailed research work conducted during a span of three years. The consensus reached during this project by the participants was incorporated in the form of “Guidelines for the Implementation of H/V Spectral Ratio Technique on Ambient Vibrations: Measurements, Processing And Interpretation”, as a practical guideline which recommended procedures for field experiment design, data processing and interpretation of the results for the implementation of the HVSR technique using ambient vibrations. It was highly recommended that prior to planning a measurement campaign on ambient vibrations, a local geological survey, especially on Quaternary
deposits, should be performed, because, interpretation of the HVSR results will be greatly enhanced when combined with geological, geophysical and geotechnical information. Based on the project SESAME the J-SESAME software was developed which organizes the input data, execute window selection and processing, and display the processing results.

Zhao et al. (2006) proposed an empirical classification scheme based on results of HVSR technique on strong ground motion stations in Japan, pointing out the advantages of using HVSR versus shear wave velocity profiles.

Claudet et al. (2006) gave a review of the HVSR technique based on ambient vibrations. They argued that considering experimental H/V ratio (i.e. derived from actual noise measured in the field) exhibit in most cases only one peak, it could be concluded that H/V ratio is (1) mainly controlled by local surface sources, (2) mainly due to the ellipticity of the fundamental Rayleigh waves. Then the amplitude of H/V peak is not able to give a good estimate of site amplification factor.

Ghasemi et al. (2009) applied HVSR form site classification for various sites in Iran. Shear wave velocity was measured recently at 107 strong motion stations. These stations were classified considering Iranian Practice Code criteria (Standard 2800). To check the applicability of the empirical methods, three different empirical techniques were applied to re-classify the stations using previously determined site classes. The first method was based only on the determination of peak periods at each station. It was found that the fundamental periods in different site categories were within the ranges proposed by Japanese Road Association. The second one was upon the site classification index (SI), suggested by Zhao et al.(2006). In this study, a new site index term was proposed for quantitative site classification using the
empirical HVSR method. It was found that the results from this scheme were comparable with those obtained by applying the method of Zhao et al. (2006) and are more reliable than the results from using only peak periods. A large number of strong motion stations were classified in Iran for more control of proposed SI applicability. The mean response spectral ratio curves for all data of ISMN stations were found to be fairly consistent with those obtained by Zhao et al. (2006). The results showed the practicality and efficiency of the proposed method in site classification. However, the authors warned that more shear wave measurements and further information, like surface geology, borehole data, etc., were still needed to clarify the uncertainties of such empirical schemes.

Laouami N., et al. (2006) carried out site effect estimation from microtremors and seismic strong motion using the HVSR and the Receiver Function Technique (RFT). The results of the study showed that the estimated fundamental frequency was the same for both microtremors and seismic motion data, while the amplification factor was different. Indeed, it appeared that the amplification factor increased significantly with the seismic motion intensity. Moreover, for the case of seismic motion data, other peaks appeared on the plotted curves and may be attributed to high mode frequencies.

Panou et al. (2007) studied the ambient noise measurements in the city of Thessaloniki (Northern Greece). It was aimed at examining the limitations of the HVSR technique for cities of similar location and geological setting. Initially, the HVSR of ambient noise were compared with HVSR of earthquake recordings in several locations, in terms of the shape of the curve, the Fundamental Frequency (FF) and the corresponding HVSR amplitude level (Am), in order to evaluate the
efficiency of the ambient noise HVSR in predicting ground motion properties. Finally, as the subsurface structure varied within the city, ambient noise was simulated for a number of different 1-D and 2-D soil profiles. Comparison between the actual and simulated HVSR outlined the reliability of FF in mapping the sediment variation thickness. They reported that results were encouraging for the use of the ambient noise HVSR as an inexpensive, fast and efficient tool in microzonation studies in urban environments, comparable to the city of Thessaloniki.

Nakamura (2008) gave an overview of the HVSR from its origin and on the application for practical disaster prevention. He claimed that that explanation in Nakamura (1989) was correct for the peak obtained with SH waves. He further reported that the H/V spectral ratio showed the amplification characteristics by the multiple reflections of the SH wave at least around the predominant frequency of ground surface \( (F_0) \) and showed the characteristics contaminated by the Rayleigh wave around the frequency of minimum group velocity \( (2F_0, \text{Airy phase}) \).

Pilz et al. (2009) studied the site amplification derived from HVSR analysis of earthquake as well as ambient noise data and SSR analysis of earthquake data. The analysis leads to the conclusion that earthquake data shows a significant dependence on the local geological structure with respect to amplitude and duration. The results showed that HVSR of ambient noise, as well as earthquake strong motion and SSR, showed good agreement in the shape of all three curves, especially for the peak of the fundamental resonance frequency.

Mundepi and Mahajan (2010) analyzed ambient noise using HVSR method for 136 sites of Jammu City, NW Himalayas. The thicknesses of the sedimentary deposits were determined from empirical relationships. Their results showed good
agreement with a 1D-MASW (Multichannel Analysis of Surface Waves) survey conducted for the area. They also commented that in their study it was found that the resonance frequency showed a progressive decrease with the increase of the thickness of the sedimentary deposits.

Arash and Sahram (2011) applied the HVSR method to the shear-wave window for the recorded ground motions to sites in the New Madrid seismic zone (NMSZ) for site effect evaluation. The database consisted of 500 seismograms from 63 events between magnitude Mw 2.5 and 5.2 that were recorded by 11 numbers of the University of Memphis Centre for Earthquake Research and Information (CERI) broadband stations. The calculated HVSR at each station showed considerable event-to-event variability; therefore, the mean H/V ratios for all events were used as an indicator of the site amplification for the sites. Stations located on lowlands deposits amplified the weak motions by factors of 2 to 4 at low-frequencies range, and stations located on uplands deposits showed amplification factors between 1.5 and 3 at low frequencies ((f ≤ 5 Hz). The obtained results were compared. Consistency was observed between the average HVSR and the soil amplifications in the upper Mississippi embayment developed by Romero and Rix (2005) from the 1D (equivalent linear) method for generic regional for low frequencies of f ≤ 2 Hz for both lowlands and highlands. They also studied the variability of the HVSR with distance but reported no discernible trends.

Hussain Et al. (2013) compared the site characteristics of Muscat Region in terms of the fundamental frequency using micro-tremors measurements with the results of numerical analysis using one-dimensional (1-D) shear wave profiles. The micro-tremor measurements were performed at 99 sites, which were distributed over
the study region to calculate the horizontal-to-vertical spectral ratio (HVSR). The numerical modeling of horizontal shear (SH) waves in soil at the selected 99 sites was assessed by carrying out 1-D ground response analysis using the program SHAKE91. The required shear wave velocity profiles for the numerical modelling of SH-waves were derived using MASW profiles. The comparison of the fundamental frequency (from amplification spectrum) obtained using SHAKE91 and HVSR showed compatibility with the general surface geology of the region and in most cases the HVSR proved to be suitable for calculating the fundamental frequency.

Wen et al. (2014) used HVSR for site classification based on the observed strong-motion records. A six-site class scheme is proposed to improve the reliability of the HVSR technique. For the study a total of 3250 records which were recorded at 92 temporary stations for 949 aftershocks between May 13 and October 10, 2008 for the Ms =8.0 (Mw =7.9) Wenchuan earthquake of May 12, 2008.

2.3.3 One Dimensional Equivalent Linear Site Response Analysis (1-DELSRA)

One-dimensional (1D) models for the study of the seismic response of soil deposits have been widely used (Sanchez-Sesma et al., 1988; Singh et al., 1988; Ordaz et al., 1992; Singh and Ordaz, 1993; Ordaz and Faccioli, 1994). Early site-response studies involved one-dimensional linear simulations to calculate the ground motion amplification from the bedrock to the soil surface [Kanai (1952), Idriss and Seed (1967a)]. Subsequent field observations indicating nonlinear soil response led to the development of nonlinear site response analysis methods. Idriss and Seed (1967a) proposed the use of the one-dimensional equivalent–linear approach, which involved the approximation of the nonlinear response by a linear analysis with modified material properties. They performed the computations in the time domain and
assumed bilinear properties for the soil. Subsequent work by Hardin and Drnevich (1972) did provide the necessary insight into the nonlinear behavior of soil, which enabled several researchers to develop more nonlinear soil models. Schnabel et al. (1972) later implemented the equivalent-linear method in the frequency domain and developed the numerical program SHAKE, which is now the most commonly used equivalent-linear computer code (Matasovic and Hashash, 2012). However, since first introduced by Seed and Idriss (1970) and the equivalent –linear approach has remained substantially the same (Matasovic and Hashash, 2012). In this method, the shear modulus (G) and damping (β) are modelled using a linear spring-dashpot system. The spring and the dashpot parameters are determined based on the secant shear modulus and the damping ratio at a given level of shear strain. For earthquake input motions, Seed and Idriss (1969) had suggested that the properties are to be calculated for a strain equal to 2/3rd of the maximum strain level in a given layer. Presently, an expression proposed by Idriss and Sun (1992) (Eq. 2.1) that relates the ratio of effective shear strain to the maximum shear strain ($R_y$) with the magnitude (M) of earthquake is commonly used

$$R_y = \frac{M-1}{10}$$ ..................(2.1)

The SHAKE2000 user’s manual (Schnabel et al., 2012) has recommended a value of 0.65 for $R_y$, which has traditionally been used in practice. However these recommendations has not been validated by published empirical or analytical results and are only based on experience matching numerical response with recorded data (Bolisetti, 2014). Idriss and Sun (1992) have found this value to vary between 0.4 and 0.75, while Yoshida et al., (2002) suggests a much larger range between 0.2 and 1.
Dickenson (1994) suggested that the response obtained using the traditional value of 0.65 for the effective shear strain ratio can be slightly improved by using a value between 0.35 and 0.55 for $M_s = 6$ to 7 events, and between 0.55 and 0.7 for $M_s = 7$ to 8 events, where $M_s$ is the surface-wave magnitude. These studies indicate that an appropriate value of $R_p$, depends largely on the characteristics of the input earthquake and not only on the model.

In this method, the wave propagation through the soil deposit is solved in the frequency domain, and any given soil layer is assumed to have constant modulus and damping throughout shaking. Equivalent –linear site response analysis uses an iterative procedure in which initial estimates of $G$ and $\xi$ is provided for each layer. Using these linear, time-dependent properties, linear elastic analyses are performed and the response of the soil deposit is evaluated. Shear strain histories are obtained from the results, and peak shear strains are evaluated for each layer. Effective shear strains are calculated as a fraction of the peak shear strains. The effective shear strain is then used to evaluate an appropriate $G$ and $\beta$ using shear strain-dependent normalized modulus reduction and damping curves described earlier. The process is repeated until the strain-compatible properties are consistent with the properties used to perform the dynamic response analyses and the analyses converge.

Modifications to the equivalent-linear model have been proposed by researchers [e.g., Assimaki et al. (2000); Yoshida et al. (2002)], which involve frequency-dependent formulations for the effective shear strain ratio, shear modulus, and damping. However, these modified versions are rarely used in practice.
2.3.3.1 Case studies (1-DELSRA)

A few case studies stating how the equivalent linear method was developed and where site response analysis was performed adopting one-dimensional equivalent linear site response analysis method are discussed below.

Idriss and Seed (1967a) first proposed the equivalent linear approach for site response analysis that calculates an approximate nonlinear response through a linear analysis with soil layer properties adjusted to account for the softening during earthquake shaking.

Schnabel et al. (1972) later implemented this method in the frequency-domain and created the program SHAKE. It is reported that SHAKE is the most widely used One-Dimensional Equivalent Linear Analysis based code used in the present times (Matasovic and Hashash, 2012; Bolisetti, 2014).

Seed et al. (1988) presented a comparative study between the characteristics of ground motions at five sites underlain by clay at which ground motions were recorded in Mexico City in the earthquake of September 16, 1985 and for which analyses of ground response were made using the Equivalent linear method. In was concluded that simple ground response analyses could provide very useful data for engineering assessment of the effects of local soil conditions on the characteristics of ground motions likely to develop at sites underlain by soft clays.

Idriss (1990) based on his study using the equivalent linear method had reported that peak ground accelerations at the surface of soil deposits are slightly greater than that on rock.
Idriss and Hudson (1993) presented a study made on the response of San Justo Dam to the Loma Prieta earthquake of October 17, 1989. They adopted the total stress Equivalent Linear Method for the analysis.

Dickenson (1994) analyzed strong motion records that were obtained at ten sites that are underlain by the various thickness of soft to medium stiff cohesive soils of the San Francisco Bay area. The records were compared to ground motions obtained by analyses made for various input ground motions by using various dynamic soil response techniques to investigate the ability of the techniques to accurately predict the response of the soil layers. Based on the study, it was suggested that the response obtained using the traditional value of 0.65 for the effective shear strain ratio can be slightly improved by using a value between 0.35 and 0.55 for Ms = 6 to 7 events, and between 0.55 and 0.7 for Ms = 7 to 8 events.

Kavazanjian and Matasovic (1995) performed parametric studies using equivalent linear and nonlinear analyses using dynamic properties of Municipal Solid Waste (such as shear wave velocity and density). They have laid emphasis on the importance of the parameters on the dynamic response of landfills.

Darragh and Idriss (1997) presented a report which compares site response at two sites (Gilroy#2 and Treasure Island) obtained from the equivalent linear method of analysis to that obtained from recorded strong-motion vertical array data.

Rathje and Bray (2001) studied and compared the results obtained from one-dimensional (1D) and two-dimensional (2D) dynamic response analyses, to determine the reliability of the common practice of using 1D analysis to evaluate the seismic response of solid-waste landfills. Results indicated that 1D analysis provides a reasonably conservative estimate of the seismic loading and earthquake-induced
permanent displacement for deep sliding surfaces. Based on the results of this study, a simplified procedure was proposed for scaling 1D results to account for 2D topographic effects.

Yoshida et al. (2002) discussed the strain dependent characteristics of stiffness and damping of the Equivalent linear dynamic response analysis method. They reasoned that since the equivalent linear method of dynamic analyses of ground is based on complex moduli and Fourier series expansion; therefore, it was not an equivalent method but an approximate method. Two deficiencies in the conventional equivalent linear method as represented by SHAKE were described first. The maximum shear strength is overestimated, resulting in an overestimation of the peak acceleration under a strong ground motion, and underestimation of the amplification at high frequency. The latter sometimes resulted in underestimation of the peak acceleration under weak ground shaking, and gave an incident wave with large unrealistic accelerations or a divergence of analysis in deconvolution analysis under strong ground motion. Both deficiencies were shown to come from the same cause, i.e. computing the effective strain as a constant fraction of the maximum strain. They suggested that since this was a key concept of the equivalent linear analysis, one cannot overcome both deficiencies at the same time in the conventional method. An apparent frequency dependence in stiffness and damping is shown to appear in the dynamic response, although soil itself does not show frequency dependent characteristics. Following this observation, they proposed a method where the effective strain is expressed in terms of frequency from the similarity concept of the strain–frequency relationship between time domain and frequency domain. This according to them enabled the reduction of both deficiencies at the same time,
resulting in a marked improvement in the equivalent linear analysis. The accuracy of the proposed method is examined by the simulations of three vertical array records during large earthquakes. They concluded that proposed method always gave much better prediction than conventional equivalent linear methods for both convolution and deconvolution analyses, and it was confirmed to be applicable at more than 1% shear strain.

Baturay and Stewart (2003) evaluated the degree to which results obtained from equivalent-linear, 1D ground response analyses are realized and used to develop recommendations for implementation into hazard calculations. The methodology included comparing spectral response accelerations ($S_a$) from recordings to predictions derived using ground response analysis procedures as well as attenuation relationships with and without amplification factors. The results were compiled for 134 motions from 68 sites, and prediction residuals were interpreted to assess the models' relative bias and dispersion. They found that ground response analyses were unbiased for $T \leq \sim 1$ sec, but underestimated longer period $S_a$ in deep basins. For soft soils, ground response analyses reduced dispersion for $T < 1$ sec relative to alternative models. This dispersion reduction was not observed for other site categories or at longer periods. These results suggested that ground response analyses (viz. equivalent site response analyses) were beneficial for $S_a$ predictions at soft soil sites, but generally provide no identifiable benefit for typical stiff soil or rock sites.

Kowk and Stewart (2006) investigated the use of site factors derived from theoretical one-dimensional ground-response analyses as a means by which to estimate seismic site effects for earthquake ground-motion prediction. A set of theoretical site factors derived from equivalent-linear analyses for specific geologic
categories in the Los Angeles area and the San Francisco Bay area was reviewed in the study.

Anbazhagan and Sitharam (2008) studied the local site effects by carrying out one-dimensional (1-D) ground response analysis (using the program SHAKE 2000) using both standard penetration test (SPT) data and shear wave velocity data from multichannel analysis of surface wave (MASW) survey. They concluded that site response studies using SPT data and MASW data were found to be comparable with the latter data showing slightly lower values as compared to the former.

Rao and Ramana (2009) performed Equivalent linear ground response analyses at four representative sites at Delhi, India to compare the free field acceleration spectra with local code of practice. Possible ground motions at rock outcrop were generated using stochastic finite source model and specific barrier model for earthquakes that were likely to occur from the central seismic gap and local sources. To take into account the uncertainty in ground motion parameters, 10 random rupture scenarios were considered for each case. Spectral Analysis of Surface Waves (SASW) technique was adopted to measure the in-situ shear wave velocity profile at the representative sites. Experimentally evaluated strain dependent modulus reduction and damping curves for local soils were adopted in the ground response analysis. A comparison of computed response with the standard code of practice being used currently in India for seismic zone of Delhi indicated that the design spectra was not able to capture site amplification due to local sources.

Raghukanth et al. (2011) made an attempt to understand the spatial distribution of ground motion in Guwahati city due to three damaging earthquakes. The rock level ground motion for the scenario earthquakes was generated based on
the stochastic finite-fault methodology. These simulated motions were further amplified up to the surface by equivalent linear site response analyses (SHAKE) using available bore log data at 100 different locations in Guwahati city. A set of twenty simulated rock level time histories for each event were used to compute the surface level ground motion. Response spectra were computed, and the results were presented in the form of contour maps, at selected natural periods. The mean amplification due to local soil deposit was reported to be as high as 2.2 at most of the sites in Guwahati city. It was also pointed out in the study that the site amplification effects estimated by their study relied mainly on the synthetic ground motion. It was suggested to validate the results by the installation of denser recording stations and using recorded ground motions as input motions in the analyses.

Roy and Sahu (2012) presented the spatial variation of ground motion in Kolkata Metropolitan District (KMD) by generating synthetic ground motion considering the point source model coupled with site response analysis. Surface level ground motion parameters were determined using SHAKE2000 software which utilizes the equivalent linear procedure as proposed by Schnabel et al. (1972). Input ground motions or the rock level acceleration time histories at 121 borehole locations in Kolkata for the vulnerable source, Eocene Hinge Zone, due to maximum credible earthquake (MCE) moment magnitude 6.2 were generated by synthetic ground motion model. Additionally, Soil investigation data of 121 boreholes were collected from the report of Soil Data Bank Project, Jadavpur University, Kolkata to define the soil profile for analysis. Site response study showed higher PGA in comparison with rock level acceleration.
Akhila et al. (2012) carried out a detailed study on ground response analysis at the Park hotel located in Kolkata city, India. Soil profiles were ascertained by conducting SPT bore holes. Shear wave velocity profiles were generated by conducting cross borehole tests. Site response analysis was conducted using DEEPSOIL (Hashash, 2009). Sikkim earthquake (2011) ground motion of moment magnitude 6.9 was used as input motion. The results showed that the peak ground acceleration values at surface to be in the range of 0.40g to as high as 0.73g and that of the bedrock were observed to vary from 0.10g to 0.30g.

Matasovic, N and Hashash, Y. (2012) synthesized a report (NCHRP Synthesis 428) on the current state of site response analysis in the transportation engineering field. The study identified and described the current practice and available methods for evaluating the influence of local ground conditions on earthquake design ground motions on a site-specific basis. The report cites the criteria used to determine when a site-specific analysis is needed, how to develop input parameters required for a site response analysis, the nature of the site response analysis performed (equivalent-linear, total stress nonlinear, effective stress nonlinear), the process of model setup, and how uncertainties are dealt with in the analysis process.

Nath, Rituraaj (2013) carried out a parametric study on the effect of subsurface layering and depth of bedrock on strong ground motion. Equivalent linear site response analysis using SHAKE2000 (Ordonez, 2003) were performed considering inbuilt stiffness and damping ratio curves of the code. The strong ground motion recorded during Bhuj earthquake 2001 was considered as input motion for the entire study. It was reported that the natural frequency shifted towards the lower side.
with the increase in the layering and increased with the decrease in the depth of bedrock.

Bolisetti et al. (2014) carried out a study which sheds light on the applicability of some industry-standard equivalent linear (SHAKE) and nonlinear (DEEPSOIL and LS-DYNA) programs across a broad range of frequencies, earthquake shaking intensities, and sites ranging from stiff sand to hard rock, all with a focus on application to safety-related nuclear structures. Results showed that the equivalent linear method was unable to reproduce the high-frequency acceleration response, resulting in almost constant spectral accelerations in the short period range.

2.4 MODULUS REDUCTION AND DAMPING RATIO CURVE

The nature and distribution of earthquake damage are strongly influenced by the response of soils to cyclic loading. This response is controlled in large part by the mechanical properties of the soil. Geotechnical earthquake engineering encompasses a wide range of problems involving any types of loading and many potential mechanisms of failure, and different soil properties influence the behavior of the soil for different problems. The behavior of soils subjected to dynamic loading is governed by the dynamic soil properties (Kramer, 1996).

Dynamic soil behavior resulting from earthquake-induced ground motion can be hysteretic, highly nonlinear and plastic. Ground response prediction methods should ideally address all those aspects while still maintaining a balance between efficiency and accuracy adequate for the problem under consideration (Guerreiro et al., 2012).
Much progress has been made in recent years in the development of analytical procedures for evaluating the response of soil deposits under seismic loading conditions. A successful application of such procedures for determining ground response in specific cases, however, is essentially dependent on the incorporation of representative soil properties in the analyses. The recommended practice for determination of dynamics soil properties is to perform laboratory tests and field tests. However, depending on the location and complexity of a project this approach might not be practical. The current state of practice for determining $G$ and $\beta$ for ground response analysis as reported by Zhang et al. (2005) involves:

(1) Estimating or measuring $V_s$ in the field

(2) Estimating or measuring the variation of $G$ and $\beta$ with strain rate ($\gamma$) primarily in the laboratory.

Typically, it is a common practice to normalize $G$ by dividing by $G_{\text{max}}$. A plot of the variation of $G/G_{\text{max}}$ with cyclic shear strain is called normalized modulus reduction curve. Similarly, a plot of variation of $\beta$ with cyclic strain is called material damping ratio curve.

Current earthquake geotechnical engineering often resorts to established $G/G_{\text{max}}$ and Damping ratio curves to tackle various problems related to ground response analysis. The accuracy and efficiency of a site response analysis depends greatly on the modulus reduction and damping ratio curves chosen or determined for the analyses. Since the literature in this topic is quite large so it is not possible to cover all the literature available till date. However, in this section, an attempt will be made to briefly discuss various major modulus reduction and damping ratio curve
families developed by various researchers along with their advantages and disadvantages.

Seismic ground response analysis requires input of dynamic soil properties in the form of stiffness and material damping information. Soil stiffness is represented by either shear wave velocity (Vs) or shear modulus (G). The small strain shear wave velocity (Vs) is directly related to small-strain shear modulus (Gmax) by Eq. 2.2.

\[ G_{\text{max}} = \rho \, V_s^2 \]  

Where, \( \rho \) = mass density of soil (total unit weight of soil divided by the acceleration due to gravity).

At moderate to high strains, the secant shear modulus (Gsec) is used to represent the average soil stiffness. Figure 2.1 illustrates the relationship between \( G_{\text{max}} \), \( G_{\text{sec}} \), shear strain (\( \gamma \)) and shear stress (\( \tau \)) in addition to the relationship between the stress-strain hysteresis loop for one cycle of loading and material damping ratio. In cases of ground response involving no residual soil displacements, the response is determined mainly by the shear modulus and damping characteristics of the soil under symmetrical cyclic loading conditions. Because most soils have curvilinear stress-strain relationships (Fig. 2.1, the shear modulus is usually expressed as the secant modulus determined by the extreme points on the hysteresis loop while the damping factor is proportional to the area inside the hysteresis loop. Laboratory tests have shown that soil stiffness is influenced by cyclic strain amplitude, void ratio, mean principal effective stress, plasticity index, over-consolidation ratio and number of loading cycles.
The secant shear modulus of a soil element varies with cyclic shear strain amplitude. At low strain amplitudes, the secant shear modulus is high, but it decreases as the strain amplitude increases. The locus of points corresponding to the tips of hysteresis loops of various cyclic strain amplitudes is called a backbone curve; its slope at the origin represents the largest value of the shear modulus, $G_{\text{max}}$. At greater cyclic strain amplitudes, the modulus ratio $G_{\text{sec}} / G_{\text{max}}$ drops to values less than 1. Characterization of the stiffness of an element of soil, therefore, requires consideration of both $G_{\text{max}}$ and the manner in which the modulus ratio varies with the cyclic strain amplitude. This variation of the modulus ratio with cyclic strain amplitude is called a modulus reduction curve.

The material damping ratio ($\xi$) represents the energy dissipated by the soil. Mechanisms that contribute to material damping are friction between soil particles,
strain rate effect, and nonlinear soil behavior. The hysteretic damping ratio can be calculated by

\[ \xi = \frac{W_D}{4\pi W_s} \]  

Where, \( W_D \) = energy dissipated in one cycle of loading, and \( W_s \) = maximum strain energy stored during the cycle.

Theoretically, there should be no dissipation of energy in the linear elastic range for the hysteretic damping model defined by Eq. 2.3. However, even at very low strain levels, there is always some energy dissipation measured in laboratory specimens. The damping ratio at very low levels is a constant value and is referred to as the small-strain damping ratio (\( \beta_{\text{min}} \)). At higher strains, nonlinearity in the stress-strain relationship leads to an increase in material damping ratio with increasing strain amplitude. A plot of the damping ratio against the cyclic shear strain amplitude, called the material damping ratio curves is generally used in ground response analyses.

The forms of the relationships expressing shear modulus and damping ratio as a function of shear strain play an important role in determining the results of ground response analyses (Sun et al., 1988). Many studies have been conducted to characterize the factors that affect \( G/G_{\text{max}} \) and \( D \) of soils (e.g., Richart et al., 1970; Seed and Idriss, 1970; Hardin and Drnevich, 1972; Iwasaki et al., 1978; Lee and Finn, 1978; Zen et al., 1978; Tatsuoka et al., 1978; Kokusho, 1980; Ishibashi, 1981; Kokusho et al., 1982; Imai and Tonouchi, 1982; Seed et al., 1983; Seed et al., 1985, Seed et al., 1986; Ni, 1987; Sun et al., 1988; Das, B.M., 1993; Rix and Stokoe, 1991; Vucatic and Dobry, 1991; Ishibashi and Zhang, 1993; EPRI, 1993; Khouri, 1984;
Rollins et al., 1998; Vucetic et al., 1998; Yegian et al., 1998; Stokoe et al., 1999; Lanzo and Vucetic, 1999; Assimiki et al., 2000; Darendeli, 2001; Roblee and Chiou, 2004; Stokoe et al., 2004, Zhang, et al., 2005; Okur and Ansal, 2007).

With the increase in the acceptance and application of equivalent linear site response analysis many researchers came forth with their findings on various types of soils under various conditions. Schnabel (1973) produced the modulus reduction and damping curves on rock, Singh and Donovan (1977) on frozen soil, Iwasaki et al. (1978) on torsional shear loading of sands, Gazetas and Dakoulas (1992) on rockfill, Idriss et al. (1995), Kavazanian and Matasovic (1995), Bray et al. (1995) on waste material; Yegian et al. (1998) on geosynthetic interface; Wehling et al. (2003) on Fibrous peaty organic soil.

2.4.1 Case Studies

Brief reviews of some studies are produced below.

Seed and Idriss (1970) presented the first comprehensive report on modulus reduction curves and damping ratio curves based on the experimental data of many researchers for sandy soils (Wiessman and Hart, 1961; Richart et al., 1962; Hall and Richart, 1963; Hardin and Richart, 1963; Hardin, 1965; Drnevich et al., 1966; Matshushita et al., 1967; Donovan, 1969; Silver and Seed, 1969; and Kishida and Takano, 1970) and saturated clays (Wilson and Drnevich, 1960; Taylor and Menzies, 1963; Parmalee et al., 1964; Taylor and Hughes, 1965; Thiers, 1965; Idriss, 1966; Krizek and Franklin, 1967; Aisiks and Tarshansky, 1968; Thiers and Seed, 1968; Kovacs, 1968; Donovan, 1969; and Hardin and Drnevich, 1970). All the results were based on various tests performed in the laboratory as well as in-situ conditions (e.g.,
Forced vibration, free vibration, torsional vibration, cyclic triaxial compression, simple shear, field shear wave velocity measurements). Seed and Idriss, 1970 based on research by Hardin and Drnevich, 1970 had suggested that the primary factors affecting moduli and damping factors are strain amplitude, effective mean principle stress, void ratio, number of cycles of loading, degree of saturation of cohesive soils; some other less important factors are octahedral shear stress, over-consolidation ratio, effective stress strength parameters, c’ and φ’ and time effects. They presented relationships to determine the values of maximum shear modulus (at zero strain) and the variations of modulus values as well as damping ratio values with strain for both sandy as well as saturated clays. Also, limited data for gravelly soils and peats were also covered.

Khour (1984) analysed available experimental data (Drnevich and Richart, 1970; Seed and Idriss, 1970; Silver and Seed, 1971; Hashiba, 1971; Hardin and Drnevich, 1972; Kuribayashi et al., 1974, 1975; Sherif and Ishibashi, 1976; Sherif et al, 1977, Iwasaki and Tatsuoka, 1977; Iwasaki et al., 1978; Tatsuoka et al., 1979; Uchida et al., 1980; Kim and Novak, 1981; Chung et al., 1984) and proposed a family of modulus reduction and damping ratio curves. The modulus reduction curves were plotted on log G/Gmax vs Log σ’o based on the general form of equivalent shear modulus equation as given by Hardin and Drnevich, 1972; Iwasaki et al., 1978; Tatsuoka et al., 1978; Kokusho, 1980; and Ishibashi, 1981. K(γ) which is decreasing the function of the cyclic shear strain amplitude, γ was determined for σ’o = 1kN/m². The plotted curve was found to be similar with that of Seed an Idriss, 1970 curves for sands. However, the curves were not necessarily comparable because the Khouri
(1984) curves were determined for $\sigma'_o = 1\text{kN/m}^2$ while Seed and Idriss curves were developed for a range of $\sigma'_o = 20$ to $400\text{kN/m}^2$.

Seed et al. (1986) presented a review on data concerning the shear modulus and damping ratios of sand and gravelly soils as determined by laboratory and field tests. They concluded that dynamic shear moduli of granular soils (sands and gravels) can conveniently be expressed as a function of effective mean principle stress ($\sigma'_m$) and a shear modulus coefficient ($K_2$), which is a function of the grain size of soil particles, relative density of the soil and the shear strain developed in the soil. A guide for the determination of $K_2$ was also given which was a function of the SPT value of the field. They further stated that damping ratios of sands and gravels were very similar and are only slightly affected by density and not significantly dependent on the grain size of the particles. The study was based on the investigations by many researchers (Weissman and Hart, 1961; Richart et al., 1962; Drnevich et al., 1966; Silver and Seed, 1969; Seed and Idriss, 1970; Hardin and Drnevich, 1972; Sherif and Ishibashi, 1977; Kokusho, 1980).

Sun et al. (1988) summarized all available experimental data on the dynamic shear moduli and damping factors for cohesive soils under cyclic loading conditions and presented the results in the form of shear modulus reduction curves and damping ratio curves. In their study emphasis was placed mainly on properties of clays but, limited data for offshore samples and mudstone were also included. The curves were developed based on the comprehensive study carried by many researchers (e.g., Taylor and Parton, 1973; Idriss, 1976; Anderson and Richart, 1976; Nishigaki, 1977; Hara and Kiyota, 1977; Ohsaki et al., 1978; Taniguchi et al. 1978; Zen and Hamada,
In this study relationship between normalized modulus reduction curves and various factors like confining pressure, plasticity index, void ratio, consolidation stress history, duration of confinement and frequency of loading. The study concluded that normalized modulus curves for cohesive soils are not significantly affected by consolidation stress history, duration of confinement, frequency of loading and sample disturbance up to moderate strain levels. The only factor reported having significantly affected the reduction curves was the plasticity index and hence it could provide a useful guide to the use of such relationships in engineering practice. It also reported that void ratio appeared to be a significant secondary factor in selecting a modulus reduction curve for analysis purpose. The development of this family of curves was important as it came on the backdrop of the 1985 Mexico City Earthquake, during which the soft Mexico clay greatly amplified the ground motions and caused severe damage in certain part of the city (Rosenblueth, 1985; Romeo and Seed, 1986; Dobry and Vucetic, 1987).

Vucetic and Dobry (1991) studied the influence of plasticity index (PI) on the cyclic stress-strain parameters of saturated soils. They proposed $G/G_{\text{max}}$ curves with PI ranging from 0 to 200 and Overconsolidation Ratio (OCR) ranging from 1-15 and Damping curves with PI ranging from 0 to 200 and OCR ranging from 1 to 8. They concluded that PI was the main factor controlling $G/G_{\text{max}}$ and D for a wide variety of soils. The study was based on the experimental results from 16 publications (Richart,
1970; Seed and Idriss, 1970; Hardin and Drnevich, 1972; Marcuson and Wahls, 1972; Richart, 1975; Idriss et al., 1976; Hardin, 1978; Anderson and Stokoe, 1978; Matshui et al., 1980; Kim and Novak, 1981; Kokusho et al., 1982; Ishihara, 1986; Romeo and Lame, 1986; Dobry and Vucetic, 1987; Vucetic, 1988; Vucetic and Dorby, 1988). They also carried out a parametric study which showed the influence of the plasticity index on the seismic response of clay sites, excited by the acceleration recorded on a rock in Mexico City during the 1985 earthquake.

EPRI (1993) was a study conducted to develop engineering estimates of earthquake ground motions for application in the eastern United States based on a physical understanding of how the earth behaves, explicitly expressing uncertainties in estimates caused by lack of knowledge both about properties of the earth and about physical processes that govern the generation and transmission of seismic energy. As a part of the objective of study, an extensive set of geotechnical and seismic investigation was conducted at three reference sites (Gilroy 2, Treasure Island and Lotung). Based on the investigations G/Gmax and Damping curves were developed for applications to cohesionless soils in the range of gravelly sands to low plasticity silts or sandy clays. Also, curves for rock were developed during the same study. The curves developed were an improvement over those previously available in that they were a function of depth, reflecting reduced nonlinearity with depth of burial. The EPRI curves were developed based on depth criteria which indirectly took into effect the confining pressure factor, had 6 groups in the cohesionless soil category (0 - 20 ft; 21-50ft; 51 - 120ft; 121 - 250ft; 251 – 500ft; 501-1000ft) and 8 groups for the rock curves category (0-20ft; 21-50ft; 51-120ft; 121-250ft; 251-500ft; 501-1000ft; 1001-2000ft).
Ishibashi and Zhang (1993) reanalyzed available experimental data on dynamic shear moduli and damping ratios of various soils including non-plastic sand to highly plastic clays. All the data were compiled to form simple unified formulas (five in total) which expressed the dynamic shear modulus and damping ratios in terms of maximum dynamic shear modulus, cyclic shear strain amplitude, mean effective confining pressure and plasticity index. The only unknown in the formulas was Gmax. They also remarked that the formulas could be extended to include moderately overconsolidated clays.

Lanzo et al. (1997) performed cyclic tests to study the secant shear modulus, Gs, of two reconstituted sand samples and three laboratory-made clay samples at small cyclic shear-strain amplitudes \( \gamma_c \approx 0.0006\%–0.02\% \). A recently developed direct, simple shear device for small-strain testing was employed. The effects of cyclic strain amplitude (\( \gamma_c \)), type of soil and plasticity index (PI), vertical effective consolidation stress (\( \sigma'_{vc} \)), and overconsolidation ratio (OCR) were investigated. The results show that the ordinates of the normalized shear modulus reduction curve, \( G_s/G_{max} - \gamma_c \), generally increase as \( \sigma'_{vc} \) and OCR increase. However, these effects of \( \sigma'_{vc} \) and OCR become smaller and may eventually disappear as the PI of the soil increases.

Yegian et al. (1998) presented a study of the dynamic response of geosynthetic interface in municipal solid waste. Laboratory tests were used to develop equivalent stiffness and damping properties of the interface. They proposed the use of these properties in the analysis of one-dimensional response of landfills using the equivalent linear method.
Rollins et. al, (1998) had presented a family of curves pertaining to gravels based on the investigations of fifteen publications including their own (Lida et. al, 1984; Seed et. al, 1986; Shamoto et al., 1986; Hatanaka et al., 1988; Hynes, 1988; Shibuya et al., 1990; Goto et al., 1992, 1994; Yasuda and Matsumoto, 1993, 1994; Kokusho and Tanaka, 1994; Konno et al., 1994; Souto et al., 1994; Hatanaka and Uchida, 1995). The mean curve for normalized shear modulus reported for gravelly soils in this study was near the mean curve reported for sands by Seed and Idriss (1970) than the curve for gravels reported by Seed et al. (1986). Moreover, the mean damping ratio curve was near the lower range of the curve for sand and gravel as reported by Seed and Idriss (1986). They also concluded that the normalized modulus reduction curves and damping ratio curves were moderately dependent on the confining pressure.

Darendeli (2001) used an extensive database (110 samples, 20 sites) from various research projects to develop the most recent of the analyzed families. The data base consisted of combined Resonant Column and Cyclic Torsional Shear (RCTS) tests, sequentially performed on intact samples from soils described as having low void ratio and not liquefiable during seismic activity. The tested samples ranged from clean natural sands to clays, characterized by broad intervals of sampling depth (3-263m), confining pressure (0.3 – 27.2 atm), Plasticity Index (0-132% and OCR (1-8). A total of 20 curves with variation of PI (0,15,30,50,100), confining pressure(0.25, 1, 4, 16 atm), number of cycles (10), Frequency of loading (1 Hz) , Number of cycles (10) and OCR (1) were proposed. It was concluded that the parameters that have an impact on the normalized modulus reduction curve and material damping curves were Strain amplitude, Mean effective confining pressure, soil type and plasticity, number
of loading cycles, frequency of loading, OCR, Void ratio, Degree of saturation, Grain characteristics, size shape gradation, mineralogy in descending order of importance. It was also remarked that the number of loading cycles had a greater impact on the material damping curves as compared to normalized reduction curves and were dependent on the soil type. The applicable strain range was 0.0001 – 0.5%.

Menq (2003) developed a large-scale, multi-mode, free-free, resonant column device (MMD) as part of the study. This new device, along with a traditional fixed-free resonant column (RC) and torsional shear (TS) device, were used to study the effects of mean effective stress, void ratio, frequency, water content, median grain size, and uniformity coefficient on the linear and nonlinear dynamic properties of sandy and gravelly soils. A total of 59 reconstituted specimens were tested in the study with a strain range 0.0001 – 0.6%. It was concluded that mean effective stress has a slightly larger effect on Gmax of loose well graded granular materials than dense, uniform materials and reference strain is mainly a function of mean effective stress and uniformity coefficient.

Roblee and Chiou (2004) developed a simple “Geoindex Model” for practical design selection of dynamic soil properties for earthquake site response analysis, which was a simplified version of the Darendeli (2001) model where \( \gamma_r \), a pseudo-reference shear strain and \( \alpha \), curvature coefficient are tabulated on the basis of soil categories defined by fines content and plasticity. The development was made on the basis of laboratory test data on 154 natural soil samples obtained from 28 sites. The curves had an applicable strain range of 0.0001 – 4.0 %.
Zhang et al. (2005) proposed predictive equations for estimating normalized shear modulus and the material damping ratio of Quaternary, Tertiary and older and residual/saprolite soils. The equations are based on a modified hyperbolic model and a statistical analysis of existing Resonant Column and Torsional Shear test results of 122 specimens obtained from South Carolina, North Carolina and Alabama of the United States of America investigated by USACE, 1978, 1979; S&ME Inc., 1993, 1998; Stokoe et al., 1995; Lee, 1996, Hwang, 1997, Borden et al., 1994, 1996; and Hoyos and Macari, 1999. The normalized shear modulus equations are expressed in terms of shear strain amplitude, confining stress and plasticity index and that of the damping ratio are expressed in terms of a polynomial function of the normalized shear modulus and a minimum damping ratio. They stated that when compared to the predictive equations developed in this study and the previously published curves it was found that the effect of confining stress is more significant and that of the plasticity index was less significant than previously thought, as found from the data across the three geologic groups considered for the study. However, the authors also remarked that more data was required to validate these conclusions, particularly from the Quaternary-age soil deposits. Thus they concluded that confining stress and age of the soils must be considered when selecting G/G\(_{\text{max}}\) and D curves for design. The applicable range of shear strain was 0.0001 – 0.3 %.

Choi (2008) produced modulus reduction and dmaping curves for Bandelier Tuff, Pajarito Plateau, NM on the basis of tests carried out on 38 samples in the shear strain range of 0.0001 – 0.4%.

Cabalar (2009) presented a study on experimental work on clays having various plasticity index (PI). Dynamic properties of saturated clays were studied
considering the effect of changing confining pressure using Stokoe Resonant Column Testing developed by Stokoe (1994). 12 undrained consolidated torsional resonant column tests were performed on various clays under confining pressures ranging from 350 to 450 kPa while pore pressure was kept at 300kPa. Shear modulus and damping ratio of the mixtures were measured over a strain range of 0.001 – 0.1 % and then compared with generic nonlinear and damping curves. It was concluded from the results that as the PI increases the shear modulus increases and damping ratio decreases under same effective stress. Also as the effective stress increases, the shear modulus increases and damping ratio decreases for the same clay type.

Araei et al. (2010) studied the dynamic characteristics of modeled gravelly soils used as construction materials in some rock filled dams in Iran by conducting large scale triaxial testing. The tested specimens were compacted to more than 95% maximum dry density. The authors concluded that fine content of gravelly soils has a distinctive effect on modulus reduction and material damping curves and those samples with fines more that 30% showed more damping values as compared to samples having fine less than 15%.

Biglari and Ashayeri (2011) presented a model for estimating shear modulus and damping ratio of unsaturated soil based on the experimental study on the measurement of shear modulus and damping ratio with suction-controlled resonant column and suction-controlled cyclic triaxial devices in the strain range 0.000001 to 0.1%.

Wichtmann and Triantafyllidis (2013) studied the modulus reduction and damping ratio curves of 27 nos of clean quartz sand in approximately 280 nos of
resonant column tests. For each material, several resonant column tests with various relative densities and pressures were performed. The effect of uniformity coefficient and mean grain size on the modulus reduction curves and damping ratio curves were studied. The authors concluded that the damping ratio curves were almost independent of the grain size.

2.5 CRITICAL REVIEW COMMENTS

From the above review, the following points become apparent.

- Although SSR method is a robust method to determine the site response, in areas of low seismicity or in areas where reference station cannot be established the method becomes redundant.
- A reference station may have its own amplification which may seriously undermine the site amplification of the soil site and should be carefully selected.
- HVSR method as proposed by Nakamura (1989) for microtremors was modified to study the behavior of strong motion recordings by Lermo and Chavez (1993).
- Theoretical validity of HVSR method is a highly debated topic of discussion in the scientific community. Although the site amplification as described by HVSR method is highly questionable, the method remains a widely chosen method because of its simplicity, low cost of application and its ability to identify the fundamental resonance frequency of a soil deposit to a fairly accurate level. The level of site response as determined by this method is comparable to other site response methods.
- HVSR method has been successfully adopted as a preliminary assessment of seismic hazards in many seismic microzonation projects around the globe.
- HVSR method has also been utilized to identify the nonlinearity of soil behavior in many cases.
- 1-DELSRA, as can be summarized, is a versatile method for probing the first estimate of site amplification.

However, it can be seen that although the North Eastern part of India has been classified under seismic zone V (IS:1893-2002), a very little study has been carried out for the region. Neither, SSR nor HVSR studies have been carried out for the region barring a study of Greater Guwahati region in which a study has been carried out in the form of Microzonation of Guwahati City, 2008. Although a few 1-DELSRA studies has been carried out of the Guwahati Region (Kumar and Krishna, 2013, Kumar and Dey, 2015) no study devoted to the Western part of Guwahati region has been carried out untill now. This study has identified this as the gap area and therefore an attempt has been made to study the site amplification factors and the local site effects in the Western Guwahati Region.
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