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Site Response Evolution and Sediment Mapping Using Horizontal to Vertical Spectral Ratios (HVSR) of Ground Ambient Noise in Jammu City, NW India

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Abstract: The technique of ground ambient noise (micro tremor) measurement and analysis has been successful for site characterization in many places around the world. This technique has the advantage of being a fast and easy way to estimate the effect of ground motion characteristics due to an earthquake. Single station ground ambient noise (micro tremor) measurements were carried out at 136 sites in the municipal limit of Jammu city, NW Himalaya. This extensive survey allows the estimation of fundamental resonance frequencies (0.432 to 7 Hz) of the region and identifies the areas prone to site amplification. The thickness of the soft sediments has been derived using empirical relationship that comes out to be 14 to 295 mts above the bedrock. The results are in good agreement with the 1-D profile derived using MASW measurements from representative sites. The resonance frequency and sediment thickness is in good agreement with the geological distribution of sedimentary units, indicating a progressive decrease of the fundamental resonance frequencies from the northeastern part (where the bedrock outcrops is exposed) to the southwestern and southern side where a thick sedimentary cover is estimated.

Keywords: Himalaya, Resonance frequency, HVSR, Soil thickness, Seismic microzonation, Jammu city.

INTRODUCTION

Many of the fastest growing cities in the Himalayan foothills are located where the narrow valleys with the carving rivers open up and the river flow becomes gentle and the sediments are deposited in larger fans. The increasing urbanization and population growth in frontal part of Himalaya is a major concern for earth scientists, as this growth is rarely recognizing the possibility of future damaging earthquakes. These Himalayan foothills are also characterised by the presence of active tectonic features i.e. Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT) and the Jammu city lies in between these two active tectonic thrusts. The western part of the city is characterised by seismically active Kashmir syntaxis and Hindukush Himalaya whereas eastern side of the city is characterised by Chamba-Kangra zone. During the last three centuries the Jammu city had experienced shaking from number of earthquakes which occurred either in Kashmir syntaxis/ Hindukush region or in Chamba-Kangra zone. The well known and historical earthquakes are: Kashmir valley earthquakes 1552 (Ms 7.5); 1554 (Ms 7.7); 1662 (Ms 7.5); 1784 (Ms 7.3); 1778 (Ms 7.7); 1884 (Ms 7.3); 1885 (Ms 7.0) and recent one 2005 (Ms 7.6) Kashmir valley earthquakes, 1905 (Ms 7.8) Kangra earthquake and 1945 Chamba earthquake (Mb 6.5) (Ambreseys and Douglas, 2004). These earthquakes significantly shook the residents of Jammu city. These events were, however, far from a pending large earthquake in the ‘central seismic gap’ (Khattri, 1999). Ram and Ram (2001) estimated a return period for an M=8 or larger to be around 130 years in the gap. According to the seismic zonation map of India Jammu region falls under seismic zone IV and V, thus needed to be considered for site response studies and to find the thickness of soft sediments.

Site amplification is an important factor that controls the damage in urban areas during moderate to severe earthquake. Such studies have been carried out in different cities located in the frontal Himalayan foothill zone by different authors (Mundepi and Kamal, 2006; Kamal and Mundepi, 2007; Mundepi, 2008; Mundepi et al. 2009; Mahajan et al. 2008). There are numerous examples of soil amplifications but only three examples to mention i.e. Northridge (Trifunac and Todorovska, 2000), San Francisco (Ohmachi et al. 1991) and the most famous, Mexico (Singh et al 1988). Basically, site amplification effects are associated with the phenomenon of the seismic waves propagation into soft soil layers. It is explained by the lower velocity and density in the unconsolidated sedimentary layers relative to the underlying basement rock. The shape, degree and frequency of wave amplification depend on the geometry and physical properties of the subsurface structure, and the degree of complexity of predicting a seismic response increase with the complexity of the structure.

Considering the presence of thick sediment cover and the geo-tectonic condition of the Jammu city, the site response of different sites are estimated using two different techniques, i.e. MASW (Multichannel Analysis of Surface Waves) and HVSR (Horizontal to Vertical Spectral Ratio). Both the techniques have complemented in finding the thickness of the sediments and its effect on the site response during an earthquake.

GEOLOGICAL SETUP

The expanding city of Jammu lies at the foothills of Siwaliks, built over a thick sedimentary basin comprising unconsolidated Quaternary sediments of Jammu Formation, older and newer alluvium (Fig.1). Main Boundary Thrust (MBT) bounds it in the north, where rocks of Lesser Himalayan zone over ride the Tertiary rocks of Siwalik Group. Himlayan Frontal Thrust (HFT) marks the southern part of Jammu city where the rocks from Siwalik Group over ride the recent alluvial sediments**.** The study area of Jammu city has been divided into three zones; the southwestern zone (comprises of alluvium), the south-eastern, central and the northwestern zone (comprises of boulder conglomerate formation; Upper Siwalik) and the northeastern zone (comprises of Nagrota Fm; Upper Siwalik). River Tawi divides the Jammu city into two parts i.e. the northwestern and southeastern parts. Thick accumulation of sediments is observed in the southern part of the city. Thick sediments cover underlying Jammu city (southern part of the city) can potentially amplify the earthquake shaking, whereas the central part of the city has thinner sedimentary cover that can have impedance contrast effect.

METHODOLOGY, DATA ACQUISITION AND PROCESSING

HVSR Technique

The horizontal to vertical spectral ratio (HVSR) of ground ambient noise has been used as a proxy for particle orbits of Rayleigh waves (Nogoshi and Igarashi, 1971) and hence the natural frequency of each site. This was popularized as Nakamura's method (Nakamura, 1989), who demonstrated that the ratio between horizontal and vertical ambient noise records is related to the fundamental frequency of the soil beneath the site and hence to the amplification factor. The consensus is that this method will show the natural frequency of a site, but there are differing views on whether HVSR peak heights can show site amplification. In the ideal case of a pure Rayleigh wave, the HVSR would increase without limit at the site frequency depending on soil properties, but for a real case, the presence of some other vertical signal at that frequency will limit the height of the HVSR peak. From this perspective, the HVSR peak height will merely show in some sense what proportion of the micro tremors is due to fundamental mode Rayleigh waves. However, it has been shown that in Thessaloniki city damage increased as the frequencies of HVSR peaks decreased and increased as the heights of HVSR peaks increased (Theodulidis et al. 2004). The later result is encouraging because it implies that as soils get softer and deeper, it shows higher HVSR values and the damage associated with earthquake shaking increases. The scientific community does not unanimously accept this theory and hypotheses but comparisons with other techniques have proven the validity and efficiency of the method (Lermo and Chavez-Garcia, 1994).

Many experiments (Lermo and Chavez-Garcia, 1993; Gitterman et al. 1996; Seekins et al. 1996; Fah et al. 1997) supported by several theoretical 1D investigations (Field and Jacob, 1993; Lachat and Bard, 1994; Lermo and Chavez-Garcia, 1994; Wakamatsu and Yasue, 1996; Tokeshi and Sugimura, 1998; Nakamura, 2000; Bonnefoy-Claudet et al. 2006) have shown that ambient noise (H/V spectral ratio) is sharply packed around the fundamental S-wave frequency, if the upper layers have a sharp impedance contrast with the underlying stiffer layers.

The main advantages of HVSR method are that it is simple and involves low cost measurements, which can be performed at any time and any place, and direct estimate of sediments resonance frequency/ period without knowing geological and S-velocity structure of the underground. Any knowledge of thickness or/and velocity of sediments and comparison with other methods and earthquake damage can significantly improve the reliability of the results (Bard, 1999).

During the field season of November - December 2007 micro tremor data were collected at 136 sites of Municipal region of Jammu (Fig.2). The micro tremor measurements were taken using velocity transducer, Guralp CMG-40T-1 (1s to 100 Hz) and 24 bit DM24-S3 digitizer at sample rate of 100 sample/sec. About 45 minutes to 1 hour of seismic

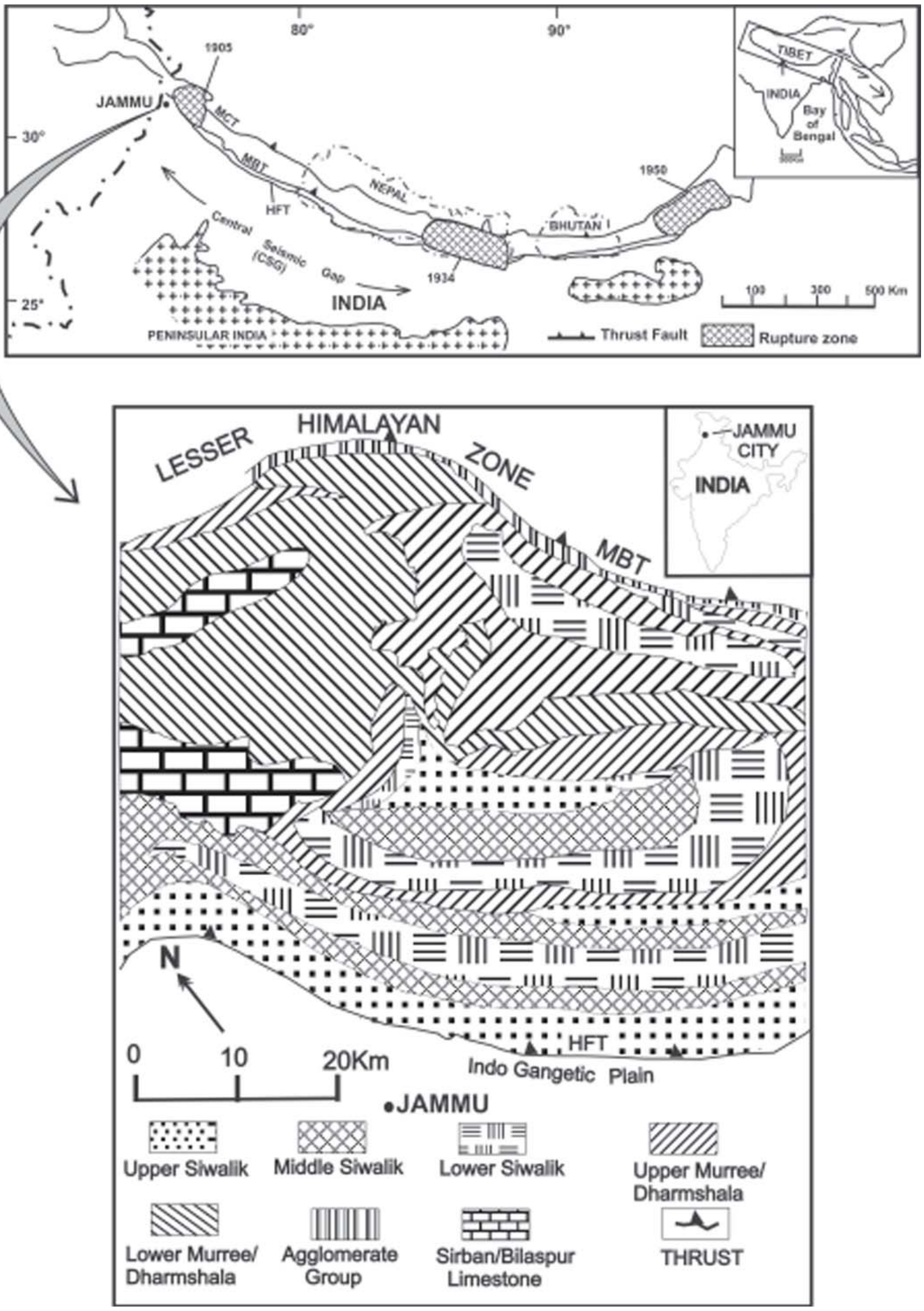

Fig.1. Geological map of Jammu region (*after* Raiverman et al. 1983) and regional tectonic framework with major rupture zones in Himalayan belt (modified after Seeber and Armbruster, 1981).

noise was recorded at each station. The location of each site was determined by using GPS receivers.

First of all the data were visually analyzed to remove singularities, if any. All three-component data were collected in Guralp Compress Format (GCF), which is transformed into Simple Alignment Format (SAF). The data processing was done with the GEOPSY software. In this study the H/V ratio is calculated using 40 to 50 windows of 60 second. Fourier amplitude spectra are smoothed following Konno and Ohmachi (1998). The quadratic means of the horizontal amplitude spectra is used in the study. The final H/V ratio was obtained by averaging the H/V ratios from all windows (SESAME, 2004).

For each site, the average resonance or fundamental frequency was determined as the mean value obtained from all the processed noise windows. In summary, it implies that an estimate of the soil response at a site can be obtained by recording ambient noise with a single 3-components

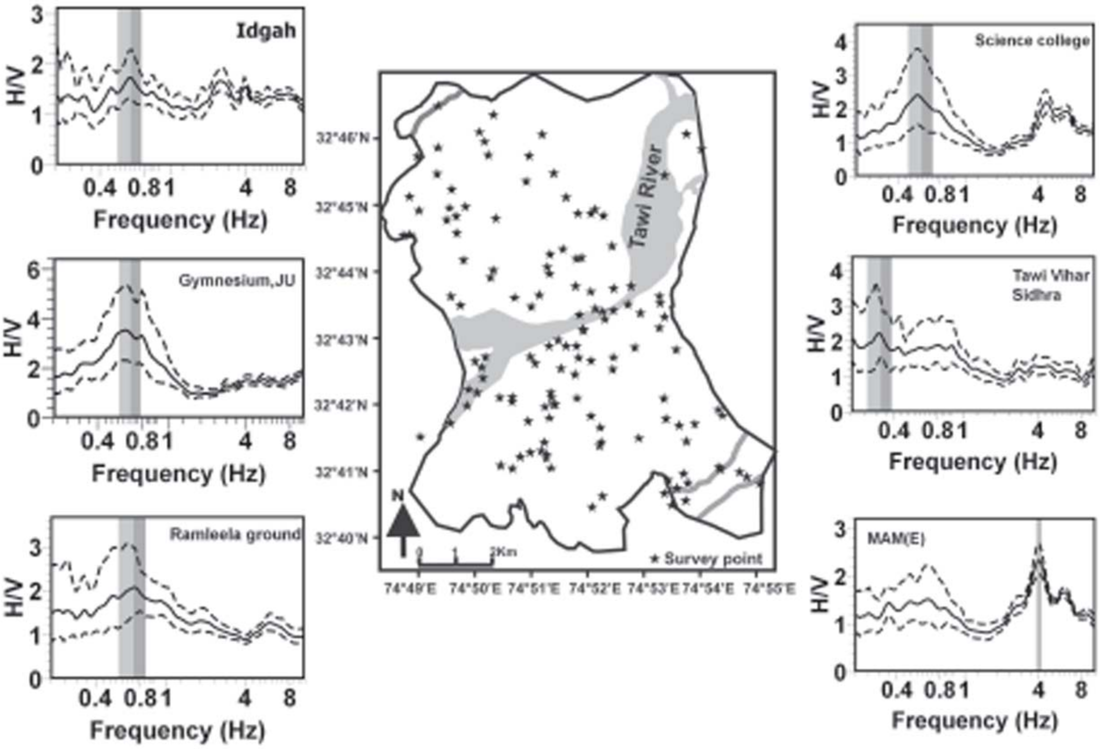

Fig.2. Location of HVSR sites (star) in the Jammu with representative HVSR plots. The solid line, upper and lower dashed line represent average, median and standard deviation of H/V spectral ratio, respectively.

seismometer. Field experience has shown that 30 to 45 minutes of records per site are long enough to record stable results in various urban environments.

MASW Technique

The methodology for carrying out such investigations has been developed by Mahajan et al. (2007), for Dehradun city. The data in Jammu city was acquired using seismodule controller software of Geometrics Inc. USA. About 30 sites were selected in the Jammu city where data were acquired along a linear transect using a 24-channel seismograph (Geode) unit with 4.5 Hz spike based geophones spaced 1m apart along the profile lines. A 40 kg weight drop hammer as a source and a small rectangular (12×12 inch) metal plate was used as a strike plate to maximize the energy transfer between weight drop and the ground. The basic field configuration in MASW with roll along technique is generally the same as used in conventional CMP method (Park et al. 1999; Mahajan et al. 2007). The technique was used to achieve a continuous multiple shot gatherer along a linear survey line by moving both the source and the receiver in incremental manner (Mahajan et al. 2007). Then, data was processed using SurfSeis software developed by Kansas Geological Survey (KGS), USA which facilitates the use of MASW (Xia et al. 1999). First the raw field data in SEG-2 format was converted to KGS format that combines all the shot gather into a single file for further processing. Then pre-processing was done, that marked the upper and lower limit for the apparent phase velocity. Muting was also carried out to filter out the unwanted signal and hence enriched the surface wave signal. Frequency range, velocity range, apparent phase velocity and type of algorithm etc are some of the important parameters, to be fixed prior to dispersion analysis. The dispersion analysis resulted in the generation of a dispersion curve (phase frequency verses phase velocity) for each geophone station. Once all the dispersion curves were generated, they were further inverted to generate a 1-D Vs (average shear wave velocity) profile using the inversion algorithm given by Xia et al. (1999). These 1-D Vs profiles were interpolated to generate a 2-D Vs profile of each site.

RESULTS AND DISCUSSION

The site effect of any area is the complex result of a number of factors, such as the material properties, the subsurface topography, the depth to the water table, the amplification and the duration of the impinging seismic waves at the base of the soil column. Most significant among these factors is the impedance contrast and the geometry between the bed rock and the overlying sediments.

A zone of ~50 km^2 (approximately) was mapped using records from the 136 sites with the spacing interval of 100 - 400 meters in the Jammu region (Fig. 2). According to the experiment, the shear wave velocity derived for different sites have been compared with the Vs profiles, ID site derived using MASW technique, and finally fundamental frequencies of each site using HVSR have been estimated. The fundamental frequencies estimated ranges 0.432 to 7.29 Hz (Fig. 3). The areas with less thickness of sediments for e.g. MAM College shows higher frequency as compared to areas with higher thickness of sediments that are prone to seismic amplification for e.g. JKPS Kunjwani (Fig.4).

These Vs profiles derived using MASW technique shows lateral and vertical variation in shear wave velocity. According to Vs profiles, the city could be divided into three main classes as per NEHRP classification i.e. class ‘E’ (< 180 m/s) in the southeastern and northwestern part, and class ‘C’ (360-760 m/s) in the central part and major part of the Jammu city that falls in class ‘D’ (360-180 m/s). Using strong motion data of given magnitude (6.8 mb) for Himalayan region assuming that the site is located 100 km from epicentral region, site response and natural period of each site column has been calculated and the maximum response evaluated ranges from 1.5 Hz to 3.3 Hz.

The average shear wave velocity (Vs) computed observed using MASW technique in the region is ~ 350 m/s (Mahajan et al. 2008). An effort has also been made to estimate the thickness of sediments through a simplified approach. Assuming a single layer over half space model, the average sediment thickness can be estimated from the equation 1.

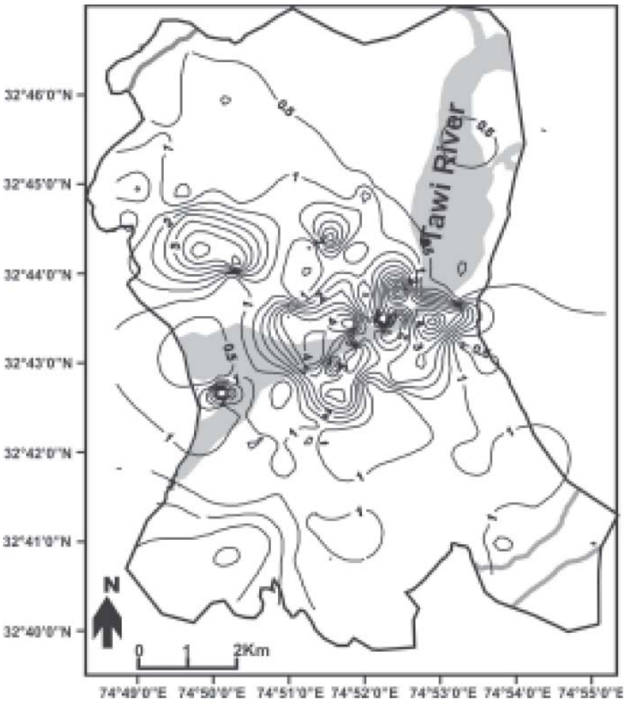

Fig.3. Contour map of resonance frequency obtained from HVSR.

$$H= V_{av}/4*f_{H/V} \qquad (1)$$

Where, V_{av} is Average shear wave velocity (Vs); H is the layer thickness; f is the fundamental resonance frequency (Bard, 2000). For a V_{av} = 350 m/s (estimated to be a fair

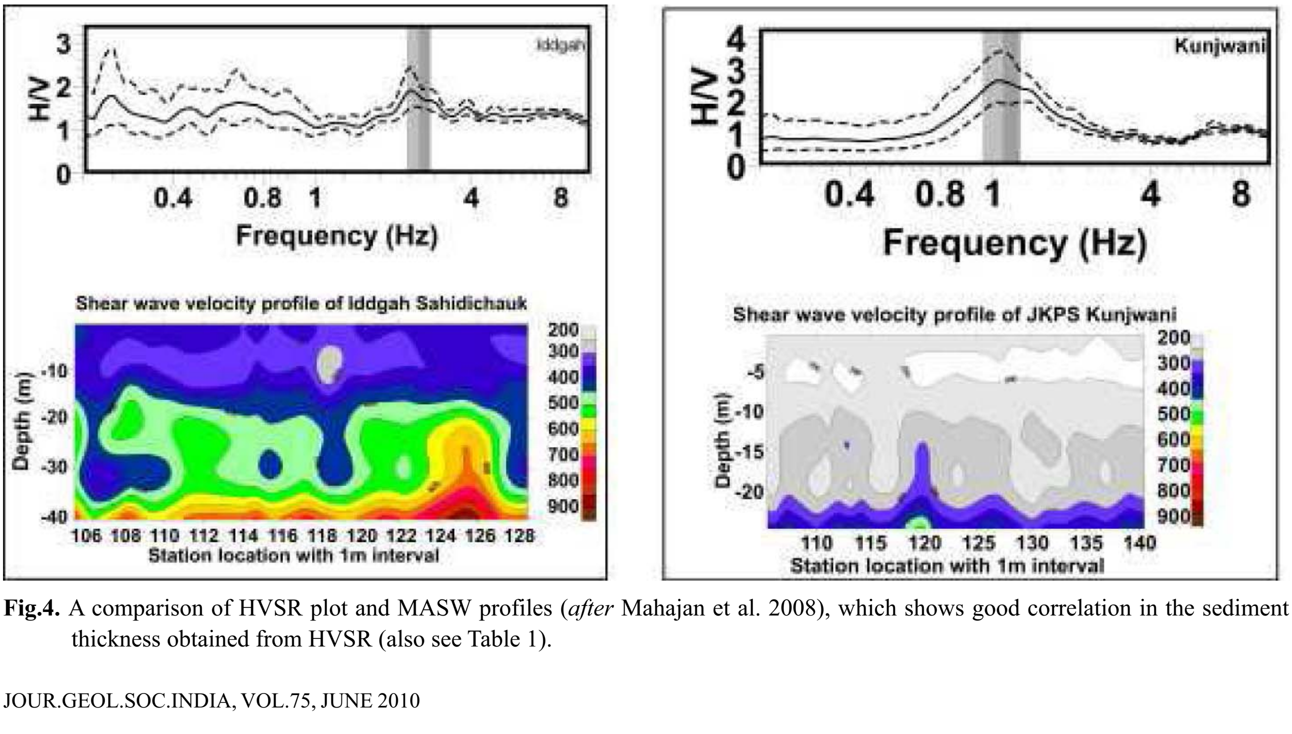

Fig.4. A comparison of HVSR plot and MASW profiles (*after* Mahajan et al. 2008), which shows good correlation in the sediment thickness obtained from HVSR (also see Table 1).

Table 1. MASW (Seismic refraction) data on thickness and S-velocity of sediments and comparison of HVSR peak fundamental frequency with calculated thickness for single layer

Location	HVSR $f_{H/V}$	MASW		HVSR $f_{H/V} = Vs/4h$ Thickness (h)
		Thickness (h)	S-Velocity (Vs)	
Idgah	2.52	33.41	297	34.72
Govt. Women College	4.12	23.92	299	21.25
G.G.H.School	3.64	27.45	289	24.04
JKPS	4.2	19.75	158	20.76

average estimate for the clay, silt and sand sediment) and f = 2.52 Hz, the value of H turns out to be 34.72 m. Comparison of thickness obtained from the MASW (seismic refraction) and frequency of HVSR calculated by empirical relationship were found in good correlation (Table 1).

This is an average estimate of the sediment thickness based on the observed resonance frequency and an average shear-wave velocity underneath Jammu based on the assumption of an underlying 1D model. Using the average shear wave velocity (Vs) structure for the city (Fig.5), the soil thickness in Jammu has been computed using this empirical relationship (equation-1) (Fig. 6). This leads to very large variation in the sediment thickness over short distances, which would result in 2-D and 3-D effects of the basin response in which case the distinct resonance frequencies may differ from the herein found average Nakamura estimate (Bard, 2000).

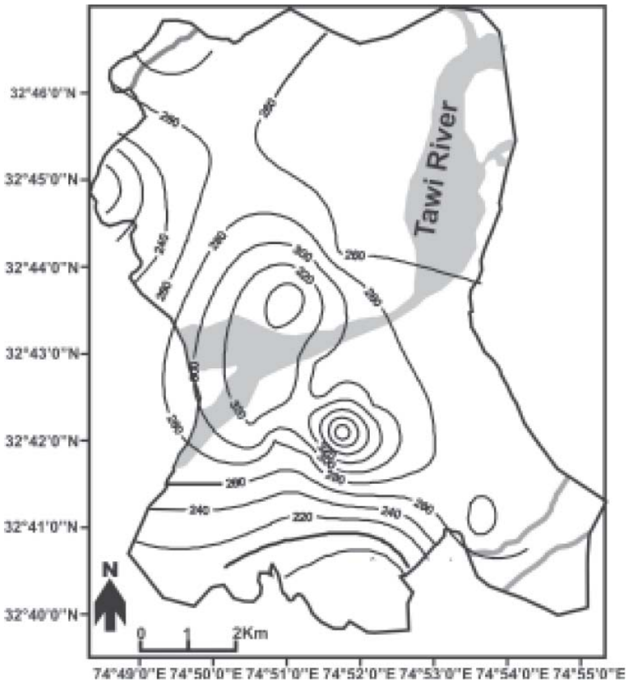

Fig.5. Contour map of shear wave velocity obtained from MASW (*after* Mahajan et al. 2008).

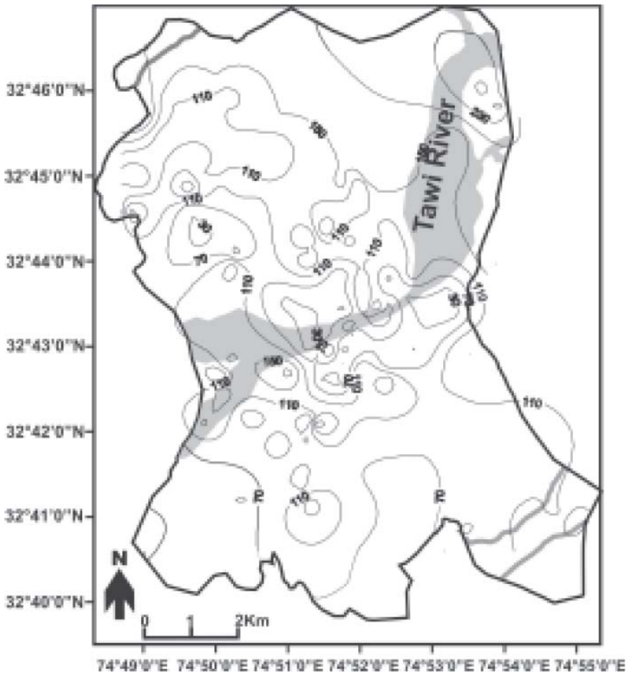

Fig.6. Contours map of sediment thickness below ground level obtained using empirical relation.

CONCLUSION

In the present study, we have applied the H/V ambient noise methodology to estimate the resonance frequencies for the sediment basin underlying the city of Jammu. Some of these sediments are soft soils, but the exact distribution and thickness is unknown due to non-availability of subsurface geometry data. The H/V ratios of micro tremor were used to determine the distribution of resonance frequency of these soils, which range from 0.432 to 7.29 Hz, and subsequently applied in a simple test model for establishing a sediment thickness, which ranges from 14 to 295 mts. We have used the resonance frequency to obtain an estimate of sediment thickness without disturbing the ground.

The Nakamura technique is widely used for determination of predominant frequencies of geological sites, and a fairly large area could be surveyed in a relatively short time with limited resource spending. In the absence of a high resolution subsurface model for Jammu, the herein established model for soil thickness and resonance frequencies may serve as a first very simple approximation that can and should be challenged in more detailed investigations in the future.

No estimate of non-linear behaviour of the soils under strong shaking can be given by the Nakamura method. The H/V technique is recognized as a fast and inexpensive way to estimate the fundamental frequency of resonance of soil sites but we have refrained from using the amplification factors beyond being indicative of a resonance frequency. The interpolation of these results has allowed us to draw up a map, which reflects the spatial distribution of the soft sediments in the study area in term of the resonance frequency. The H/V method may be easily applied in subsequent detailed studies and future investigations in this direction would greatly benefit from more geotechnical information that will allow for the establishment/ rejection of a correlation with results from the H/V technique.

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References

Ambraseys, N.N. and Douglas, J. (2004) Magnitude calibration of north Indian earthquakes. Geophys. Jour. Internat., v.159, pp.165-206.

Bard, P.Y. (1999) Micro tremor measurements: a tool for site effect estimation? Proc. 2nd Internat. Symp. Effect of Surface Geology on Seismic Motion. Yokohama, Japan. pp.1251-1279.

Bard, P.Y. (2000) Lecture notes on 'Seismology, Seismic Hazard Assessment and Risk Mitigation'. International Training Course, Potsdam, p.160.

Bonnefoy-Claudet, S., Cornou, C., Bard, P.Y., Cotton, F., Moczo, P., Kristek, J. and Fäh, D. (2006) H/V ratio: a tool for site effects evaluation: results from 1D noise simulations, Geophys. Jour., v.167(2), pp.827-837.

Fah, D.J., Ruttener, E., Noack, T. and Kruspan, P. (1997) Microzonation of the city of Basle. Jour. Seismology, v.1, pp.87-102.

Field, E.H. and Jacob, K.H. (1993) The theoretical response of sedimentary layers to ambient seismic noise. Geophys. Res. Lett., v.20, pp.2925-2928.

Gitterman, Y., Zaslavsky, Y., Shapira, A. and Shtivelman, V. (1996) Empirical site response evaluations: case studies in Israel. Soil Dynamics and Earthquake Engineering, v.15, pp.447-463.

Kamal and Mundepi, A.K. (2007) Site response studies in Dehradun city: First step towards seismic microzonation. *In:* O.P. Verma, A. K. Mahajan and V. Gupta (Eds.), Natural Hazards. Spec. Vol. of IGC), pp.175-181.

Khattri, K.N. (1999) An evaluation of earthquakes hazard and risk in northern India. Himalayan Geol., v.20, pp.1-46.

Konno, K. and Ohmachi, T. (1998) Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremors. Bull. Seismological Soc. Amer., v.88, pp.228-241.

Lachet, C. and Bard, P.Y. (1994) Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique. Jour. Physics Earth, v.42, pp.377-397.

Lermo, J. and Chavez-Garcia, F.J. (1993) Site effect evolution using spectral ratios with only one station. Bull. Seismological Soc. Amer., v.83, pp.1574-1594.

Lermo, J. and Chavez-Garcia, F.J. (1994) Are microtremor useful in site response evolution. Bull. Seismological Soc. Amer., v.84, pp.1350-1364.

Mahajan, A.K., Mundepi, A.K. and Chauhan, Neetu (2008) Shear wave velocity investigations in Jammu city- a step towards microzonation. International Symposium on Mountain Building and Climate-Tectonic Interaction. Wadia Institute of Himalayan Geology, Dehradun. October 23-25, 2008. Himalayan Geol., v.29(3), 48p.

Mahajan, A.K., Sporry, R. J., Champati Ray, P.K., Ranjan, R., Slob, S. and Westren, C.J. (2007) Development of methodology for site response studies using Multichannel analysis of surface waves (MASW) technique in Dehradun city. Curr. Sci., v.92(7), pp.945-955.

Mundepi, A.K. (2008) Site Response studies using horizontal to vertical ratio in the city of Chandigarh, North India. Himalayan Geol., v.29(1), pp.87-93.

Mundepi, A.K. and Kamal (2006) Effective soft sediment thickness in Dehradun city (India) using ambient vibrations. Himalayan Geol., v.27(2), pp.183-188.

Mundepi, A.K., Lindholm, C. and Kamal, (2009) Soft soil using Horizontal to Vertical Spectral Ratio (HVSR) for seismic hazard assessment of Chandigarh City in Himalayan foothills, North India. Jour. Geol. Soc. India, v.74, pp.551-558.

Nakamura, Y. (1989) A method for dynamic characteristics estimation of sub surface using microtremor on the surface. Railway Technical Research Institute Report. pp.3025-3033.

Nakamura, Y. (2000) Clear identification of fundamental idea of Nakamura's technique and its application. Proceedings of the XII World Conf. Earthquake Engg., Auckland, New Zealand, 8p.

Nogoshi, M. and Igarashi, T. (1971) On the Amplitude Characteristics of Microtremor. Jour. Seismological Soc. Japan, v.24, pp.26-40.

Ohmachi, T., Nakamura, Y. and Toshinawa, T. (1991) Ground motion characteristics the San Francisco Bay area detected by microtremor measurements. Proc. 2nd Internat. Conf. on Recent Advances in Geotechniques, Earthquake Engineering and Soil Dynamics. San Louis, Missouri. 11-15 March, pp.1643-1648.

Park, C.B., Miller, R.D. and Xia, J. (1999) Multichannel Analysis of Surface Waves (MASW). Geophysics, v.64, pp.800-808.

Raiverman, V., Kunte, S.V. and Mukherjea, A. (1983) Basin geometry, cenozoic sedimentation and hydrocarbon prospects in North Western Himalaya and Indo-Gangetic plains. Petroleum Asia Jour., v.6, pp.67-92.

Ram, S.C. and Ram, A. (2001) Estimation of average return period for large earthquakes in north-west India. *In:* Proc. Workshop on recent earthquake of Chamoli and Bhuj, May 24-26, 2001, Roorkee.

Seeber, L. and Armbruster, J.G. (1981) Great detachment earthquake along the Himalayan arc and long term forecasting. In Earthquake Prediction: An International Review, Maurice Ewing Series, 4. Amer. Geophys. Union, Washington D.C., pp.259-277.

Seekins, L.C., Wennerberg, L., Margheriti, L. and Liu, H-P. (1996) Site amplification at five locations in San Francisco, California: a comparison of S waves, codas and microtremors. Bull. Seismological Soc. Amer., v.86, pp.627-35.

SESAME (2004) Guidelines for the implementation of the H/V spectral ration technique on ambient vibrations measurements, processing and interpretation. SESAME European research project WP12 – Deliverable D23.12, December, 2004.

Singh, S.K., Lermo J., Dominguez T., Ordaz, M., Espinosa, J.M., Mena, E. and Quass, R. (1988) The Mexico earthquake of September 19, 1985 – a study of seismic waves in the valley of Mexico with respect to a hill zone site. Earthquake Spectra, v.4, pp.653-673.

Theodulidis, N., Kalogeras I., Papazachos, C., Karastathis V., Margaris, B. Papaioannou, C. and Skarlatoudis, A. (2004) HEAD 1.0: A unified Hellenic Accelerogram Database. Seismological Res. Lett., v.75, pp.36-45.

Tokeshi, J.C. and Sugimura, Y. (1998) A comparison of the Fourier phase spectral method with the Nakamura technique for a horizontally layered structure, Proceedings of the XIth European Conference on Earthquake Engineering, Paris, September 6-11, Bisch, Labbe and Pecker Editors, Balkema.

Trifunac, M.D. and Todorovska, M.I. (2000) Long period microtremors, microseism and earthquake damage: Northridge,C.A. earthquake of 17 January 1994. Soil Dynamics and Earthquake Engineering. v.19(4), pp.253-267.

Wakamatsu, K. and Yasui, Y. (1996) Possibility of estimation for amplification characteristics of soil deposits based on ratio of horizontal to vertical spectra of microtremors. Proc. 11th World Conference on Earthquake Engineering. Acapulco, Mexico.

Xia, J., Miller, R.D. and Park, C.B. (1999) Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves. Geophysics, v.64, pp.691-700.

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