Estimation of local site effects using microtremor testing in Vijayawada city, India

by

Manne Akhila, Dr D Neelima Satyam

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Centre for Earthquake Engineering
International Institute of Information Technology
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Estimation of local site effects using microtremor testing in Vijayawada city, India

A. MANNE* and N. D. SATYAM*

The microtremor method is very useful in urban areas to estimate local site effects for microzonation purposes. As seismic waves propagate from bedrock to the ground, their characteristics are site specific due to the heterogeneity of substrata. Source, path and site effects are prime parameters that affect ground response. Many destructive earthquakes that occurred in the past (e.g. Bhuj 2001, Bingol 2003, Kashmir 2005, Haiti 2010, Tohoku 2011, Van 2011 and Yunnan 2012) clearly illustrate the effects of local soils on damage severity and pattern. The Indian sub-continent has more than 400 major faults that influence seismic activity and India has experienced several devastating earthquakes (Assam 1897 (M = 8.7), Kangra 1905 (M = 8.6), Bihar-Nepal 1934 (M = 8.4), Assam-Tibet 1950 (M = 8.7), Latur 1993 (M = 6.4), Chamoli 1999 (M = 6.8), Bhuj 2001 (M = 7.6) and Sikkim 2011 (M = 6.9)). The state of Andhra Pradesh is located in the central part of peninsular India (zones II and III according to Indian seismic code) and has a record of earthquakes along the coast. This study considered Vijayawada (zone III), the third largest city in the state. Microtremor surveys were carried out at 75 different locations in the Vijayawada urban area and analysis was carried out using the Nakamura technique. Dynamic characterisation was carried out by considering the shape of the response curve, horizontal to vertical (H/V) amplitude, predominant frequency and the characteristic soil profile at all the test sites. Based on this detailed analysis, a classification is proposed and a predominant frequency map of the study area was developed. It was found that areas in the north eastern and south eastern parts of the city, with silty and clayey sand formations, have comparatively high predominant frequencies (> 4 Hz). The northern and western parts of the city, with high silty clay and silty sand, are characterised by moderate frequency values (2–4 Hz). Low (< 2 Hz) values of predominant frequencies were observed at a few locations. The H/V amplitudes are high (2–3) in the eastern and western regions.

KEYWORDS: earthquakes; ground movements; in situ testing; seismicity; vibration

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NOTATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_h$</td>
<td>amplification factor for horizontal motion of body wave</td>
</tr>
<tr>
<td>$A_v$</td>
<td>amplification factor for vertical motion of body wave</td>
</tr>
<tr>
<td>$F_{EW}$</td>
<td>Fourier amplitude spectrum of the east–west component</td>
</tr>
<tr>
<td>$F_{NS}$</td>
<td>Fourier amplitude spectrum of the north–south component</td>
</tr>
<tr>
<td>$F_v$</td>
<td>Fourier amplitude spectrum of the vertical component</td>
</tr>
<tr>
<td>$H_b$</td>
<td>horizontal spectrum in the basement under the surface ground</td>
</tr>
<tr>
<td>$H_s$</td>
<td>spectrum of horizontal direction of Rayleigh waves</td>
</tr>
<tr>
<td>$T_b$</td>
<td>amplification factor for vertical motion of surface sedimentary ground based on seismic motion on the exposed rock ground near the basin</td>
</tr>
<tr>
<td>$T_v$</td>
<td>amplification factor for vertical motion of surface sedimentary ground based on seismic motion on the exposed rock ground near the basin</td>
</tr>
<tr>
<td>$V_b$</td>
<td>vertical spectrum in the basement under the surface ground</td>
</tr>
<tr>
<td>$V_1$</td>
<td>vertical spectrum in the basement on the surface ground</td>
</tr>
<tr>
<td>$V_s$</td>
<td>spectrum of vertical directions of Rayleigh waves</td>
</tr>
</tbody>
</table>

INTRODUCTION

Local site effects are phenomena caused by seismic wave propagation in geological formations or irregularities near the surface. Damage to life and property during seismic shaking is governed by local site conditions, as exemplified in earthquakes worldwide (e.g. Mexico City 1985, Loma Prieta 1989, Northridge 1994, Kobe 1995, Bhuj 2001, Tohoku 2011 and Christchurch 2011). Local soil conditions play a significant role in the amplification of seismic waves (Street et al., 2001; Slob et al., 2002; Ansal et al., 2004). Amplification depends on the frequency of the ground motion, and younger softer soils generally amplify the ground motion more than older more competent soils or bedrock (Aki, 1993). Local amplifications of unconsolidated sediments were responsible for intensity variations of about two degrees on the modified Mercalli intensity scale during the San Francisco 1906 earthquake (Borcherdt & Gibbs, 1976) and the Loma Prieta 1989 earthquake (Seed et al., 1988). In the Bhuj earthquake in India in 2001, the damage pattern was greatly influenced by loose soil cover and topographical features in the Rann area (Krinitsky & Hynes, 2002). Apart from soft sediments and topography, the water table and bedrock depth also influence site effects. Earthquake damage induced by such effects thus...
needs to be considered in seismic regulations, land use planning or the design of critical facilities.

The current area of study, the Vijayawada urban area, is located at 16.52° N latitude, 80.62° E longitude and is the third most populated metropolitan area in the state of Andhra Pradesh, India. Occupying an area of about 73 km², it is an important urban agglomeration in the country with considerable historical and agricultural importance and cultural heritage (Fig. 1). The city is located along the stream of the Krishna River and is covered by dominant amounts of silty clay (MH–CH) of about 76% and some silty sands and sandy silts (Manne & Satyam, 2011). The geology of the city is interesting and varied. Vijayawada is the only city in the world with two rivers and three canals. The lithological formations vary from Khondalites, Peninsular Gneisses, Dharwars and Proterozoic groups of rocks to sandstones of the Gondwana group and coastal alluvia. Medium- to small-range hills cover the eastern and western parts of city. With about 22 seismic sources in and around the city (GoI, 2000) and prone to frequent tremors, the city (zone III (BIS, 2002)) is seismically active (Manne & Satyam, 2011). Considering the seismic and geotechnical characteristics of the city it seems necessary to estimate site effects due to probable seismic hazard. To estimate the seismic hazard of Vijayawada, microtremor testing (using the Nakamura (1989) method) was carried out and peak frequency and amplitude maps were generated.

THE NAKAMURA METHOD
The Nakamura method, also termed the H/V (horizontal to vertical spectral ratio) method, is an experimental technique to evaluate the characteristics of soil deposits. Microtremors are low-amplitude (micrometres) waves of vibration caused by natural and artificial disturbances. From microtremor measurements, Nakamura (1989) found that site characteristics are related to a site transfer function derived from the ratio of Fourier spectra of the horizontal and vertical components of the microtremor recording at the surface. The method facilitates recordings without the need for a reference site, and the ratio of horizontal to vertical spectra is evaluated to eliminate path effects. The curve obtained by dividing horizontal and vertical spectra shows a peak at the resonance frequency of the site and the corresponding amplitude of vibration.

The H/V technique is very effective at estimating the natural frequency of soft soil sites when there is a large impedance contrast with the underlying bedrock. The H/V amplitude does not coincide with the amplitude of the soil column, but the frequency coincides in almost all cases. A typical geological structure for estimation of loose sediment frequency using microtremor testing is shown in Fig. 2. Nakamura (2000) deduced the quasi transfer spectra, or H/V, as follows.

\[
H_f = A_h H_b + H_t \quad (1a)
\]
\[
V_f = A_v V_b + V_t \quad (1b)
\]
\[
T_h = H_f / H_b \quad (1c)
\]
\[
T_v = V_f / V_b \quad (1d)
\]
\( T_h \) and \( T_v \) are the amplification factors for horizontal and vertical motion of surface sedimentary ground based on seismic motion on the exposed rock ground near the basin.

\[
T_h = \frac{T_h}{T_v} = \frac{H_i/V_i}{H_b/V_b} = \frac{H/V}{H_b/V_b} \tag{2}
\]

where the horizontal to vertical spectral ratio \( H/V = H_i/V_i \).

According to measurements at rock sites, \( H_b/V_b \equiv 1 \), therefore \( T_h \equiv H/V \).

In equations (1) and (2), \( A_h \) and \( A_v \) are the amplification factors of horizontal and vertical motions of the body wave, \( H_s \) and \( V_s \) are spectra of the horizontal and vertical directions of Rayleigh waves and \( T_h \) and \( T_v \) represent amplification factors of the horizontal and vertical motion of surface sedimentary ground based on seismic motion on the exposed rock ground near the basin. The spectra of horizontal and vertical motion in the basement under the surface ground and on the surface ground are represented by \( H_b \) and \( V_b \) and \( H_i \) and \( V_i \), respectively.

Microtremor studies provide a fundamental basis for ground response analysis, particularly in densely populated urban areas where there is difficulty in utilising conventional seismic techniques. The study area of Vijayawada is underlain by loose sandy silts and silty clay, which makes it vulnerable to damage caused due to the ground motion amplification of the young and loose soil deposits in the area. The city consists of low- to medium-range hills in the northern, north western and south western parts of the city, which give rise to topographic effects. The high water table (2–6 m) in these regions can be causative of large ground displacements and liquefaction effects even for low-frequency seismic waves. Hence, to estimate local site effects in Vijayawada, \( H/V \) analysis of ambient noise measurements was considered.

**ACQUISITION OF FIELD DATA**

The microtremor setup consisted mainly of a recorder unit (MR2002-CE, SYSCOM (http://www.syscom.ch/)) and velocity sensor (MS2003+, SYSCOM) (Fig. 3). The measurement of ambient vibration can be achieved using the communication software WINCOM (SYSCOM) with this setup. To obtain reliable estimates of site effect parameters, experimental conditions have to be perfectly maintained to obtain good-quality data. After setting up the recorder and sensor, base line correction has to be performed to ensure recording of a signal centred on zero.

Extensive ambient noise measurements were obtained in Vijayawada, spreading from Enikepadu in the east, Jakkampudi in the north and the national highway in the south. Test sites such as flat ground areas, open spaces, low-noise localities and so on were thus selected to prevent any interaction from traffic movement, construction activities, blasting, etc. Ambient noise measurements were obtained at 75 locations (Fig. 4). Sample data were taken for about 15 min to measure and setup trigger levels in all orthogonal directions to prevent errors in recordings. The vibrations were recorded for a duration of 60 min with 1 s each of pre-event and post-event time. A GPS was used to record the latitude and longitude of the test locations. To ensure noise levels were low, the data were collected in early morning and late evening.
Fig. 5. H/V amplitude versus frequency plots
DATA ANALYSIS
The H/V technique was applied to the recorded data to analyse the behaviour of the ground under dynamic loading. H/V is computed as the average of two horizontal component spectra divided by the vertical spectrum obtained for each window using View 2002 software (http://www.syscom.ch/). Care was taken to record the trigger levels before actual recording was carried out at every test site, and signals erroneously recorded based on the trigger levels were removed before carrying out the analysis.

The recorded 1 min files at a particular test site were processed using the file group option. Fourier analysis (Bracewell, 1986) based on the H/V spectral ratio was applied for each location. The microtremor recordings were transformed into the frequency domain using the fast Fourier transform method (Walker, 1996). Fourier spectra of the filtered data were generated by vectorial summation of two horizontal component spectra (EW and NS) to obtain the resultant horizontal spectrum H. The H/V spectrum was then obtained by dividing the horizontal spectral amplitude by the vertical component spectral amplitude at each frequency

\[
H/V = \left( \frac{F_{NS}^2 + F_{EW}^2}{F_V^2} \right)^{1/2}
\]  

(3)

H/V is the horizontal to vertical component ratio and \( F_{NS} \), \( F_{EW} \) and \( F_V \) are the Fourier amplitude spectra of the north–south, east–west and vertical components, respectively.

The final plot produced by the program includes H/V as the ordinate and frequency as the abscissa. For clear identification of peak frequency, the spectrum is smoothed using the moving average technique.

RESULTS AND DISCUSSION
Field recordings of ambient noise were conducted in Vijayawada city to estimate amplitude and frequency parameters. As noted earlier, care was taken to prevent any possible error in obtaining the data. The records were processed using View 2002. Different peaks were observed in the plots of H/V versus frequency (Fig. 5). Only peaks in the frequency range 0–10 Hz were considered for analysis of the 75 sites and a classification is proposed. All test locations were classified into three categories (T1, T2 and T3) based on shape of the curve, soil characteristics, H/V amplitude and predominant frequency. Most of the peaks are clear and often sharp, but a number of sites exhibited peaks of high amplitude (\( > 4 \text{ Hz} \)).

The Fourier spectra of higher frequency (\( > 4 \text{ Hz} \)) are classified as type T1. The spectra in this classification are characterised by peaks starting from 1–10 H/V amplitude and shifting towards the left in an increasing fashion. Most of the central and eastern parts (53% of the tested locations) of the city are covered by such peaks. The eastern regions of the city (Autonagar, Moghalirajapuram, Jakkampudi, Madhuranagar, Machavaram, Ramavarrapanu, Kasturbaipet, Governerpet, Prasadampadu, etc.) are covered by silty clay and silty sand. The areas of Moghalirajapuram, Patamata and Madhuranagar had almost the same peak ground frequency. Figure 6 shows a map of fundamental frequencies of the sediments with a distribution in a wide range of 0.5 to 9.85 Hz.

In type T2, the frequency ranges from 2–0 to 4–0 Hz; 35% of the locations fall under this category. Almost all the western and southern parts of the city exhibit such frequencies, with Barati Nagar, Jakkampudi, Gunadala, Enikepadu, Pakirgudem, Brahmin Street, Bhavanipuram, Crombay, PNT colony, Vambay and Labbipet falling into this classification. In this category, peaks are shifted towards the origin. The predominant soil in these locations is sandy silt and silty clay, but clayey sand is predominant (3.0–7.5 m) in a few locations (e.g. Labbipet). The spectra of type T2 have strikingly differentiable peaks.

Type T3 classification is for low frequency (\( < 2 \text{ Hz} \)). These locations (MG Road, Brindhavan colony, Jakkampudi, NH9, Ramalingeswara Nagar, Ayyapa Nagar) are few (12%) and have clayey sand and silty clay formations.

The spread of H/V amplitude throughout the city is shown in Fig. 7. It is interesting to observe that H/V amplitudes are less than 2 for locations along the river and surrounding the canals. These locations are covered by

![Fig. 6. Predominant frequency map for Vijayawada city](image-url)
sandy silt and silty sand. Higher amplitudes (H/V = 2–4) were observed in the north western and eastern parts of the city where most of the hills are concentrated. The locations covered by such high amplitudes have dominant amounts of silty clay and clayey sand.

CONCLUSIONS
The microtremor technique is a rapid, cost-effective and efficient method for ground response study. It can be used to estimate ground response in densely populated urban areas where there are constraints in using conventional seismic techniques. Microtremor investigations can be used to survey a large area in a reasonable time at relatively low cost in order to detect the potential danger of soil structure resonance.

Microtremor measurements were taken at 75 different locations in the Vijayawada urban region and the Nakamura (H/V) technique was adopted for analysis of the results. Reliability of the results and rapidity of data collection was ensured by H/V measurements from ambient noise recordings. The ambient noise data were processed using the computer program VIEW 2002 to generate an H/V plot for each site. Depending on the shape of the response curve and the estimated resonance frequency, all the sites were classified into one of three categories. The H/V approach thus provided a simple means of determining the predominant frequency of a soil site. The H/V spectra revealed that most of the amplification peaks are in the frequency range 1–0–9.85 Hz. The high-frequency range (7.5–9.0 Hz) is characteristic of the north western and south eastern parts of the city. The northern part of the city is characterised by medium sediment frequencies (4.5–6.0 Hz). The transition between lower frequencies in the western part and medium frequencies in the eastern part is 1.5–6.0 Hz. Amplification factors were also identified and representative maps developed.

The Nakamura technique provided a simple means of determining the predominant frequency of a soil site. The results can be used to establish seismic microzonation of a city and hence this study can help assess the potential parameters for seismic hazard estimation.

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REFERENCES


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