CHAPTER 6

HORIZONTAL TO VERTICAL SPECTRAL RATIO

(HVSR) ANALYSIS

6.1 INTRODUCTION

Horizontal to Vertical Spectral Ratio (HVSR) method which is a non-reference site technique was originally proposed by Nakamura (1989) to interpret microtremors measurements and provides an alternative for SSR method. Since this method requires no measurement at a reference site, this method overcomes the basic difficulty faced by SSR technique which is the availability of a reference station. This method rests on the hypothesis that the vertical component of ground motion contains more information of the source of ground motion than does the horizontal components. (Lermo and Chavez, 1993). This technique, originally applied to microtremors (Ohmachi et. al., 1991; Field et. al., 1993; Lachet and Bard, 1994), has also been applied to weak ground motion studies (Lermo and Chavez, 1993; Duval, 1994; Field, 1994) and, in some cases, to strong ground motion studies (Lermo and Chavez, 1993; Theodulidis and Bard, 1995; DST, 2008).

Non-reference site technique or single station Horizontal to Vertical Spectral Ratio (Lermo & Chavez-Garcia, 1993), follows the same idea of Nakamura technique, i.e., in the case of a soft layer that overlaps a generic stiff bedrock the incident vertical wave field does not undergo significant modification along the whole source to site path with respect to the horizontal one. In this wave supposing a 1D configuration of the considered site, the simple ratio between the Fourier Amplitude Spectrum (FAS)
of the horizontal component and FAS of the vertical component (both selected on S-phase) allows to detect the real response of the site (due to the body wave only).

The H/V method has been used for microzonation studies to predict site response to earthquake seismicity (Nakamura, 1989; Rial et. al., 1992; Konno and Ohmachi, 1998) and also as a method to estimate unconsolidated sediment thickness, map the bedrock surface, and infer fault locations (e.g., Ibsvon Seht and Wohlenberg, 1999; Delgado et. al., 2000; Parolai et. al., 2002).

A large number of experiments (Lermo and Chavez, 1993; Gitterman et. al., 1996; Seekins et. al. 1996; Fah, 1997) have shown that the HVSR procedure can be successfully applied for identification of the fundamental frequency of sedimentary deposits. These observations were supported by several theoretical 1-D investigations (Field and Jacob, 1993; Lachet and Bard, 1994; Lermo & Chavez Garcia, 1994; Wakamatsu & Yasui, 1996; Tokeshi & Sugimura, 1998). Although HVSR method has been able to identify the fundamental frequency of soil site having relatively simple geology, the amplification factor of HVSR is highly debated (Bard, 1998; Bour et. al., 1998; Mucciarelli, 1998; Al Yuncha & Luzon, 2000; Maresca et. al., 2003; Rodriguez & Midorikawa, 2003), and a comprehensive conclusion as to how the amplification can be explained using this method is yet to be defined. However, owing to its simplicity this method has been used for various microzonation studies (Microzonation of Guwahati City; DST, 2008) to have a preliminary assessment of the seismic vulnerability of a site due to seismic amplification.
6.2 HVSР TECHNIQUE

The technique was originally proposed by Nakamura (1989) to interpret microtremor measurements. The method states that, microtremor energy consists mainly of Rayleigh waves and that site amplification is due to the presence of the surface of a soft layer overlying a half-space. Under these conditions, there are four component of ground motion involved: horizontal and vertical components in the half-space, and horizontal and vertical components at the surface. According to Nakamura, it is possible to estimate the amplitude effect of the source, $A_S$, by the ratio,

$$A_S = \frac{V_S}{V_B} \quad \text{(6.1)}$$

Where, $V_S = \text{FAS of the vertical component of motion at the surface}$,

$$V_B = \text{FAS of the vertical component of motion at the half-space.}$$

Therefore, the definition of estimate of site effect of interest in earthquake engineering, $S_E$, can be given as the ratio

$$S_E = \frac{H_S}{H_B} \quad \text{(6.2)}$$

where, $H_S = \text{FAS of the horizontal component of motion at the surface}$, and,

$$H_B = \text{FAS of the horizontal component of motion at the base of the soil layer.}$$

Now, to compensate $S_E$ by the effect of the source, a modified site effect function, $S_M$, is calculated, where

[193]
\[ S_M = \frac{S_E}{A_S} \] .................................................................(6.3)

Which is equivalent to,

\[ S_M = \frac{\frac{H_S}{V_S}}{\frac{H_B}{V_B}} \] .................................................................(6.4)

Now, if it is accepted that the ratio \( H_B/V_B \) is equal to unity, the site effect function, corrected by the source term, may be written as.

\[ S_M = \frac{H_S}{V_s} \] .................................................................(6.5)

The assumption that \( H_B/V_B \) is equal to unity (within a factor of 2, the usual uncertainty when using spectral ratios, e.g. Tucker and King, 1984; Tucker et. al., 1984) was verified by Nakamura experimentally, using microtremor measurements at various depths in the borehole.

Mucciarelli and Gallipolli (2001) had reported that the HVSR technique as is generally known is not a single entity but several variations of the HVSR method is present. In this study, the HVSR methodology of Microzonation of Guwahati City (DST, 2008) has been adopted for the analysis with an attempt to supplement the site response study carried out earlier in the greater Guwahati region.

### 6.2.1 HVSR Methodology Adopted

In the present study, the HVSR\(_j\)\(_k\)(\(f_k\)) is computed at each j site for the \(i^{th}\) event at the central frequency \(f_k\) from the root mean square average of the amplitude spectra (DST, 2008) as
\[ HVSR_{ij}(f_k) = \frac{\frac{1}{\sqrt{2}} \left[ \text{abs} \left| H_{ij}(f_k) \right|_{\text{NS}} \right]^2 + \text{abs} \left| H_{ij}(f_k) \right|_{\text{EW}}^2}{\text{abs} \left| V_{ij}(f_k) \right|} \] ............................(6.6)

Where,

\[ |H_{ij}(f_k)|_{\text{NS}} = \text{FAS of horizontal NS component} \]

\[ |H_{ij}(f_k)|_{\text{EW}} = \text{FAS of horizontal EW component} \]

\[ V_{ij}(f_k) = \text{FAS of vertical component} \]

Finally, the event average \( HVSR_{ij}^{\text{ave}}(f_k) \) (Field and Jacob, 1995) is computed at each site for the \( k^{\text{th}} \) frequency to consider the contribution of all the seismic events recorded at that station.

Additionally, amplification of PGA, PGV and PGD is also determined by obtaining the ratio of the horizontal to the vertical component.

### 6.3 SELECTION OF RECORDS

Earthquake records (accelerograms) considered for HVSR analysis, were adopted from DATASET 2. Since the method involves recordings of a single station, earthquake records were selected only for those stations which were of importance with respect to the present study. The selected sites were Guwahati, Boko-Palashbari, and Goalpara. Out of the 30(thirty) earthquake events of DATASET 2, it was found that 15(fifteen) events (as given in Table 6.1) were responsible for triggering the selected 3 nos. of stations.
Table 6.1: Selected Earthquake Motions & Epicentral Distances

<table>
<thead>
<tr>
<th>Earthquake Event</th>
<th>Epicenter</th>
<th>Magnitude (Mw)</th>
<th>Focal Depth (km)</th>
<th>Boko-Palashbari (Soil site)</th>
<th>Guwahati Central (Soil site)</th>
<th>Goalpara (Soil site)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Apr.2009</td>
<td>26.4N 91.7E</td>
<td>4</td>
<td>10</td>
<td>66</td>
<td>24</td>
<td>**</td>
</tr>
<tr>
<td>11 Aug.2009</td>
<td>24.4N 94.8E</td>
<td>5.6</td>
<td>22</td>
<td>400</td>
<td>366</td>
<td>463</td>
</tr>
<tr>
<td>19 Aug.2009</td>
<td>26.6N 92.5E</td>
<td>4.9</td>
<td>20</td>
<td>152</td>
<td>88</td>
<td>**</td>
</tr>
<tr>
<td>30 Aug.2009</td>
<td>25.4N 94.8E</td>
<td>5.3</td>
<td>85</td>
<td>364</td>
<td>318</td>
<td>**</td>
</tr>
<tr>
<td>03 Sep.2009</td>
<td>24.3N 94.6E</td>
<td>5.9</td>
<td>100</td>
<td>388</td>
<td>356</td>
<td>450</td>
</tr>
<tr>
<td>21 Sep.2009</td>
<td>27.3N 91.5E</td>
<td>6.2</td>
<td>8</td>
<td>148</td>
<td>125</td>
<td>153</td>
</tr>
<tr>
<td>29 Oct.2009</td>
<td>27.3N 91.4E</td>
<td>5.2</td>
<td>5</td>
<td>**</td>
<td>**</td>
<td>147</td>
</tr>
<tr>
<td>29 Oct.2009</td>
<td>26.6N 90.0E</td>
<td>4.2</td>
<td>10</td>
<td>**</td>
<td>**</td>
<td>80</td>
</tr>
<tr>
<td>29 Dec.2009</td>
<td>24.5N 94.8E</td>
<td>5.5</td>
<td>80</td>
<td>**</td>
<td>318</td>
<td>426</td>
</tr>
<tr>
<td>31 Dec.2009</td>
<td>27.3N 91.4E</td>
<td>5.5</td>
<td>7</td>
<td>**</td>
<td>127</td>
<td>147</td>
</tr>
<tr>
<td>26 Feb.2010</td>
<td>28.5N 86.7E</td>
<td>5.4</td>
<td>28</td>
<td>**</td>
<td>561</td>
<td>468</td>
</tr>
<tr>
<td>12 Mar.2010</td>
<td>23.0N 94.5E</td>
<td>5.6</td>
<td>96</td>
<td>**</td>
<td>450</td>
<td>526</td>
</tr>
<tr>
<td>26 Jul.2010</td>
<td>26.5N 91.3E</td>
<td>4.1</td>
<td>31</td>
<td>**</td>
<td>56</td>
<td>**</td>
</tr>
<tr>
<td>11 Sep.2010</td>
<td>25.9N 90.2E</td>
<td>5</td>
<td>20</td>
<td>**</td>
<td>158</td>
<td>**</td>
</tr>
<tr>
<td>21 Nov.2010</td>
<td>25.1N 95.3E</td>
<td>5.8</td>
<td>80</td>
<td>**</td>
<td>377</td>
<td>**</td>
</tr>
</tbody>
</table>

All the recordings had three components of motion, two orthogonal and one vertical. Of the selected 15(fifteen) events, Boko-Palashbari station was triggered by 6(six) events, Guwahati by 13(thirteen) events and Goalpara by 9(nine) events. Thus, a total of 28(twenty eight) three component motions were recorded.
All the 74 (28 x 3) records were Fourier transformed and smoothed as described in section 4.5.4.3. The individual properties of each component of the recordings are indicated in Table 6.2, 6.3, 6.4 for the respective stations.

**Table 6.2: Properties of Recorded Motions (Boko-Palashbari Station)**

<table>
<thead>
<tr>
<th>Earthquake Event</th>
<th>Maximum Acceleration (g)</th>
<th>Maximum Velocity (m/sec)</th>
<th>Maximum displacement (m)</th>
<th>Duration (second)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EW</td>
<td>NS</td>
<td>VT</td>
<td>EW</td>
</tr>
<tr>
<td>25Apr.2009</td>
<td>0.011</td>
<td>0.009</td>
<td>0.010</td>
<td>0.004</td>
</tr>
<tr>
<td>11Aug.2009</td>
<td>0.016</td>
<td>0.017</td>
<td>0.008</td>
<td>0.006</td>
</tr>
<tr>
<td>19Aug.2009</td>
<td>0.008</td>
<td>0.019</td>
<td>0.005</td>
<td>0.002</td>
</tr>
<tr>
<td>30Aug.2009</td>
<td>0.007</td>
<td>0.012</td>
<td>0.005</td>
<td>0.002</td>
</tr>
<tr>
<td>03Sep.2009</td>
<td>0.014</td>
<td>0.009</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>21Sep.2009</td>
<td>0.021</td>
<td>0.021</td>
<td>0.013</td>
<td>0.012</td>
</tr>
</tbody>
</table>

**Table 6.3: Properties of Recorded Motions (Goalpara Station)**

<table>
<thead>
<tr>
<th>Earthquake Event</th>
<th>Maximum Acceleration (g)</th>
<th>Maximum Velocity (m/sec)</th>
<th>Maximum displacement (m)</th>
<th>Duration (second)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>EW</td>
<td>NS</td>
<td>VT</td>
<td>EW</td>
</tr>
<tr>
<td>11Aug.2009</td>
<td>0.016</td>
<td>0.013</td>
<td>0.008</td>
<td>0.005</td>
</tr>
<tr>
<td>03Sep.2009</td>
<td>0.006</td>
<td>0.006</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td>21Sep.2009</td>
<td>0.042</td>
<td>0.041</td>
<td>0.024</td>
<td>0.033</td>
</tr>
<tr>
<td>29Oct.2009</td>
<td>0.015</td>
<td>0.011</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>29Dec.2009</td>
<td>0.008</td>
<td>0.010</td>
<td>0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>31Dec.2009</td>
<td>0.010</td>
<td>0.009</td>
<td>0.009</td>
<td>0.006</td>
</tr>
<tr>
<td>26Feb.2010</td>
<td>0.005</td>
<td>0.005</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>12Mar.2010</td>
<td>0.004</td>
<td>0.005</td>
<td>0.003</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Table 6.4: Properties of Recorded Motions (Guwahati-Central Station)

<table>
<thead>
<tr>
<th>Earthquake Event</th>
<th>Maximum Acceleration (g)</th>
<th>Maximum Velocity (m/sec)</th>
<th>Maximum displacement (m)</th>
<th>Duration (second)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EW</td>
<td>NS</td>
<td>VT</td>
<td>EW</td>
</tr>
<tr>
<td>25Apr.2009</td>
<td>0.013</td>
<td>0.014</td>
<td>0.015</td>
<td>0.002</td>
</tr>
<tr>
<td>11Aug.2009</td>
<td>0.013</td>
<td>0.011</td>
<td>0.013</td>
<td>0.006</td>
</tr>
<tr>
<td>19Aug.2009</td>
<td>0.020</td>
<td>0.030</td>
<td>0.021</td>
<td>0.006</td>
</tr>
<tr>
<td>30Aug.2009</td>
<td>0.015</td>
<td>0.009</td>
<td>0.010</td>
<td>0.005</td>
</tr>
<tr>
<td>03Sep.2009</td>
<td>0.012</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>21Sep.2009</td>
<td>0.028</td>
<td>0.024</td>
<td>0.013</td>
<td>0.011</td>
</tr>
<tr>
<td>29Dec.2009</td>
<td>0.011</td>
<td>0.005</td>
<td>0.009</td>
<td>0.004</td>
</tr>
<tr>
<td>31Dec.2009</td>
<td>0.010</td>
<td>0.007</td>
<td>0.006</td>
<td>0.004</td>
</tr>
<tr>
<td>26Feb.2010</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>12Mar.2010</td>
<td>0.006</td>
<td>0.005</td>
<td>0.005</td>
<td>0.002</td>
</tr>
<tr>
<td>26Jul.2010</td>
<td>0.022</td>
<td>0.016</td>
<td>0.017</td>
<td>0.005</td>
</tr>
<tr>
<td>11Sep.2010</td>
<td>0.004</td>
<td>0.005</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>21Nov.2010</td>
<td>0.009</td>
<td>0.009</td>
<td>0.007</td>
<td>0.005</td>
</tr>
</tbody>
</table>

### 6.4 SELECTION OF TIME WINDOW

While determining HVSR the entire horizontal and vertical accelerogram are divided into a fixed number of time-windows and then the average HVSR of each time-window is considered for interpretation. Sairam et, al. (2011) had used a time window of 10.50 second, starting from 0.50 second before S-wave phase arrival. This time-window was chosen to best contain most of the high-amplitude of the S-wave energy of earthquake records. In Microzonation of Guwahati city (DST, 2008) a time window of 5.0 second duration starting from the onset of S-wave arrival and containing the maximum of S-wave arrival was considered for analysis. Bonilla et. al. (1997) had stated that using longer time results in better spectral resolution. Borcherdt et. al. (1989) had 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.

However, it was also stated by Bonilla et. al. (1997) that, using longer time windows will result in the inclusion of scattered and reflected the energy and also the effect of surface waves in the spectra. Bonilla et. al. (1997) and Field and Jacob (1995) found no statistical variation in site response computed with spectra of different time windows. However, Castro et. al. (1997) suggested that S-waves could be contaminated at a larger epicentral distance, which demands variable time windows for the estimation of the HVSR using S-waves.

In this study, the entire accelerogram is used for analysis considering it as a single window in order to obtain a better spectral resolution and stable estimate of site response.

6.5 ANALYSIS RESULTS

All the records considered were analyzed using spreadsheets developed for the purpose. The records were analyzed for the usual frequency range of 0.1 – 10.0 Hertz, which is the frequency range of practical interest in engineering (Salazar et. al., 2013). The HVSR vs. Frequency data were plotted on a semi-log plot. Figure 6.1, 6.2 & 6.3 shows the HVSR plots for Guwahati-Central, Boko-Palashbari and Goalpara respectively
Figure 6.1: HVSR Plot of Earthquake Recordings of Guwahati-Central Station

Figure 6.2: HVSR Plot of Earthquake Recordings of Boko-Palashbari Station
Figure 6.3: HVSR Plot of Earthquake Recordings of Goalpara Station

6.5.1 Site Amplification from HVSR of Strong Motion

Site Amplification from HVSR has often been a debated topic with various quarters putting forth various reasoning regarding its adequacy in determining site amplification. Since the application of HVSR to earthquake motions various scholars (Lermo and Chavez, 1993; S.K.Nath et. al., 2003, Lang, 2004) have used the term amplification to define the site effects from HVSR method. Lang (2004) had studied the qualitative evaluation of different empirical methods on instrumented seismic data as per scientific literature and had commented that HVSR method when applied to earthquake data provided the predominant site frequency (Fundamental Frequency) and level of site amplification with high accuracy. It is however not quantified, as to how and to what degree the accuracy was applicable. Following Lang(2004) an attempt has been made in this study to define the site amplification.
Generally, site amplification from HVSR is defined as the maximum amplitude of the HVSR curve obtained. The results obtained from this study, where three sites have been evaluated are tabulated in Table 6.5.

The HVSR curve from 13 (thirteen) earthquake events used in case of Guwahati site produced curves which are consistent in shape and have shown site amplification with a minimum of 2.16 and maximum of 3.81. Goalpara site showed site amplification within the range of 4.68 to 7.60 for the 9 earthquake events considered for the site, while Boko-Palashbari site indicated site amplification in the range of 3.21 to 5.15 for the 6 earthquake events considered.

6.5.2 Determination of Fundamental Frequency

The Fundamental Frequency (FF) is defined as the frequency at which the HVSR curve has a peak value, or, in other terms it is the frequency (for a particular earthquake) or frequency range (for a set of earthquakes) at which the amplitude ratio value of the curve is maximum; and is a characteristic of a site. Nakamura (1989) suggested that this peak value ratio is at the S-waves resonance frequency of the layered structure and the location of the peak does not depend on the source characteristics. This suggestion is further strengthened by Lachet and Bard (1994), who reported that the H/V spectral ratios obtained for different source characteristics clearly exhibit a peak whose position was constant regardless of the source type and the source function. Lachet and Bard (1994) further based on their study on the peak frequency of HVSR for various geological structures suggested that H/V spectra was a reliable indication of the fundamental resonance frequency of a horizontally layered structure which have been asserted by many authors (Lebrun, 1997; Riepl at. Al.,

[202]
The fundamental frequencies as obtained in this study for the three sites are indicated in Table 6.5.

The Fundamental Frequency range of Guwahati site as obtained from the HVSR curves is in the frequency band of 1.14 Hz to 2.69 Hz, for Goalpara site it is 0.80 Hz to 0.93 Hz while for Boko-Palashbari it is 0.63 Hz to 0.82 Hz.

Table 6.5: Fundamental Frequency (FF) and Corresponding Amplification (Am)

<table>
<thead>
<tr>
<th>Earthquake Event</th>
<th>Epicenter</th>
<th>Magnitude (Mw)</th>
<th>Focal Depth (km)</th>
<th>Boko-Palashbari</th>
<th>Guwahati Central</th>
<th>Goalpara</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Apr.2009</td>
<td>26.4N 91.7E</td>
<td>4</td>
<td>10</td>
<td>0.82</td>
<td>2.50</td>
<td>**</td>
</tr>
<tr>
<td>11 Aug.2009</td>
<td>24.4N 94.8E</td>
<td>5.6</td>
<td>22</td>
<td>0.63</td>
<td>1.25</td>
<td>0.81</td>
</tr>
<tr>
<td>19 Aug.2009</td>
<td>26.6N 92.5E</td>
<td>4.9</td>
<td>20</td>
<td>0.85</td>
<td>2.06</td>
<td>**</td>
</tr>
<tr>
<td>30 Aug.2009</td>
<td>25.4N 94.8E</td>
<td>5.3</td>
<td>85</td>
<td>0.79</td>
<td>2.20</td>
<td>**</td>
</tr>
<tr>
<td>03 Sep.2009</td>
<td>24.3N 94.6E</td>
<td>5.9</td>
<td>100</td>
<td>0.68</td>
<td>1.25</td>
<td>0.81</td>
</tr>
<tr>
<td>21 Sep.2009</td>
<td>27.3N 91.5E</td>
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<td>0.76</td>
<td>2.26</td>
<td>0.81</td>
</tr>
<tr>
<td>29 Oct.2009</td>
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<td>5</td>
<td>**</td>
<td>**</td>
<td>0.84</td>
</tr>
<tr>
<td>29 Oct.2009</td>
<td>26.6N 90.0E</td>
<td>4.2</td>
<td>10</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>29 Dec.2009</td>
<td>24.5N 94.8E</td>
<td>5.5</td>
<td>80</td>
<td>**</td>
<td>**</td>
<td>1.26</td>
</tr>
<tr>
<td>31 Dec.2009</td>
<td>27.3N 91.4E</td>
<td>5.5</td>
<td>7</td>
<td>**</td>
<td>**</td>
<td>1.14</td>
</tr>
<tr>
<td>26 Feb.2010</td>
<td>28.5N 86.7E</td>
<td>5.4</td>
<td>28</td>
<td>**</td>
<td>**</td>
<td>1.63</td>
</tr>
<tr>
<td>12 Mar.2010</td>
<td>23.0N 94.5E</td>
<td>5.6</td>
<td>96</td>
<td>**</td>
<td>**</td>
<td>2.39</td>
</tr>
<tr>
<td>26 Jul.2010</td>
<td>26.5N 91.3E</td>
<td>4.1</td>
<td>31</td>
<td>**</td>
<td>**</td>
<td>2.30</td>
</tr>
<tr>
<td>11 Sep.2010</td>
<td>25.9N 90.2E</td>
<td>5</td>
<td>20</td>
<td>**</td>
<td>**</td>
<td>2.50</td>
</tr>
<tr>
<td>21 Nov.2010</td>
<td>25.1N 95.3E</td>
<td>5.8</td>
<td>80</td>
<td>**</td>
<td>**</td>
<td>2.69</td>
</tr>
</tbody>
</table>

** not analysed

From Fig. 6, multiple HVSR peaks in Guwahati as compared to Boko-Palashbari and Goalpara is observed which may be attributed to Rayleigh wave ellipticity for site with high-impedance contrasts at two very different scales. This has
resulted in the fundamental frequency band being wider as compared to Boko-
Palashbari and Goalpara respectively. From Fig. 6.2 and Fig. 6.3, for Boko-Palashbari
and Goalpara respectively, where the bedrock depth were almost at depth >= 100
meters clear peaks were identifiable.

6.5.3 Determination of Bedrock Depth

The depth to bedrock is related to the fundamental frequency by the relation
(Salazar et. al. 2013).

\[ FF = \frac{V_s}{4H} \] \hspace{1cm} (6.7)

Where, \( FF \) = Fundamental Frequency

\( V_s \) = Shear wave velocity

\( H \) = Depth to bedrock

Using the relation the bedrock to for all the three sites is determined. The
Shear wave velocities are adopted from Mittal et. al.(2012), where it is classified that
Guwahati, Boko-Palashbari, and Goalpara sites fall under the site class C (alluvium)
and had a shear wave velocity range of 200m/sec to 375m/sec. However it must be
mentioned that the shear wave velocity as mentioned by Mittal et. al. (2012) is for the
top 30m of the soil strata, and its applicability for the calculation of the depth to
bedrock is questionable. Despite this fact, it could be assumed that in the case where
the shear wave velocity profile is not available, a good preliminary estimate of the
bedrock depth could be made from the above assumption. The calculations of depth to
bedrock are summarized in Table 6.6.
### Table 6.6: Depth of Bedrock

<table>
<thead>
<tr>
<th>Site</th>
<th>Fundamental Frequency (FF) band (Hz)</th>
<th>Shear Wave Velocity Range, Vs (m/sec)</th>
<th>Depth to Bedrock (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boko – Palashbari</td>
<td>0.80 – 0.93</td>
<td>200 – 375</td>
<td>53.76 to 117.18</td>
</tr>
<tr>
<td>Guwahati-Central</td>
<td>1.14 – 2.69</td>
<td>200 – 375</td>
<td>18.59 to 82.24</td>
</tr>
<tr>
<td>Goalpara</td>
<td>0.63 – 0.82</td>
<td>200 - 375</td>
<td>60.98 to 148.81</td>
</tr>
</tbody>
</table>

#### 6.6 OBSERVATIONS AND DISCUSSIONS

In this chapter, an attempt to determine site transfer function, fundamental frequency and depth of bedrock was carried out. From the results obtained for Guwahati station which is situated at greater Guwahati and other two stations, which lies in the study region, it can be seen that as we travel towards the western part of Guwahati the fundamental frequency range shifts to the lower range indicating trapping of seismic energy by the soft alluvial layer. Also, it is seen that amplification ratio increase significantly (from 2.16 to 7.60) as we move towards the western part of the Guwahati region. This perhaps explains the reason why site response analysis should be taken up for the western part of Guwahati. It is observed that the peak amplification in Guwahati-Central is observed to be 3.81. Nath et. al. (2008) has reported a peak amplification value of 6.5 for the same area. The deviation of results can be attributed to various reasons. For example, first of all, the derivation of the present peak amplification factor is based on the evaluation of 13(thirteen) earthquake strong motion recordings, while that of Nath et. al. (2008) is based on 2(two) recordings. Furthermore, Nath et.al. (2008) has adopted a cubic spline interpolation smoothing technique, while in this study a log-triangle smoothing procedure as developed by David Boore and adapted by DEEPSOIL (Hashash et. al., 2015) is
applied. Additionally, Numerical instability as reported by Kausel and Assimiki (2002) could be another reason for the varying results. However, considering all these uncertainties, it can be said that the method has predicted fairly reasonable results of peak amplification in case of Nath et al. (2008) and this study.

Further site amplification ranges are given in Table 6.7 & 6.8 for the frequency ranges 0.1 – 1.0 Hz, 1.0 – 3.0 Hz and 3.0 – 10.0 Hz. These frequency ranges are considered based on the fact that the natural frequencies of multistoried buildings (3-10 floors) range between 1 and 3 Hz, whereas the natural frequencies for 1 – 3 storey buildings vary from 3 to 10 Hz. The frequency range 0.1 – 1.0 Hz is the natural frequency of more than 10 storey buildings. It can be easily seen that in the frequency range which will govern the design of buildings in Boko-Palashbari and Goalpara is 0.1-1.0Hz, while for Guwahati it is critical that buildings falling in the frequency range of 1.0-3.0Hz are likely to be affected more.

Additionally, Table 6.9 provides the various amplification parameters in terms of HVSR, PGA, PGV, PGD amplification respectively.

A comparison of the results of SSR (Table 5.13) and that of HVSR (Table 6.9) shows that the FAS amplification is of greater magnitude in case of SSR as compared to HVSR. However, PGA, PGV and PGD amplification can be considered broadly to be within the same range.
Table 6.7: Site Amplification in Frequency Range for Earthquake Events

<table>
<thead>
<tr>
<th>Earthquake Event</th>
<th>Peak Amplification in frequency range (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boko-Palashbari</td>
</tr>
<tr>
<td></td>
<td>0.1–1.0</td>
</tr>
<tr>
<td>25 Apr.2009</td>
<td>3.21</td>
</tr>
<tr>
<td>11 Aug.2009</td>
<td>5.15</td>
</tr>
<tr>
<td>19 Aug.2009</td>
<td>4.32</td>
</tr>
<tr>
<td>30 Aug.2009</td>
<td>3.42</td>
</tr>
<tr>
<td>03 Sep.2009</td>
<td>4.33</td>
</tr>
<tr>
<td>21 Sep.2009</td>
<td>3.78</td>
</tr>
<tr>
<td>29 Oct.2009</td>
<td>**</td>
</tr>
<tr>
<td>29 Oct.2009</td>
<td>**</td>
</tr>
<tr>
<td>29 Dec.2009</td>
<td>**</td>
</tr>
<tr>
<td>31 Dec.2009</td>
<td>**</td>
</tr>
<tr>
<td>26 Feb.2010</td>
<td>**</td>
</tr>
<tr>
<td>12 Mar.2010</td>
<td>**</td>
</tr>
<tr>
<td>26 Jul.2010</td>
<td>**</td>
</tr>
<tr>
<td>11 Sep.2010</td>
<td>**</td>
</tr>
<tr>
<td>21 Nov.2010</td>
<td>**</td>
</tr>
</tbody>
</table>

Table 6.8: Site Amplification Range in Frequency Range

<table>
<thead>
<tr>
<th>Site</th>
<th>Amplification range in frequency range</th>
<th>Peak Amplification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1–1.0 Hz</td>
<td>1.0–3.0 Hz</td>
</tr>
<tr>
<td>Boko–Palashbari</td>
<td>3.21–5.15</td>
<td>2.90–3.92</td>
</tr>
<tr>
<td>Guwahati-Central</td>
<td>1.51–3.32</td>
<td>2.16–3.81</td>
</tr>
<tr>
<td>Goalpara</td>
<td>4.68–7.60</td>
<td>3.04–6.11</td>
</tr>
</tbody>
</table>
Table 6.9: HVSR Results

<table>
<thead>
<tr>
<th>Site</th>
<th>Amplification Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak HVSR (Amplification)</td>
</tr>
<tr>
<td></td>
<td>PGA (PGA_{EW,NS} / PGA_{VT})</td>
</tr>
<tr>
<td></td>
<td>PGV (PGV_{EW,NS} / PGV_{VT})</td>
</tr>
<tr>
<td></td>
<td>PGD (PGD_{EW,NS} / PGD_{VT})</td>
</tr>
<tr>
<td>Boko –Palashbari</td>
<td>5.15</td>
</tr>
<tr>
<td></td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>4.40</td>
</tr>
<tr>
<td>Guwahati-Central</td>
<td>3.81</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
</tr>
<tr>
<td>Goalpara</td>
<td>7.60</td>
</tr>
<tr>
<td></td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td>3.67</td>
</tr>
<tr>
<td></td>
<td>6.56</td>
</tr>
</tbody>
</table>

6.7 SUMMARY

In this chapter, an introduction to HVSR analysis of strong motion is provided. HVSR analysis of three soil sites is carried out and the results presented. Also, determination of FF and bedrock depth is attempted from the results of HVSR analysis. Further, the results are provided in the form of peak HVSR ratio, PGA, PGV and PGD amplification respectively. Lermo and Chavez-Garcia (1993), Kudo (1995), Mucciarelli & Gallipolli (2001) etc. are a few of the studies which have reported that the HVSR method is known to be able to identify the fundamental frequency of a site under observation. It has been found in this study that the fundamental frequency range of the Boko-Palashbari site is 0.80 – 0.93 Hz; Guwahati-Central is 1.14 – 2.69 Hz and that of Goalpara is 0.63 – 0.82 Hz. DST (2008) has reported a fundamental frequency of 1.5 – 2.5 Hz which compares well with the results of present study. Further, basement depth obtained from HVSR method implies that Boko-Palashbari, Guwahati Central and Goalpara may have bedrock at depth ranging from 53.76-117.18m; 18.59 – 82.24m and 60.98 – 148.81m respectively. This range of values of
bedrock depth compares well with that of the bedrock depth of < 100m for Guwahati-Central and > 100m for Boko Palashbari and Goalpara respectively as given by the Litholog as given in Appendix B. Further, the site amplification of the western Guwahati region as per HVSR method can be ranged between 5.1. – 7.60.
REFERENCES:


[214]


vertical spectra of microtremors”, Proceedings of the 11th World Conference on Earthquake Engineering, Acapulco, Mexico.