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Soft Soil Mapping Using Horizontal to Vertical Spectral Ratio (HVSR) for Seismic Hazard Assessment of Chandigarh City in Himalayan Foothills, North India

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Abstract: The populated and expanding city of Chandigarh is located in the foothills of Himalaya, near the potentially active Main Frontal Thrust (MFT). A hazard assessment for this city is consequently of major importance. Thick sediments underlies the city and that can potentially amplify the earthquake shaking and contribute to an earthquake disaster in the city. The present study applies the Horizontal to Vertical Spectral Ratio (HVSR) ambient noise methodology to estimate the resonance frequency of the soft sediments and to obtain a first order estimate of sediment thickness.

The study indicates that the soil thickness range from 30 to 270 m and that the resonance frequencies vary from 0.236 to 1.479 Hz. A smooth correlation function between soil thickness and resonance frequency is found, indicating relatively homogeneous soil.

Keywords: Site response, H/V ratio, Seismic microzonation, Chandigarh, Himalaya.

INTRODUCTION

The behaviour of the ground motion during an earthquake is generally well explained by the geological surface structure, in the place where the phenomenon is studied. Past and recent observations have shown that the damage caused by strong earthquakes is more severe in sedimentary basins than on hard rock structures. The socio-economic disruption caused by earthquakes is enormous in different parts of India. Rapid urbanization of major and metro/cosmopolitan cities located at the foot hill of Himalaya become vulnerable to high seismic risk due to their locations close to active seismogenic sources.

Chandigarh city falls in the zone of IV in the seismic zonation map of India (BIS, 2002), and the city has experienced several major earthquakes (> 6M) in the historical times. The city is located in the frontal part of the Himalaya and relatively near the active Main Frontal Trust (MFT), which may be the host fault for large future earthquakes in the region (Ram and Ram, 2001).

A seismic microzonation of the city is therefore of importance for planners and disaster managers to adapt to a safer land use planning and application of the building code in the construction practice. The rapid growing city mainly comprises three to four storey buildings except for a few multi storey structures. As with other cities exposed to high earthquake hazards, the rapid and largely uncontrolled urbanization of Chandigarh may lead to serve disasters from future earthquakes.

The Indian plate pushes into the Asian plate at a rate of 18 mm/year (Larson et al. 1999), and as a result of the collision between the two plates, the state of stress in the Indian plate is high, which in turn increases the earthquake risk, particularly in northern India along the Himalayan collision zone. The plate collision lead to crustal shortening which was evidenced in the 8 October, 2005, Kashmir earthquake; a horizontal shortening of about 1 meter was directly observed across a river parallel to the fault (Lindholm, personal observation). The geodynamics as well as infrequent occurrence of great earthquakes in the Himalayas is well summarized by Seeber and Armbruster (1981), Khattri (1999) and Bilham and Gaur (2000).

In the recent years two moderate earthquakes have occurred in the Garhwal Himalayas, the 1991 Uttarkashi earthquake, Mw 6.8 and the 1999 Chamoli earthquake, Mw 6.5 (Kumar and Mahajan, 1993; Kayal et al. 2003); both occurred to the east of Chandigarh. These earthquakes caused significant damages. 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 M=8 or larger to be around 130 years in the gap.

Generally, the damage from earthquakes decreases strongly with distance from the rupturing fault. Sometimes, however, an uneven geographical damage distribution from large earthquake can be observed, and the spatial distribution of the most affected areas can then often correlated with unconsolidated soil deposits; less damage can be correlated with hard rock underlying the structures (e.g. Oliveira et al. 2006). There are numerous examples of soil amplified damages, for example in Northridge (Trifunac and Todorovska, 2000), San Francisco (Ohmachi et al. 1991) and in Mexico City (Singh et al. 1988) to name a few. The average shear wave velocities in the upper most 30m of the soil column have a major influence on the ground motion at the site; however the resonant period and the attenuation characteristics of the entire soil column are significant for site amplification. Proper estimate of the soil response in various geological environments is therefore an important challenge; both empirical and analytical methodologies have been developed.

The empirical methods are based on seismic records from a site such that the dominant frequency and amplification factor can be determined directly. The empirical methods are of two types, those that use a reference site (Borcherdt, 1970), and those that are independent of a reference site (Tucker and King, 1984; Aki, 1988; Lermo and Chavez Garcia, 1993; Field and Jacob, 1993). A technique introduced by Nakamura (1989) is based on the horizontal to vertical spectral ratio (H/V) of ambient noise measurements. This H/V technique is at present one of the most widely used methods to derive the resonance frequency of a site (Yamanaka et al. 1994; Ohmachi et al. 1991; Field and Jacob, 1993; Field et al. 1995; Riepl et al. 1998).

We have applied the H/V method in Chandigarh, as it is convenient and inexpensive, and the rapid city growth makes a microzonation study necessary for the city development. Nakamura (1989) demonstrated that the H/V ratio of the ambient noise records is related to the fundamental frequency of the soil beneath the site and to the amplification characteristics. Although the Nakamura (H/V) method is not unanimously accepted by the scientific community, but in comparison to other techniques the validity and efficiency of the method is proved by many authors (e.g. Bour et al.1998; Lermo and Chavez-Garcia, 1993, 1994).

GEOLOGICAL SETTING

Chandigarh is situated in a valley, filled with river deposits from the mountains to the north of the city. The subsurface formations comprise beds of boulders, pebbles, gravels, silt, sand and clay. Chandigarh lies on the southern fringe of the Himalaya (Fig. 1), where the undeformed succession of the Indo-Gangetic Plains, is separated from the folded and faulted Upper Siwalik Hills of lower Pliocene to early Pleistocene (Malik et al. 2003). To the north of the present study area, one finds numerous NNW- SSE trending faults that are part of the MBT and MFT systems. In the north eastern part, subsidiary thrusts of the MBT system, namely the Palampur/Nahan thrust, the Barsar/Gambhar thrust and the Jwalamukhi thrust, cut through the Tertairy succession (Valdiya, 1980). The Barsar thrust marks the boundary between the lower Siwalik Hill range and the Pinjore Dun, where the Jwalamukhi thrust cuts the middle and lower Siwaliks succession. The southern edge of Himalaya is marked by the MFT that delineates the boundary between the detached complex folded – faulted Upper Siwalik Hills comprising molassic sediments of early Pleistocene age and the undeformed succession of the Indo – Gangetic plains (Fig.1). The piedmont deposits at the foot of Siwalik Hills consist of cobble, gravels and boulders associated with sand, silt and clay. The piedmont deposits followed by the alluvial plains consist of clay, silt and sand.

SEISMICITY

Chandigarh located in the foot hills of Himalaya lies in the highly earthquake prone Himalayan belt, (seismicity zone IV; BIS, 2002). Earthquake Hazard Index (EHI) quantitatively classifies the terrain into six hazard levels, while five classes could be identified following the Bureau of Indian Standards (BIS) PGA nomenclature for the seismic zonation of India. The EHI is found to vary between 0.15 to 0.83 quantitatively classifying the terrain into six hazard levels as "Low" corresponding to BIS Zone II, "Moderate" corresponding to BIS Zone III, "Moderately High" belonging to BIS Zone IV, "High" corresponding to BIS Zone V(A), "Very High" and "Severe" with new BIS zones to Zone V(B) and V(C) respectively (Fig.2).

The city has often been rattled by felt earthquakes with epicentral distances even more than 350 Km away from the city, as for example, Hindukush earthquakes. There are numerous seismogenic thrust/faults to the north of study area, and the city is extremely vulnerable to earthquake damages. According to the Global Seismic Hazard Assessment

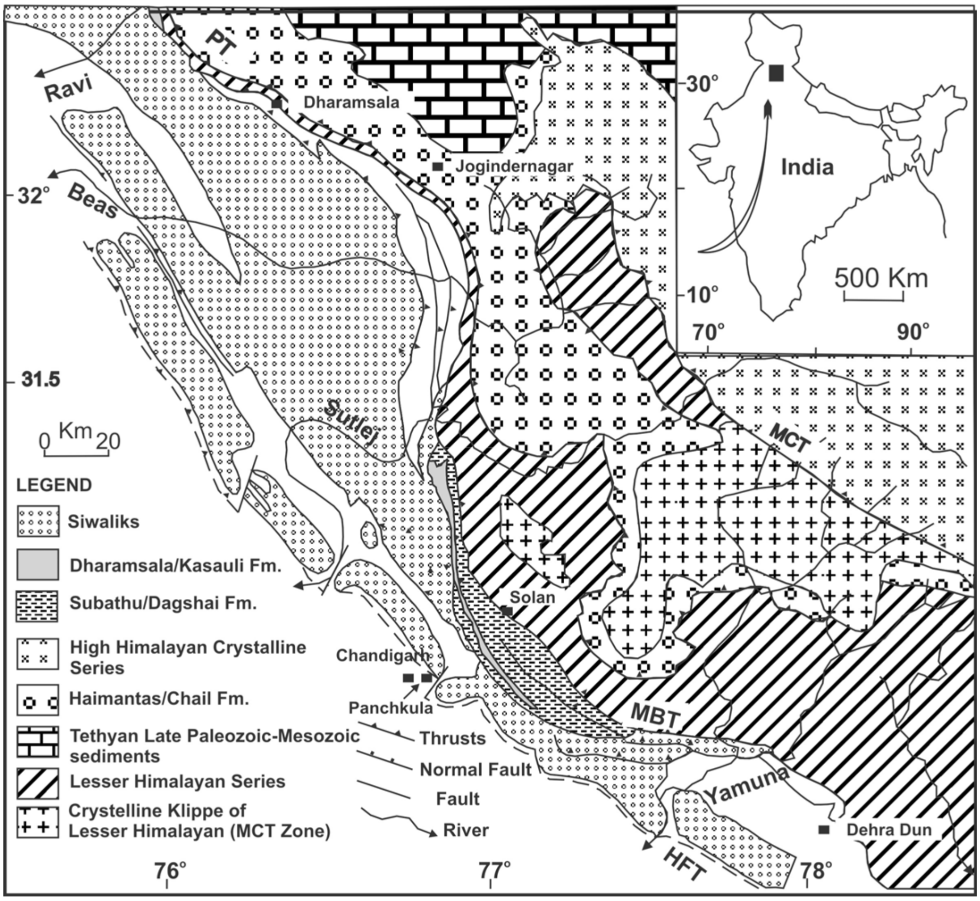

Fig.1. The regional geology of the Himalayas around the city of Chandigarh located close to Main Frontal Thrust (MFT) (*after* Karunakaran and Rao, 1979; Raiverman et al. 1983).

Program (GSHAP) the city of Chandigarh should expect to have a Peak Ground Acceleration (PGA) up to 0.32g at a 0.002 annual exceedance probability (www.asc-india.org: Seismic hazard of Chandigarh, 2008).

Sub-surface Geological Cross-section and Shear Wave Velocity

The sub-surface geological cross section of Chandigarh reveals that the topsoil comprising clay type materials varies in thickness from less than a meter to 10 m and is underlain by beds of clay and caliches, sand and gravel. Along the Sukhna Choe, three prominent sand beds occur within a depth of about 100 m. The upper sand beds are about 15 m thick and occur 8 m below ground level (bgl). The middle sand bed is about 18 m thick and occurs at about depths varying from 21-38 m. The deeper sand bed occurs at depth varying from 39-76 m and it is about 27 m thick (Dharmaraju et al. 2007). The soils in Chandigarh are loamy sand at the surface and calcareous sandy loam in the subsurface layers. The hard clay forms pans at depths varying between 20 m and 30 m. In the northern parts, the soil is sandy to sandy loam whereas it is loamy to silty loam in the southern parts (Dharmaraju et al. 2007). The analysis of the borehole data shows that the strata in general comprises of clay type silt soil in the top layers followed by sandy silt to silty sand at depth in the most of the sectors (Dharmaraju et al. 2007). A typical geological cross section from the area is shown in Fig.3 (CGWC, 2000).

In the northern and the northeastern part of the city, shear wave velocities shows higher values up to 300 m/sec, whereas in the southern and southwestern part it varies from 220 to 245 m/sec (Fig.4). 24 shallow boreholes have been explored, in which Standard Penetration Test (SPT) were carried out at different depth levels and soil samples were taken for geotechnical tests (GSI, 2008).

Data Collection and Processing

The ambient noise was recorded with Guralp DM 24 - S 3 instruments, which is a digital multi channel seismic data acquisition system. A sampling rate of 100 sample/second

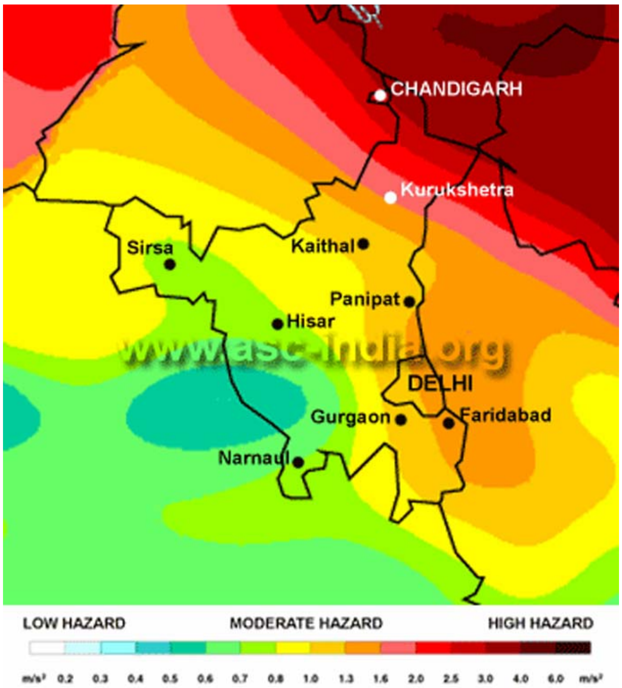

Fig.2. Seismic Hazard of Chandigarh (*source:* www.asc-india.org)

was used for the 3 orthogonally oriented seismometers (the CMG 40T-1). The location of each site was determined by standard Garmin GPS receivers, yielding a location precision of about 10 m.

The data from 59 sites were collected from December 2004 through January 2005. The area was girdded with approximately 500 - 600 m grid spacing (Fig.5), and at each site ambient noise was recorded at a time window of 30 - 45 minutes. Each site was prepared with 5-10 cm excavated hole for the sensor placement, and the sensor was pressed into the hard soil. The ambient noise was collected during the 6 AM to 14 Hr (local time) and wind speed never exceeded 5 km/hour during the recording time. Generally, it was attempted to follow the recommendations as provided in the SESAME (2004) guidelines.

The data processing was done with the GEOPSY software. For the analysis 30 windows of 60 seconds length were selected with no overlap. The 30 windows were appropriate for retrieving the resonance frequency at least down to 0.2 Hz as recommended by the SESAME user's guide line. The data were Fourier transformed for each time window, and spectral smoothing was done with a Konno and Ohmachi (1998) filter with parameter b set to equal 40.00 and the two horizontal components were averaged by the geometric means as recommended by the SESAME (2004). At a few sites day and night noise-data were collected; these two data sets were compared in terms of frequency response and amplitude but no distinct differences were observed. For each site the average fundamental frequency and the absolute amplification factor were determined as the mean value obtained from all the processed noise windows.

RESULTS AND DISCUSSION

The site effect of any area is a complex result of number

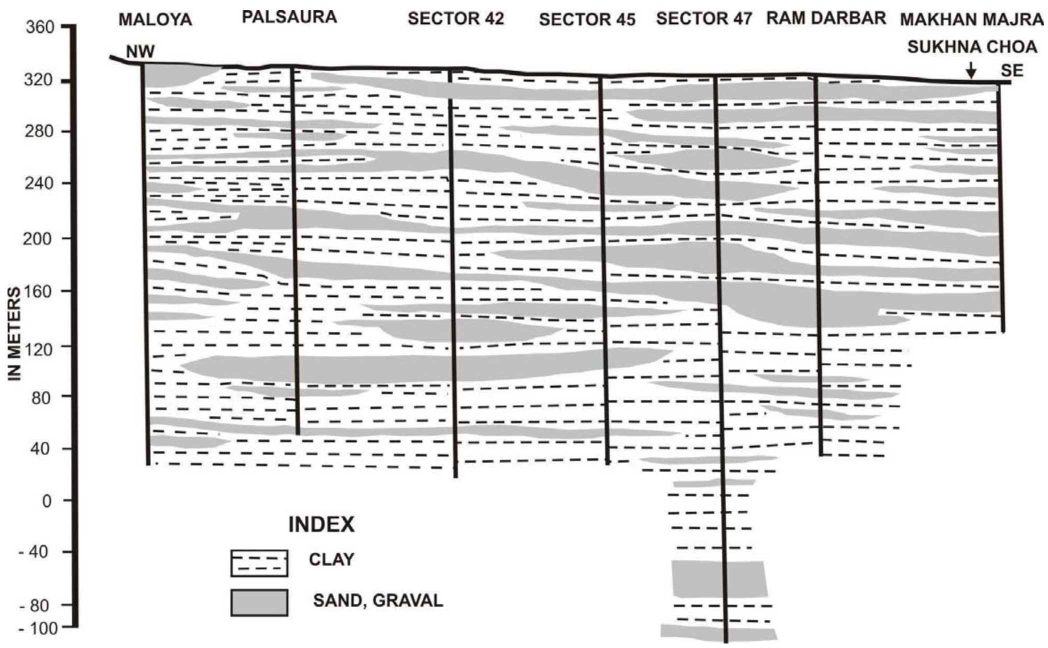

Fig.3. Subsurface geological cross section along NW-SE profile (*after* CGWC, 2002).

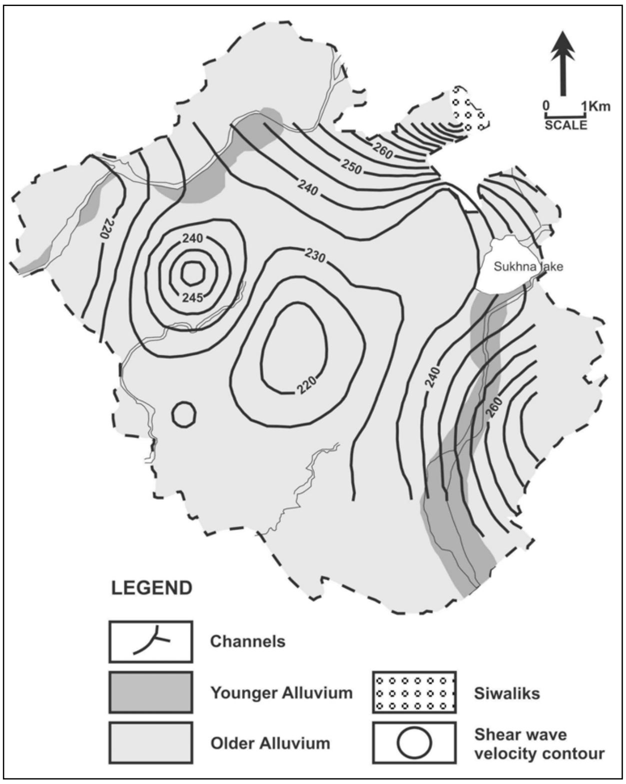

Fig.4. Shear wave velocity map of Chandigarh (*after* GSI, NW circle, 2008).

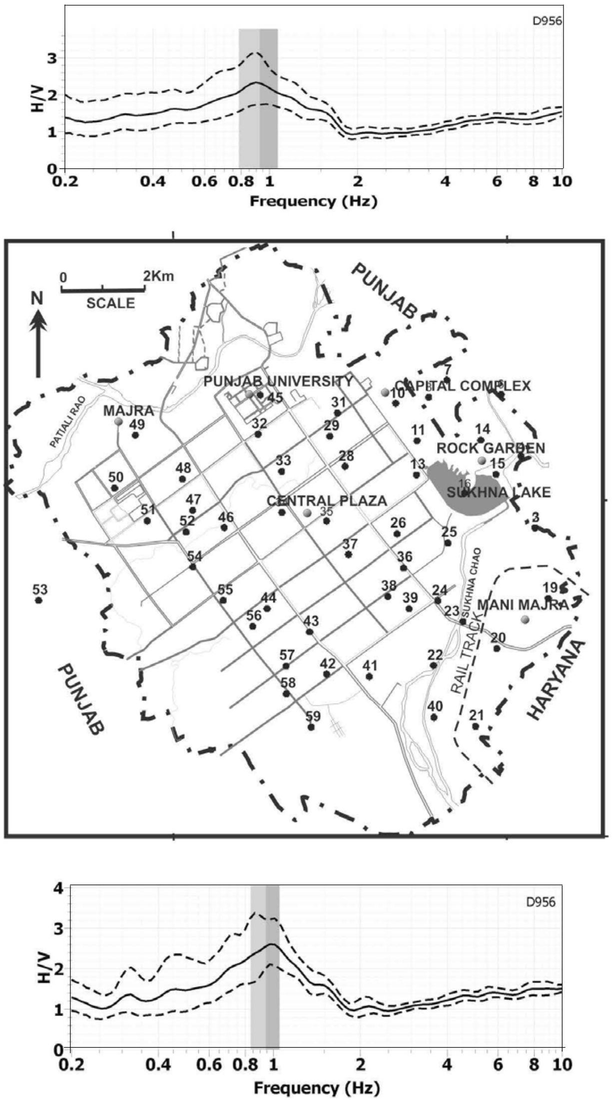

Fig.5. Survey points (Black dot) along with the representative H/V plot in the Chandigarh area.

of factors, such as the material properties, the subsurface topography, the depth of 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 ~25 km^2 was mapped using records from the 59 sites with the spacing interval of 500 - 600 meters in the Chandigarh city area (Fig.5). The resonance frequencies obtained at each site were spatially smoothed and interpolated and were mapped as shown in Fig.6. It is observed that the fundamental frequency of resonance between 0.236 and 1.479 Hz (Mundepi, 2008). The resonance frequency distribution shows a distribution that cannot immediately be associated with known base rock geometry. The southern and western part of the city show higher frequency response from 1 to 1.479 Hz, the central part responds to the frequency from 0.4 to 1.2 Hz and the northeastern and eastern parts respond to 0.23 to 0.8 Hz. The lower frequencies in the northeastern and eastern may be attributed to recent deposits transported from the mountains. The higher frequencies in the southern and western parts may reflect compact soil in comparison to the lower degree of compaction in the northeastern and eastern part of city. On the basis of these resonance frequencies the city can be broadly divided into three sub zones.

It has been argued that the amplification factors directly obtained through the H/V processing are not reliable (Bard, 1999; Bonnefoy-Claudet et al. 2008). However, we have attempted to correlate these results to the thickness of the sediments through a simplified approach. Assuming a single layer over half space model, the average sediment thickness can be estimated from the equation 1.

$$H = V_{av}/4*f_{H/V} \tag{1}$$

where V_{av} is average S wave velocity; H is the layer thickness; f is the fundamental resonance frequency (Bard, 2000). For a V_{av} = 240 m/s (estimated to be a fair average of

Fig.6. Map showing the contour of resonance frequency in Chandigarh city.

the clay, silt and sand sediment below the Chandigarh city) and f = 1.6 Hz, the value of H turns out to be 150 m. This is an average estimate of the sediment thickness based on the observed resonance frequency and an average shear-wave velocity underneath the city based on the assumption of an 1D model. Using the detailed shear wave velocity (Vs) structure for the city (Fig. 4), the soil thickness has been computed using this relationship (Fig.7). This simple exercise leads to a large variation in sediment thickness over short distances, which would result in 2D and 3 D effects of the basin response, in which case the distinct resonance frequencies may differ from the average Nakamura estimate (Bard, 2000).

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 Chandigarh. Some of these sediments are soft soils, but the exact distribution and thickness is unknown. The H/V ratios of ambient noise were used to determine the distribution of these soils in terms of resonance frequencies and subsequently applied in a simple test model for establishing a sediment thickness model. 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. In the absence of a high resolution subsurface model for Chandigarh, the herein established model for soil thickness and resonance frequencies may serve as a first simple approximation that can and should be confirmed 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

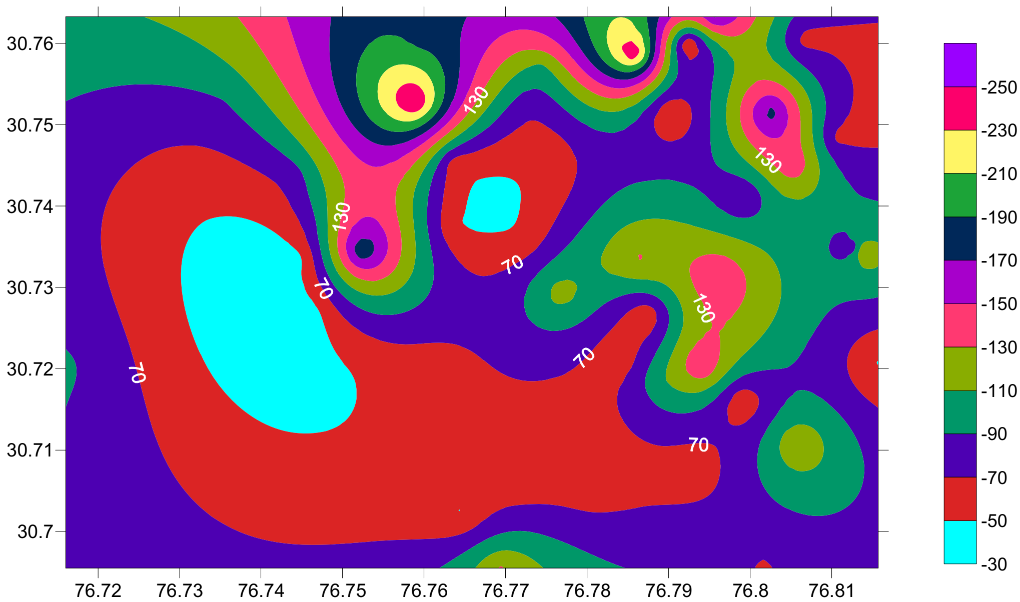

Fig.7. Estimated soil thickness (in meters), using empirical relationship, in the Chandigarh city.

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 terms of the resonance frequencies. 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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