CHAPTER 3: MICRO-SEISMIC STUDIES

3.1 Seismic Studies: A Theoretical Background

The term microtremor summarises all ground vibrations excluding event of short duration vibrations caused by earthquakes or explosions (Steinwachs, 1974). Microtremor studies were originated in Japan and have gained broad recognition in the study of site effect in earthquake ground motion (Kanai, 1957; Kanai and Tanaka, 1961; Nakamura, 1989; Seo, 1992; Lermo and Chavez-Garcia, 1993; Morales et al., 1993; Lermo and Chavez-Garcia, 1994; Arai and Tokimatsu, 2005). In recent years, microtremors have also been used in investigating shallow subsurface structure of a basin (Parolai et al.; Field et al., 1990; Field and Jacob, 1993; Ibs-von Seht and Wohlenberg, 1999; Al Yuncha and Luzon, 2000; Parolai et al., 2002; Zhao et al., 2007).

The frequency of seismic noise shows both temporal and regional variations depending on the influence of source and site. In case of thick unconsolidated sediment overlying the bedrock, the seismic waves give high mechanical contrast, where the upper unconsolidated sediment amplifies the seismic motion. The frequency of resonating waves in the unconsolidated upper layer is related to the velocity as well as the thickness of the sediment. Such site amplification can be estimated using an ambient noise method introduced by Kanai (1957). Several studies have shown that ambient seismic noise records reveal the fundamental resonant frequency of surface sediments (Ohta et al., 1978; Celebi et al., 1987; Lermo et al., 1988; Field et al., 1990; Hough et al., 1991; Konno and Ohmachi, 1998). To infer the site amplification characteristics from ambient noise, one however needs to remove source effect. Nakamura (1989) proposed a method to remove the source effect and estimate site response by dividing the horizontal component of the noise spectrum by the vertical component (H/V). Several modifications, shortcomings and applications of this method were studied thereafter (Ohta et al., 1978; Celebi et al., 1987; Lermo et al., 1988; Field et al., 1990; Hough et al., 1991; Lermo and Chavez-Garcia, 1993, 1994;

Konno and Ohmachi, 1998; Zhao et al., 2007). Several researchers have applied microtremor H/V spectrum for site investigation and measuring thickness of the top soil cover over the bedrock in Europe, China, Japan [Tertiary – Quaternary interphase: Yamanaka et al. (1994), Ibs-von Seht and Wohlenberg (1999), Delgado et al. (2000), Parolai et al. (2002), Garcia-Jerez et al. (2006), Zhao et al. (2007)] and mapping of regolith thickness over Archeans (Dinesh et al., 2010). In both the cases there is high mechanical contrast, however in former case the variation of Quaternary – Tertiary interphase in the basin is predictable, whereas regolith cover would have wide variation locally. Studies by Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) proposed equations relating the fundamental resonant frequency to the thickness of soft sediment cover (Quaternary sediments) from the observed well data and theoretical calculations. Ibs-von Seht and Wohlenberg (1999) investigated western Lower Rhine Embayment in Germany comprising a variable thickness of sediment belonging to Tertiary and Quaternary age. On the other hand, Parolai et al. (2002) investigated Cologne area in Germany comprising sediments of Quaternary and Tertiary age covering Devonian bedrock. In the recent work Dinesh et al. (2010) have derived an equation for the Archean meta-sediments and the overlying sediment cover at Bangalore City, India.

The present investigation is the first attempt to map the thickness of the Quaternary sediments in the lower reaches of Narmada valley located at the southern margin of Jambusar -Bharuch Block of Cambay Basin (Figure 3-), a potential hydrocarbon block in western India (Mukherjee, 1983) using microtremors. In the study area along the south eastern portion, the Tertiary sediments occur at shallow depths and are enveloped by unconsolidated thin layer of Quaternary sediment, whereas towards the northwest portion of the study area, the Tertiary sediments extend only in the subsurface (Rao, 1969; Agarwal, 1984; Ramanathan and Pandey, 1988). The only subsurface information regarding Quaternary-Tertiary contact in the lower reaches of Narmada Valley within the study area is estimated through cross profiles along Broach–Dadhal (Rao, 1969) as shown in Figure 3-.

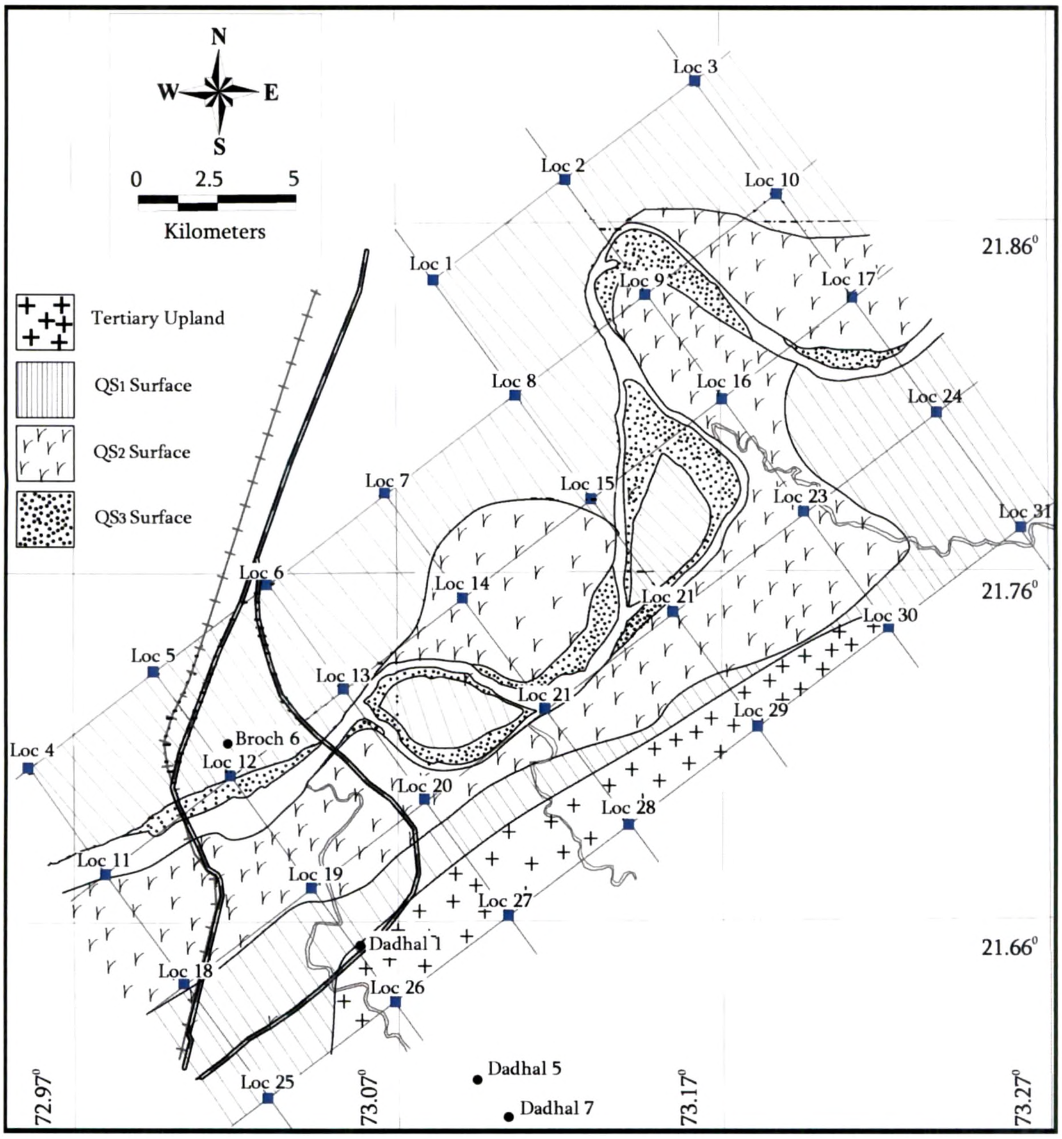


Figure 3-: Locations of Microtremor stations in the study area.

Further, the area has been investigated by different researchers in terms of mapping of the exposed sedimentary sequence, their depositional environment and neo-tectonic characteristics (Allchin and Hegde, 1969; Gadekar et al., 1981; Bedi and Vaidyanadhan, 1982; Sant and Karanth, 1993; Rajaguru et al., 1995; Bhandari et al., 2001; Chamyal et al., 2002; Bhandari, 2004b; Bhandari et al., 2005; Raj, 2007, 2008;

Raj and Yadava, 2009). However, the area still lacks information on variation in floor of Tertiary bedrock, thickness of Quaternary sediments and its relation with surface topography / landforms.

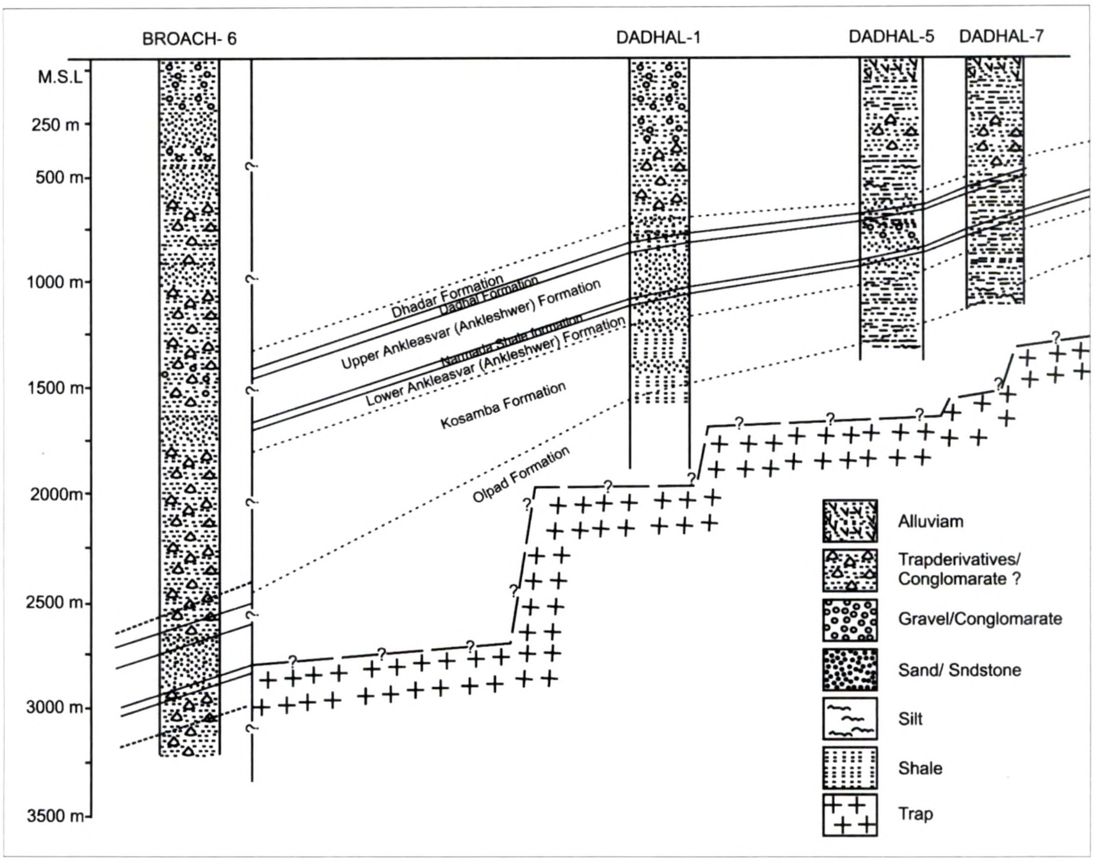


Figure 3-: Image showing borehole correlations from the available boreholes in the present study area (adopted from Rao (1969), Fig. 2, p. 27). See Figure 3-1 for location of boreholes.

3.1.1 Field Observations and Methodology

The lower reaches of Narmada exemplify various well preserved palaeo and neo landforms. In general the southern portion of the study area forms three surfaces, namely, QS_1, QS_2 and QS_3 (Section 2.2). The area poses flat to rolling topography with palaeobank and neobank as a paired landform which runs ENE-WSW direction from Rajpardi in east to Ankleshwer and further west of Bharuch. (Allchin and Hegde, 1969; Bedi and Vaidyanadhan, 1982; Mukherjee, 1983; Sant and

Karanth, 1993). The incised river channels have exposed a few meters to 40 m of Quaternary sediments belonging to QS_1.

An ENE-WSW trending reverse basin marginal fault, traverse through the southern boundary of the study area (Kaila et al., 1981). As a result, the basin marginal fault exposes Tertiary sequence immediately along the southern periphery. The structural studies on exposed Tertiary rocks suggest that they have undergone last deformation during Plio-Pleistocene time, resulting in development of several anticlines – syncline structures (Agarwal, 1986). Towards the north of the fault, the late Tertiary rocks form the bedrock for unconsolidated Quaternary sediments whose thickness varies depending on the late Tertiary – Early Quaternary topography.

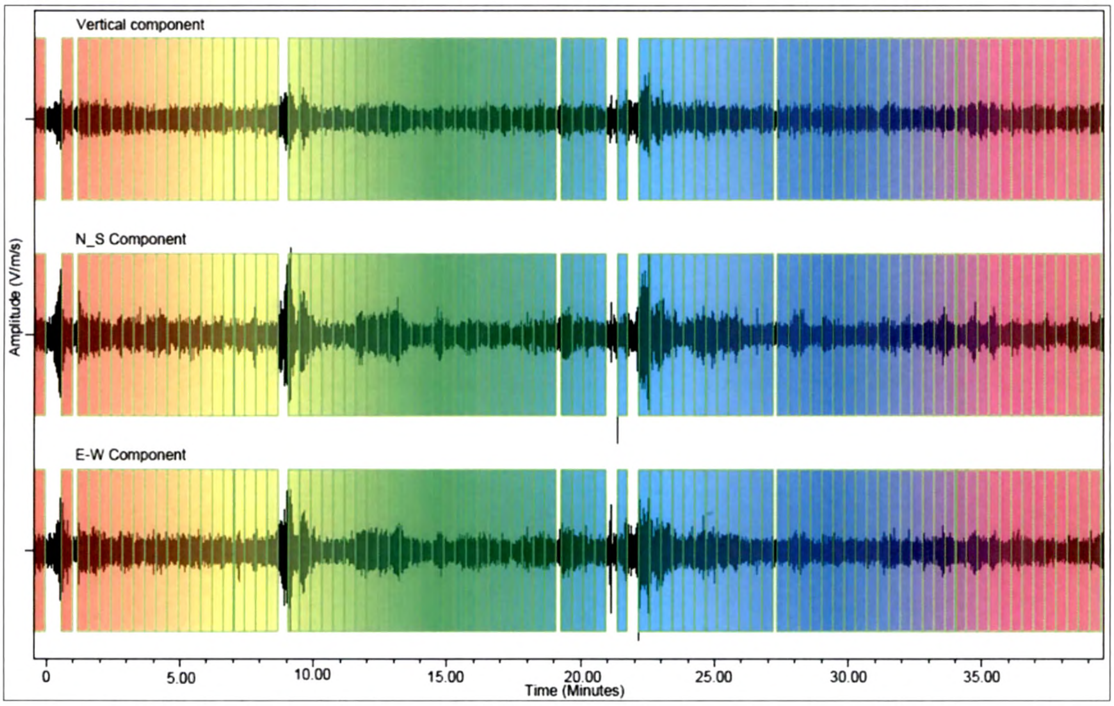


Figure 3-: An example of waveform recorded (Location 13) by Lennartz seismometer (5 s period) with City shark-II data acquisition system. X axis shows the time and Y axis shows the different components of amplitude viz. NS, EW and vertical.

The present study apply the seismic method using ambient noise to decode a two-layered model demarcating unconsolidated Quaternary sediment and the bedrock belonging to Tertiary age. The measurements using ambient noise were carried out using the Lennartz seismometer (5 second period) with City shark-II data acquisition system for 31 sites located on different landforms. The data acquisition was done in a gridded pattern at a resolution of 5 km covering an area of 470 sq. km that includes Tertiary high land surface in the south east to a flat flood plain towards North West (Figure 3-). The present study has acquired the microtremor data at 100 samples / seconds for each site. However, the frequency range between 0.2 Hz to 10 Hz has been analysed in the present study. The acquisition system records frequencies as three components viz. EW, NS and vertical vibration directions for time duration of 40 minutes (Figure 3-). The noise recordings were processed using GEOPSY software (http://www.geopsy.org/) to determine the fundamental resonant frequency after generating the H/V spectral ratio for each station (Figure 3- 4).

3.1.2 Theoretical Calculation

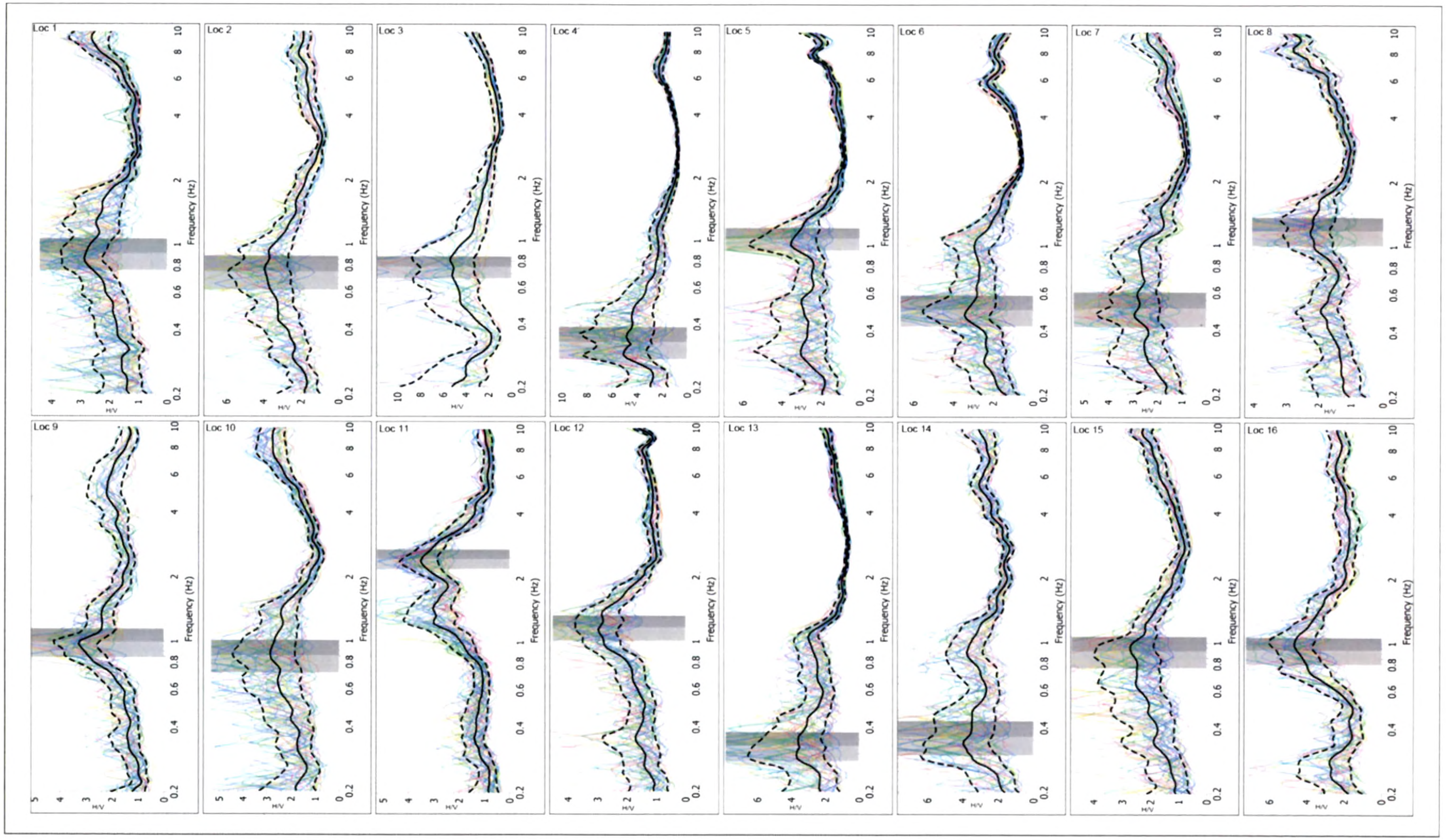
Theoretical estimation of the thickness (h) of the soil layer over the bedrock can be related to the fundamental resonant frequency (f_r) of H/V spectral ratio by an allometric function as given by equation 1 (Ibs-von Seht and Wohlenberg,1999),

$$h = a f_r^{b} \qquad (1)$$

Where,

a and *b* are the standard errors of the correlation coefficients.

The estimated terrain specific equation was justified studying Quaternary – Tertiary inter phase at western Lower Rhine Embayment (Ibs-von Seht and Wohlenberg, 1999; based on 34 boreholes ranging in depth from 15m to 1257 m and data from 102 seismic stations: equation 2A) and the Cologne area in Germany (Parolai et al., 2002; based on 32 boreholes having a depth of <402 m and 337data from seismic stations: equation 2B) simulating the thickness of soil cover (Quaternary sediments) above bedrock (Tertiary rocks).


Loc 1
Loc 2
Loc 3
Loc 4
Loc 5
Loc 6
Loc 7
Loc 8
Loc 9
Loc 10
Loc 11
Loc 12
Loc 13
Loc 14
Loc 15
Loc 16
Frequency (Hz)
H/V

Continue…

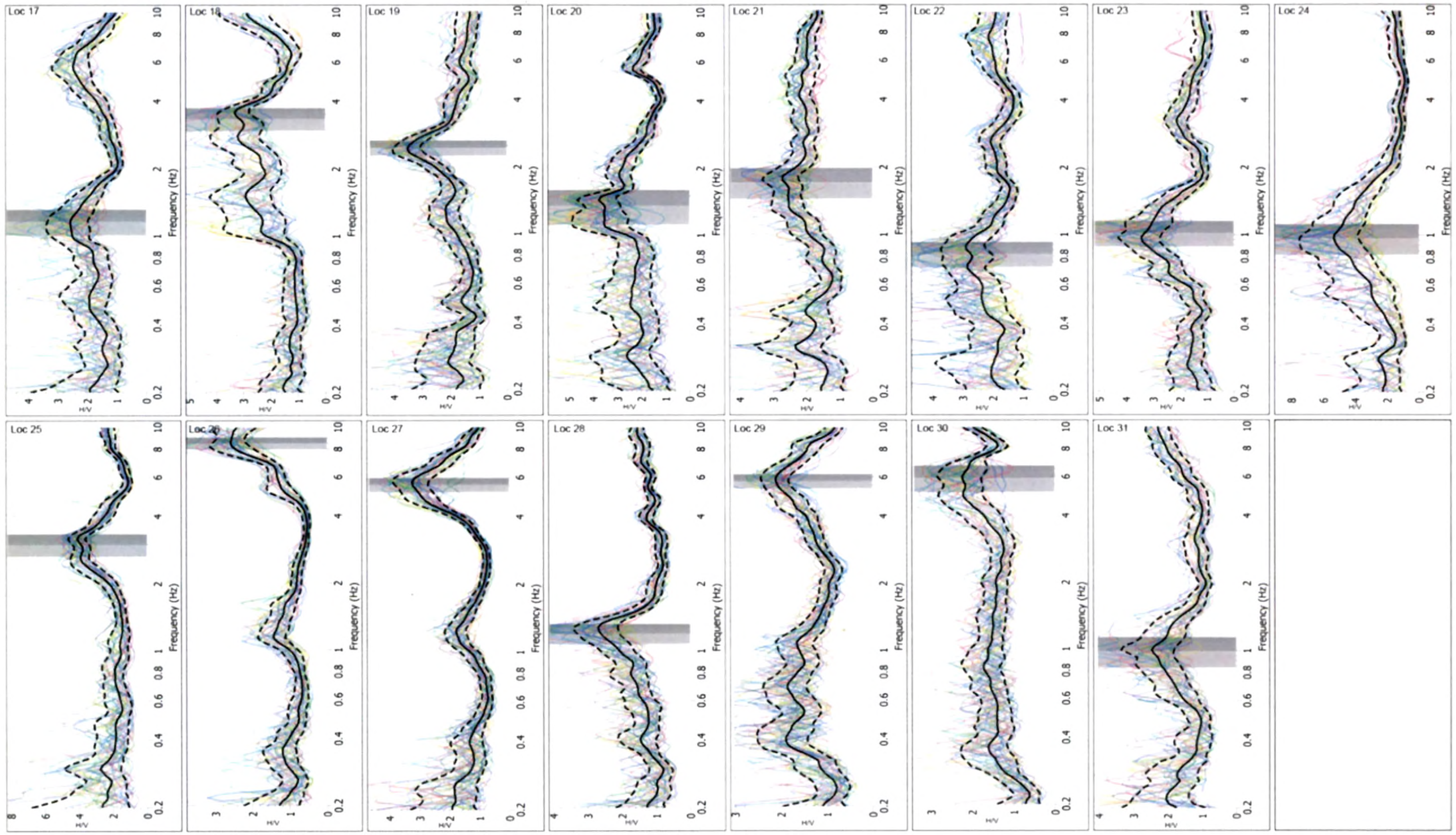


Figure 3-: H/V spectral ratio for 31 stations (frequency range 0.2–10 Hz). The coloured thin lines are H/V spectral ratio for different windows, black solid line is the average value and black dashed lines are ±standard deviation. The bar shows the fundamental frequency with two grey shades representing ±standard deviation.

Dinesh et al. (2010) derived terrain specific equation (Equation 2C) for the distinctly different terrain around Bangalore in India (inter phase of soil and regolith with metamorphic rock and granites).

$$\mathbf{h = 96\, f_r^{-1.388}} \qquad \mathbf{(2A)}$$

$$\mathbf{h = 108\, f_r^{-1.551}} \qquad \mathbf{(2B)}$$

$$\mathbf{h = (58 \pm 8.8)\, f_r^{(-0.95 \pm 0.1)}} \qquad \mathbf{(2C)}$$

To map Quaternary – Tertiary interphase in the lower reaches of Narmada valley; the present study adopt terrain specific equations by Ibs-von Seht and Wohlenberg, (1999), Parolai et al., (2002) and Dinesh et al., (2010). A theoretical thickness for the unconsolidated Quaternary sediment is calculated using the fundamental frequency (f_r) values of each station (Table 3-).

The underlying assumption to the present calculation is that the H/V spectral ratio depends primarily on the source / site characteristics rather the geographical location. Comparing the data estimated using the three equations; it has been observed that the variation of estimated depth is more in the case of Dinesh et al., (2010). The large deviation in the depths could be inferred due to the high mechanical contrast of between Archean meta-sediments and the overlying soil cover. While, the depths calculated using Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) show significantly low variations in the thickness due to the comparable geotechnical characteristics of geological formation. Further, the values of thickness obtained from Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) were compared for each station (Figure 3-). This analysis clearly brings out that the thickness calculated for H/V spectral frequency >0.5 Hz (26 data points) show an averaged standard deviation of 8 m in thickness, whereas the H/V spectra frequency <0.5 Hz (5 data points) show averaged standard deviation of 114 m in thickness. In other words, there is not much difference between results obtained using the above two equations.

Table 3-: Calculated thickness of unconsolidated sediments over Tertiary bedrock using equations of Ibs-von Seht and Wohlenberg (1999), Parolai et al. (2002) and Dinesh et al. (2010).

Loc. on Map	F (H/V) (Hz)	Thickness(m) Ibs-von Seht and Wohlenberg, 1999) $h = 96f_r^{-1.388}$	Thickness (m) (Parolai et al., 2002) $h = 108f_r^{-1.551}$	Thickness (m) (Dinesh et al., 2010) $h = (58\pm8.8)f_r^{(-0.95\pm0.1)}$
Loc 01	0.90	111.11	127.17	67.13
Loc 02	0.747	143.91	169.78	86.94
Loc 03	0.754	142.06	167.34	85.82
Loc 04	0.333	441.69	594.44	266.85
Loc 05	1.085	85.72	95.16	51.79
Loc 06	0.499	251.94	317.44	152.21
Loc 07	0.504	248.48	312.57	150.12
Loc 08	1.185	75.84	83.00	45.82
Loc 09	0.973	99.717	112.68	60.24
Loc 10	0.865	117.40	135.24	70.93
Loc 11	2.476	27.27	26.46	16.47
Loc 12	1.173	76.92	84.32	46.47
Loc 13	0.324	458.81	620.25	277.19
Loc 14	0.361	394.86	524.48	238.56
Loc 15	0.918	108.10	123.32	65.31
Loc 16	0.936	105.23	119.66	63.57
Loc 17	1.150	79.07	86.95	47.77
Loc 18	3.326	18.10	16.74	10.93
Loc 19	2.428	28.02	27.28	16.93
Loc 20	1.360	62.64	67.03	37.85
Loc 21	1.721	45.18	46.52	27.30
Loc 22	0.832	123.9	143.65	74.86
Loc 23	1.012	94.42	106.02	57.04
Loc 24	0.973	99.71	112.68	60.24
Loc 25	2.985	21.04	19.80	12.71
Loc 26	8.585	4.85	3.84	2.93
Loc 27	5.545	8.90	7.57	5.38
Loc 28	1.208	73.85	80.56	44.61
Loc 29	5.767	8.43	7.13	5.09
Loc 30	5.998	7.98	6.71	4.82
Loc 31	0.993	96.94	109.18	58.56

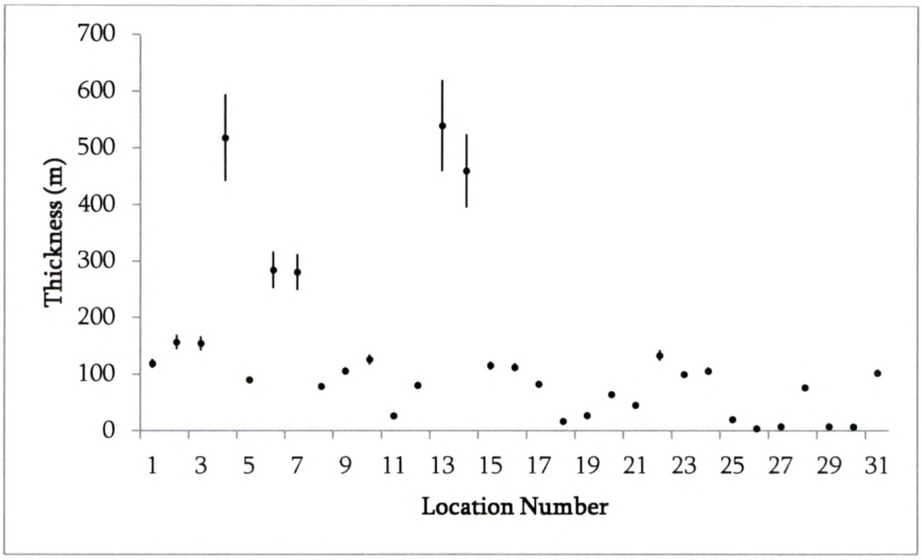


Figure 3-: Comparison between depths calculated using Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) relationships (Eqs. (2A) and (2B)). The circle indicates the average value whereas the length of the line suggests deviation from the average.

The study further averaged the values derived using equation 2A and 2B giving a best fit equation for the lower reaches of the Narmada valley (equation 3).

$$\bar{h} = 102.1\, f_r^{-1.47} \qquad (3)$$

The equation (3) is further used for deriving primary information on the relative depth variation of the interface between the two mechanically contrasting layers of Quaternary sediment (soil) and Tertiary rock (bedrock) in the study area (Table 3-).

3.1.3 Results and Discussion

The calculated values give a shallow interface of Quaternary and Tertiary sediments in the Ankleshwer and Rajpardi segment and deep in the Bharuch and Nareshwar segment. This observation is validated by correlation of wells across Narmada River (Figure 3-). The correlation profile shows a thick sediment cover at the Broach well. A thin cover of sediment inferred from the locations Loc 26, Loc 27, Loc 29 and Loc 30 validates occurrence of Tertiary rocks at observed shallower depth. However, the observed depth of 77 m at Loc 28 forms in the Tertiary bedrock indicates a local depression.

Table 3-: Relative variation of the thickness of Quaternary sediment cover at 31 locations which is further used for the elevation models.

Loc. on Map	Latitude	Longitude	Elevation (m)	F (H/V) (Hz)	Relative variation of average thickness (m) $\overline{h}= 102.1\ f_r^{-1.47}$
Loc 01	21.84895°	73.08142°	25	0.9	119.1451
Loc 02	21.8773°	73.12202°	22	0.747	156.85
Loc 03	21.90541°	73.1619°	25	0.754	154.70
Loc 04	21.71003°	72.95635°	28	0.333	518.06
Loc 05	21.73744°	72.99498°	24	1.085	90.44
Loc 06	21.7622°	73.02984°	18	0.499	284.69
Loc 07	21.78819°	73.0663°	20	0.504	280.52
Loc 08	21.81587°	73.1064°	36	1.185	79.42
Loc 09	21.84444°	73.14631°	23	0.973	106.20
Loc 10	21.87292°	73.18669°	34	0.865	126.32
Loc 11	21.67962°	72.98013°	19	2.476	26.87
Loc 12	21.70752°	73.01841°	19	1.173	80.62
Loc 13	21.7323°	73.05333°	23	0.324	539.53
Loc 14	21.75803°	73.09002°	15	0.361	459.67
Loc 15	21.78613°	73.12948°	23	0.918	115.71
Loc 16	21.81451°	73.16965°	20	0.936	112.44
Loc 17	21.84339°	73.20974°	20	1.15	83.01
Loc 18	21.64826°	73.00391°	11	3.326	17.42
Loc 19	21.67547°	73.04317°	17	2.428	27.65
Loc 20	21.70058°	73.07807°	14	1.36	64.84
Loc 21	21.72634°	73.11506°	12	1.721	45.85
Loc 22	21.75382°	73.15429°	17	0.832	133.78
Loc 23	21.78227°	73.19457°	14	1.012	100.22
Loc 24	21.8104°	73.23541°	33	0.973	106.20
Loc 25	21.61547°	73.0295°	29	2.985	20.42
Loc 26	21.64276°	73.06886°	25	8.585	4.3515
Loc 27	21.6674°	73.10354°	39	5.545	8.24
Loc 28	21.69308°	73.14048°	22	1.208	77.20
Loc 29	21.72093°	73.18014°	29	5.767	7.78
Loc 30	21.74903°	73.22044°	48	5.998	7.34
Loc 31	21.77744°	73.26117°	19	0.993	103.06

Calculated depth of the interface between the two layers (using equation 3) is used to plot cross-profiles and digital elevation model (DEM) for lower reaches of Narmada valley. Figure 3-A and Figure 3-B shows NW- SE and NE-SW cross-sections respectively. The NW-SE profile shows a gentle northerly slope of the consolidated bedrock viz. Loc 1-Loc 29, Loc 2-Loc 30 and Loc 3-Loc 31 profiles, whereas the profiles along Loc 4-Loc 25, Loc 6- Loc 27 and Loc 7-Loc 28 show steeper slope and increase in the unconsolidated sediment thickness.

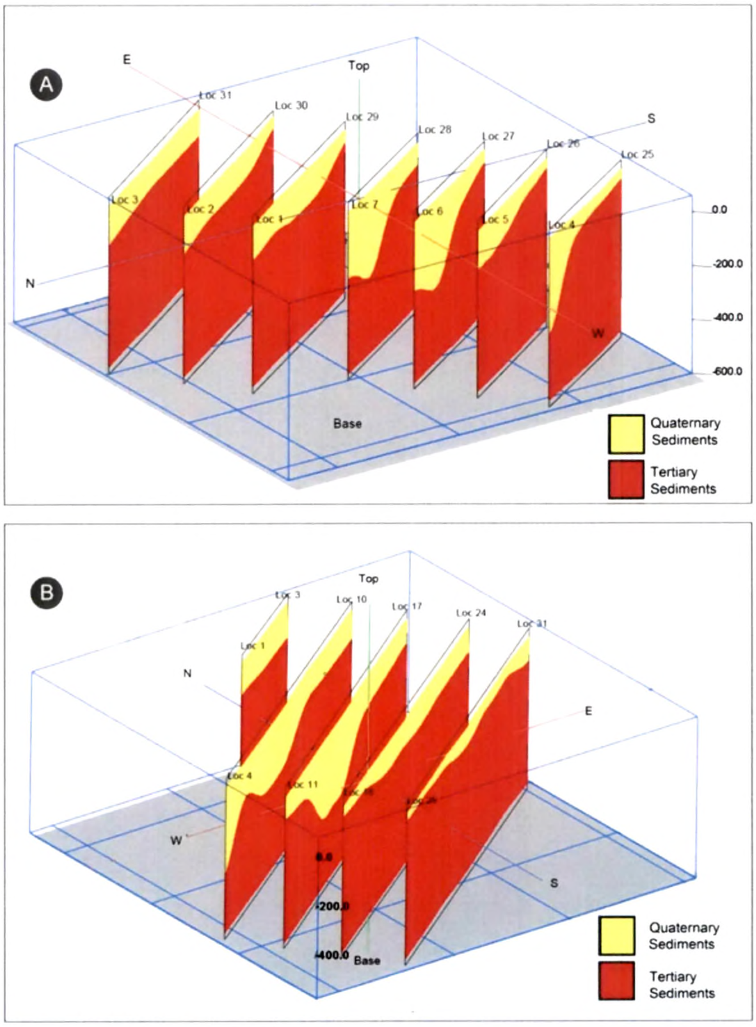


Figure 3-: Cross profiles showing the contact of unconsolidated soft sediment and consolidated bedrock variations of Quaternary sediments. (A) NW–SE profile and (B) NE–SW profiles.

The profile Loc 5-Loc 26 appears to form a ridge dividing depressions into two (Loc 4 and Loc 6). The variation in the depth of consolidated bedrock in the SW portion of the study area can better be appreciated along NE-SW profiles (Figure 3-B). The study of cross profiles implies linkages between the depo-centers and the source in the different direction. The DEM for the bedrock further reveals Late Tertiary – Early Quaternary palaeo-depressions (I) between Loc 6, Loc 7, Loc 13 and Loc 14 showing relative depth variations of 284 m, 280 m, 539 m, 459 m respectively and depression (II) Loc 4 reaching a depth of 518 m (Figure 3-).

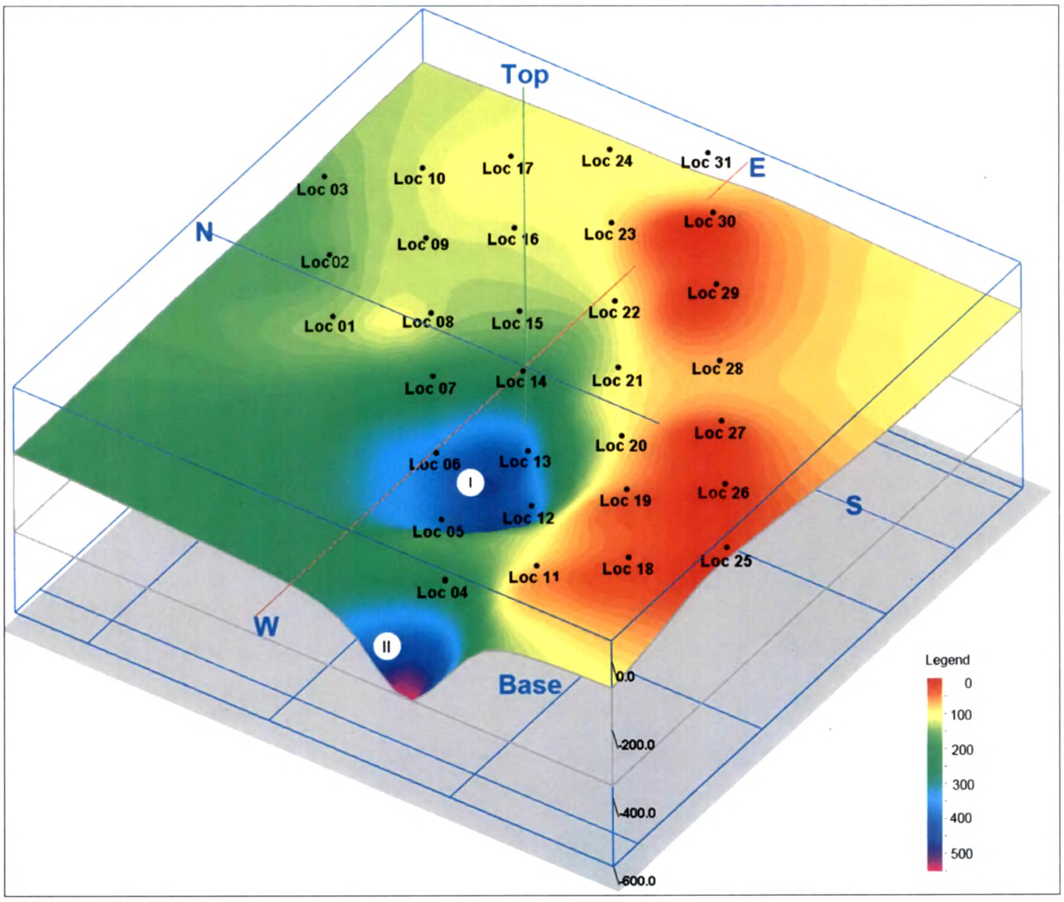


Figure 3-: Late Tertiary–Early Quaternary palaeo-topography of area under study in the lower reaches of Narmada valley. I and II are the depressions carved over Late Tertiary–Early Quaternary surface forming the sites of thickest Quaternary sediment in the study area.

Comparing the geomorphology with digital elevation model of the bedrock raises two possible explanations for the variation in the bedrock profile (Figure 3-). Firstly, the steeply dipping Tertiary rock between Loc 18 and Loc 23 is correlating with the surface expression of palaeobank. While the region connecting Loc 18, Loc 19, Loc 20, Loc 21, Loc 22, Loc 15 and Loc 14 shows control of shallow Tertiary rocks to the present braided channel of River Narmada. The profile connecting Loc 15 and Loc 12 suggest a steep channel gradient of River Narmada during late Tertiary – early Quaternary. The ridge formed by Loc 12 and Loc 19 between depression I and II may be correlated with thick gravel lobe exposed along the southern bank of Narmada (within locations 20, 21, 27 and 25) brought by transverse River system into the depression. Secondly, both the Quaternary depressions appear to be structurally controlled as they lie adjacent to ENE-WSW Cambay basin block fault identified along DSS profile (Kaila et al., 1981). High resolution H/V spectral records from the area would give detail variations that would help to resolve the role of process and structure.

3.2 Conclusion

The present study evaluates the usefulness of the H/V spectral ratio of microtremor investigations. This is a relatively quick, easy and economic method for estimating the thickness of unconsolidated sediments for a given terrain. An equation for a geologically comparable terrain can be recalculated using the average values of Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) records of H/V measured from the terrain.

The lower reaches of Narmada Valley where estimation of Pre-Quaternary topography has been difficult due to its wide variation has now been profiled using a nonlinear regression equation ($\bar{h} = 102.1 f_r^{-1.47}$). Two significant Quaternary depo-centres have been outlined in the lower reaches of Narmada valley. The present discovery is significant as it lies adjacent to ENE-WSW Jambusar - Bharuch margin fault where the presence of shallow gas reservoirs is being exploited.