

Site response studies in Mumbai using (H/V) Nakamura technique

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Abstract The importance of characterizing the site effects in urban areas, especially Mumbai, the commercial capital of India, with a quarter of land below sea level, is well realized. Mumbai is built on a cluster of seven basaltic islands that were merged together through reclamation of land from the Arabian Sea. Due to rapid urbanization, the demarcation between reclaimed areas and original islands is blurred. A pilot study is undertaken to investigate and characterize the local site effects at 27 locations in Mumbai. The Nakamura technique is used to estimate the fundamental frequency of soft soils at each site, characterized by the ratio (H/V) of the Fourier spectra of the horizontal and vertical components of ambient noise measurements made with a 3-component short period (1 Hz) seismograph. Validation of peak frequency was done using both pre-event and event data. The peak amplification was also validated through measurements at a 10-m exposed soil section and over a soil dump. Overall, the site responses correlate well with the local geology and the lithologs obtained at 40 boreholes at 8 locations. The reclaimed areas are characterized by resonance frequencies ranging from 3.3 to 4.6 Hz with significant peak amplification (>4) in contrast to hard rock sites that do not exhibit peak amplification. The hard rock sites with soil cover exhibit peak amplification in the frequency range 3.3–10.5 Hz indicating large variations in soil thickness. The H/V curves at most sites exhibit clear single peaks with large amplitude, which could be associated with sharp discontinuities corresponding to a uni-model of a single layer with large velocity contrast overlying the basement. The low resonance frequencies together with large amplification of site responses enable identifying and demarcating reclaimed areas that form important inputs in the seismic microzonation of Mumbai.

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1 Introduction

Mumbai, the financial capital of India, is a coastal mega city in western India with a population of over 16 million. Mumbai falls in zone III of the Global Seismic Hazard Map (GSHAP) as a region with a probabilistic hazard of 0.1 g (Ravi Kumar and Bhatia 1999). The city lies in western Deccan Volcanic Province (DVP) of India (Fig. 1), which has experienced several intra-plate earthquakes in the past two decades including the $M_w = 7.5$ Bhuj earthquake in 2001. Historical records indicate that earthquakes of intensity up to IX have occurred in and around Mumbai in the past (Chandra 1977; Bansal and Gupta 1998). The seismotectonic setting together with the importance of Mumbai city makes it pertinent to address issues related to the seismic hazard of Mumbai. Very little work has been done in the context of microzonation for the city of Mumbai. Kanth and Iyengar (2006) estimated the seismic hazard of Mumbai by using the probabilistic analysis. The uniform hazard response spectra (UHRS) were derived, incorporating the uncertainties in location, magnitude and recurrence of earthquakes, which could be used for engineering purposes in Mumbai. An issue of prime concern is the identification of areas vulnerable to damage due to local site amplification caused by the passage of seismic waves in the soft sediments at a site. Damage due to an earthquake may vary even within few meters due to variation in local site conditions such as soil type and thickness. Studies have shown that the damage caused by large earthquakes is more significant in sedimentary areas than on hard rock primarily due to amplification of ground motion in the soft sediments that results from the trapping of seismic waves due to the acoustic impedance contrast between sediments and bedrock. The extent of damage due to an earthquake predominantly depends upon the local geology of the area. As a significant portion of Mumbai is covered with alluvium, characterizing the site effects is critical to microzonation of Mumbai.

The antique maps of Survey of India (1990) show that Mumbai once comprised of seven islands that were merged together forming a single entity with the mainland (Fig. 1). The

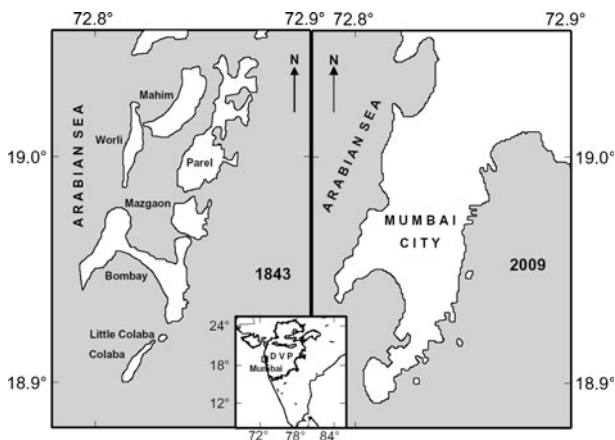


Fig. 1 Map showing the seven basaltic islands of Mumbai (*left*) and present day Mumbai (*right*)

regions between the islands as well as the periphery of some islands have been systematically reclaimed over the past two centuries. Thus, large tracts of reclaimed land are primarily filled up with sediments whose thicknesses and properties are unknown. Over a period of time, many high rise constructions have come up on these reclaimed areas that are indistinguishable from the original basaltic islands, which have ceased to exist in public memory. As the reclaimed parts of Mumbai are underlain by soft weathered material systematic studies are necessary to demarcate the reclaimed areas and estimate the resonance frequency and amplification due to sediments at different sites as the extent of damage due to an earthquake is influenced by the local site conditions. The present work is a pilot study undertaken to characterize the site effects in Mumbai and study the feasibility of demarcating the reclaimed land from the original islands based on soil amplification. The present study utilizes the popular Nakamura technique to determine the resonance frequency (f_0) of amplification (A_0).

2 Geology and seismicity of the study area

Mumbai comprises of the flat lying plains in western Deccan Volcanic Province adjoining the Arabian Sea. The lithology comprises of basaltic flows and the associated pyroclastics and the plutonic rocks of upper Cretaceous to Palaeogene ages. The Deccan basalts of Mumbai are considered to be the youngest basalts of Eocene age. The overall geology of Mumbai (Fig. 2) and it's immediate surroundings indicates the presence of ultrabasic, basic and acidic differentiates with intertrappean beds, agglomerates and tuffs, and large tracts of land covered with alluvium (GSI 2001). Acidic rock includes rhyolite and quartz trachyte. The basaltic flows are categorized primarily as simple and compound flows and flows that do not fall in these categories are termed as unclassified flows. Several

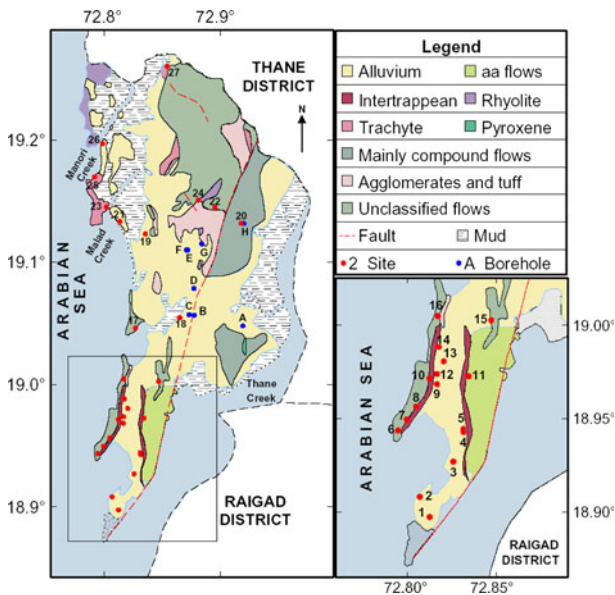
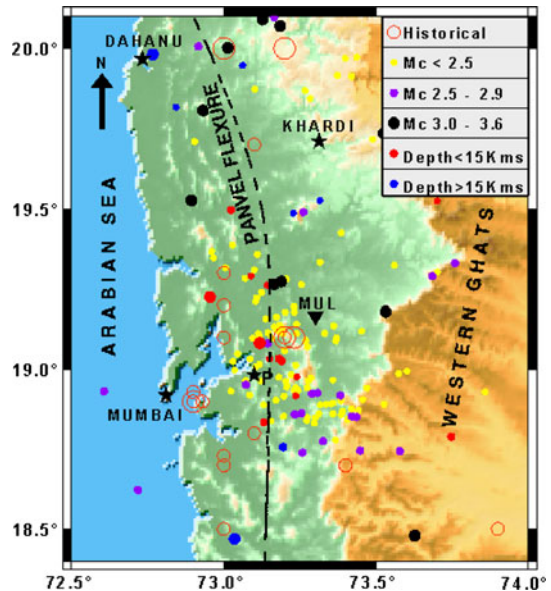


Fig. 2 Geological map of Mumbai showing the locations noise survey sites and Boreholes (modified after Geological Survey of India 2001)

Fig. 3 Seismicity map of Mumbai and surrounding region. Panvel is denoted as *P* and MUL denotes a Broadband seismic station (after Mohan et al. 2007)



lineaments and faults are reported in and around Mumbai with the coast parallel Panvel flexure about 30 km east of Mumbai being the most prominent lineament. Recent microseismic studies (Mohan et al. 2007) around Mumbai during 1998–2005 revealed the occurrence of about 41 earthquakes of magnitude ranging between 2.5 and 3.5 along the Panvel flexure at crustal depths suggesting the presence of an active fault system beneath it (Fig. 3), which is over 100 km long and a potential source of earthquakes. The largest event with magnitude 4.5 followed by a swarm of activity occurred about 100 km from Mumbai at Khardi in 1981 (Rastogi et al. 1986). The Koyna region that experiences continuous, unabated seismicity over the past 40 years is located about 200 km south of Mumbai. The Deccan Volcanic Province has also witnessed 4 large intraplate stable continental earthquakes of magnitude 6.0 and greater in the last four decades, which include Koyna (1967), Latur (1993), Jabalpur (1999) and Bhuj (2001).

3 Borehole lithology

The litholog information from 40 boreholes from 8 places (Fig. 2) in Mumbai including a 10-m section of an excavated site at IITB was collected. The boreholes were predominantly located in northern and central Mumbai. The lithologs representing the average depths to the subsurface lithology at each borehole location are shown in Fig. 4. The subsurface lithology is classified into three layers as (1) top soil and filling material (2) boulders followed by sandy soil and gravel (3) moderately weathered to hard compact basalt. The average thickness of the top soil comprising of highly weathered basalts and/or filling material ranges between 1.2 and 4.2 m. The average thickness of the unconsolidated soil cover above the compact hard rock is given by the depth to the top of the third layer that varies between 3 and 10 m. The observations suggest significant variation in the thickness of the unconsolidated soil across the reclaimed areas of Mumbai.

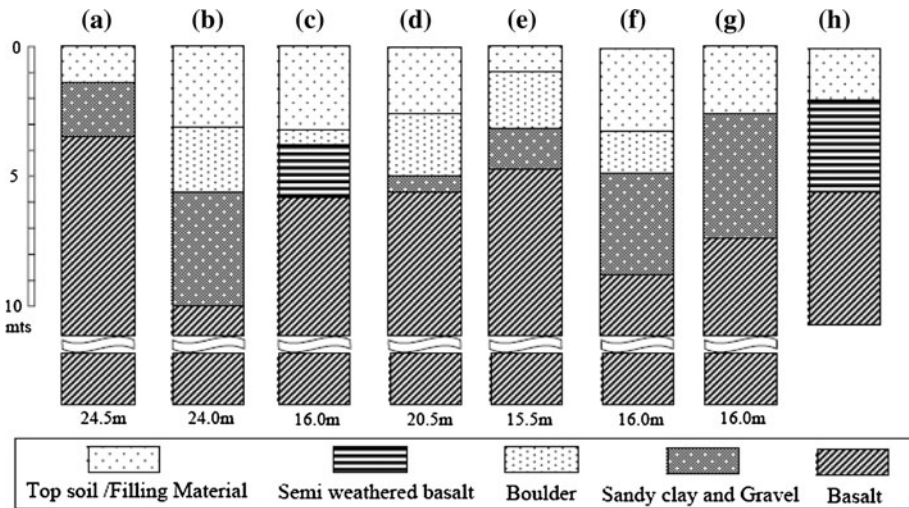


Fig. 4 Lithologs depicting the average thickness of the subsurface lithology obtained from the boreholes (a–h) shown in Fig. 2

4 Methodology

Site response studies are used to determine the fundamental frequency (f_0) of site amplification (A_0) at a given site, which forms an important parameter in estimating the seismic hazard for a given area. Several techniques viz., the reference-site method (RSM), generalized inversion technique (GIT) and Nakamura method are used for computing the site response. In the present study, the Nakamura technique (Nakamura 1989), a non-reference site method that is popularly employed for estimating the site response in urban areas is used. Nogoshi and Igarashi (1971) initially introduced this technique while Nakamura (1989) made it popular. The technique involves computing the Fourier spectra of the horizontal and vertical components and taking their ratio (H/V). The H/V ratio provides the fundamental natural frequency of the soil deposits corresponding to the peak of the H/V curve. The efficacy and theoretical objections to H/V Nakamura technique (NHV) are debatable. For instance, Nakamura (1989) suggest that, neglecting the surface waves, the NHV is a reliable estimate of the S-wave site response, while others (Lermo and Chavez-Garcia 1994; Lachet and Bard 1994) show that NHV ratios are related to the ellipticity of Rayleigh waves. However, several experimental studies (Ohmachi et al. 1991; Field and Jacob 1993; Lachet and Bard 1994; Lermo and Chavez-Garcia 1994; Lachet et al. 1996; Fah et al. 1997; Parolai et al. 2004) find that the H/V technique provides reliable estimation of the fundamental frequency of soft deposits. Parolai et al. (2004) used 272 aftershocks of the 1999 Izmit earthquake, to show that the resonant frequency estimated using the ambient noise (NHV) is consistent with that obtained using earthquake data (EHV) with discrepancy only in the level of amplification. The Nakamura technique has also been extended to reliably map the sediment thickness ranging from a few meters to 1,000 m in Rhine Embayment, Germany by Ibs-von Seht and Wohlenberg (1999), who proposed an empirical relationship between the peak frequency and the sediment thickness. The relationship suggests that higher the frequency, smaller is the sediment thickness and vice versa. This technique provides accurate and reliable estimate of the resonance frequency,

but the amplitudes of the dominant frequencies could be underestimated and hence do not represent the actual amplification value for a given site. However, the amplification values at different sites can still be useful for a qualitative study.

5 Data analysis

Ambient noise measurements were made at 27 sites that are plotted on the lithological map of Mumbai (Fig. 2). A digital seismograph equipped with a 24-bit data acquisition system and a short period seismometer (L-4C-3D) with a natural frequency of 1 Hz was used for data acquisition. A minimum of 2 h data at a sampling frequency of 50 Hz was recorded at each site. The raw data were processed using the J-SESAME software developed within the European project SESAME (2004). Windows of 20 s length were selected and the Fourier spectra of all the three components calculated and smoothed. The horizontal components were merged together using geometric mean option and divided by the spectra of vertical component to compute the H/V spectral ratios. The resonance frequency and the corresponding amplitude at each site were computed. Stringent criteria for reliability of results were adopted (SESAME 2004). The primary requirement for reliable H/V curves is that the obtained H/V curve be representative of H/V curves that could be obtained with other ambient vibration recording or other physically reasonable window selection. Thus, it is ensured that at least 10 significant cycles were present in each window in the frequency of interest, large number of windows (at least >10) were taken and low level of scattering in each window was considered. The reliable H/V curves next require to satisfy the stability criteria for a clear peak which is related to several characteristics i.e., the amplitude of the H/V peak and its relative value with respect to the H/V value in other frequency bands, the relative value of the standard deviation and the standard deviation of the peak frequency from individual windows (SESAME 2004). All the H/V curves exhibiting amplification need to satisfy the primary requirement of reliable H/V curves and at least 5 out of six stability criteria specified by SESAME (2004) need to be fulfilled for reliable estimates of the dominant frequency and amplitude of a clear H/V peak. While the reliability of the peak value will increase with the sharpness of the H/V peak, no straight forward information can be linked to the H/V peak amplitude A_0 . The amplitude value may be indicative of the impedance contrasts at the site under study. Large H/V peak values >4 are generally associated with sharp discontinuities and large velocity contrasts.

6 Validation studies

Experimental site response studies were carried out at an excavation site within IITB Bombay where a 10-m subsurface soil section is exposed. The exposed cross-section indicates a 2-m thick top soil, 5-m thick semi-weathered basalts overlying a 3-m thick compact basalt (Fig. 5). The measurements were carried out at the top of the exposed section and at the bottom on the hard rock as well as at the place where the excavated soil was dumped. The site responses at the three places are given in Fig. 5 along with the photograph of the soil section. The site response over the exposed hard rock shows a flat response as expected for the frequency band under study. The site response curve at the site on top of the exposed section also does not show significant amplification despite a 7-m thick layer above the compact basalt. The area under study is a basaltic ridge where the weathered soil cover above the hard rock was stiff that possibly influences the site

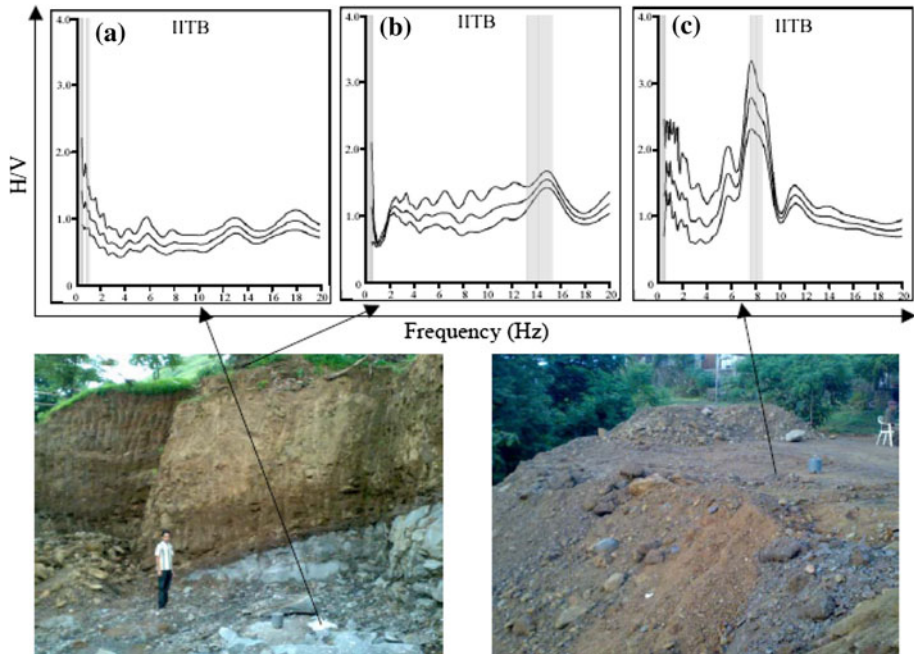


Fig. 5 Site responses (H/V plots) with mean and standard deviations obtained for ambient noise measurements at the **a** bottom (hard rock) and **b** top of the exposed soil section and at the **c** soil dump in IITB campus

response. However, the response at the site of soil dump showed peak amplification at 8 Hz indicating that loose unconsolidated soil clearly responds differently from that of a stiff soil and hard rock.

An experimental study was done to compare the site response obtained using pre-event ambient noise with those obtained for event data corresponding to a teleseismic and a local earthquake recorded at IITB. *P* and *S*-wave segments of the seismograms of the 7.5 Mw teleseismic earthquake at Andaman (10th August, 2009) and a 5.1 magnitude local earthquake (12th December 2009) at Koyna that occurred about 250 km south of Mumbai were used for computing the site responses. The site responses obtained using the earthquake data and noise, respectively, are similar (Fig. 6). The estimated fundamental resonance frequency is consistent at 5.9 Hz, but the level of amplification is inconsistent, implying that the resonant frequency obtained using the Nakamura technique is reliable.

7 Results

The site responses (Fig. 7a–c) were computed at 27 sites in Mumbai. The H/V responses at 16 sites exhibit peak amplification ($A_0 \geq 2$), of which three sites TIFR(2), MANT(3) and NAVJ(5) do not satisfy the stability criteria and hence were neglected. The H/V curves at 11 sites do not show any dominant frequency of amplification. The dominant frequency (f_0) of peak amplification (A_0) for the H/V curves exhibiting clear peaks and satisfying at least 5 out of 6 stability criteria were reliably estimated at 13 sites (Table 1). A distinct difference in terms of amplification, frequency and nature of site responses was observed on

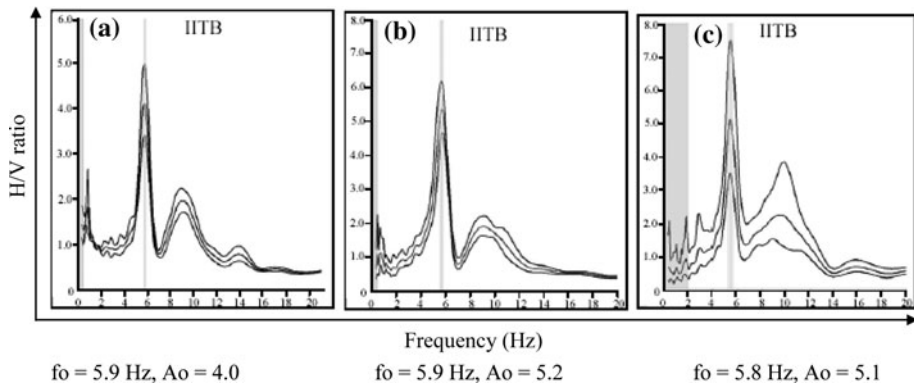


Fig. 6 Site responses (H/V plots) with mean and standard deviations obtained at IITB using data corresponding to **a** ambient noise, **b** teleseismic event, **c** local event

alluvium and hard rock terrains. All the site responses over alluvium terrain clearly exhibit peak amplification >2 , while the responses on typical hard rock sites are nearly flat or exhibit peak amplifications that do not satisfy the stability criteria. The site responses at a few sites that are broadly categorized as compound flows/trachyte/rhyolite deviate from the typical hard rock response suggesting the presence of weathered soil of varying thickness. Thus, based on the site responses the sites were classified as Type I and Type II sites corresponding to sites that exhibit peak amplification and those that do not exhibit peak amplification. The nature of the H/V curves exhibiting amplification is of two types—clear single peaks of amplification are observed at most sites while a few sites exhibit two peaks of amplification with the dominant resonance frequency exhibiting larger amplification.

7.1 Type 1: Sites exhibiting amplification

Most sites on alluvium exhibit site responses (Fig. 7a) dominated by clear single peaks with significant amplification >4.0 corresponding to resonance frequencies falling in a narrow range between 3.3 and 4.6 Hz. Maximum amplification (A_o) with a factor of 8 and 9 are found at RTOF(12) and MLAX(13) at frequencies 3.8 and 4.6 Hz, respectively. Certain sites e.g., 16, 17 and 20 falling in the area classified as hard rock (Fig. 2) also show significant amplification ranging from 3.7 to 4.2 at frequencies ranging between 4.0 and 7.1 Hz (Fig. 7b). Field observations at these sites confirm the presence of weathered soil overlying the hard rock suggesting that despite the broad geological classification, locally the site conditions could vary depending on the presence or absence of weathered soil and its thickness.

7.2 Type 2: Sites exhibiting insignificant amplification

Typical hard rock site responses (Fig. 7c) are observed at 11 out of the 14 hard rock sites. The hard rock sites in south Mumbai are mostly located on the original islands comprising of unclassified flows, while those in north Mumbai comprise of compound flows/trachyte/unclassified flows. The H/V responses at several hard rock sites do not exhibit any distinct resonance peaks of amplification, while at a few sites amplification is observed but the reliability and stability criteria are not satisfied. These H/V curves are indicative of non-weathered reference sites with minimal or no amplification even at high frequencies.

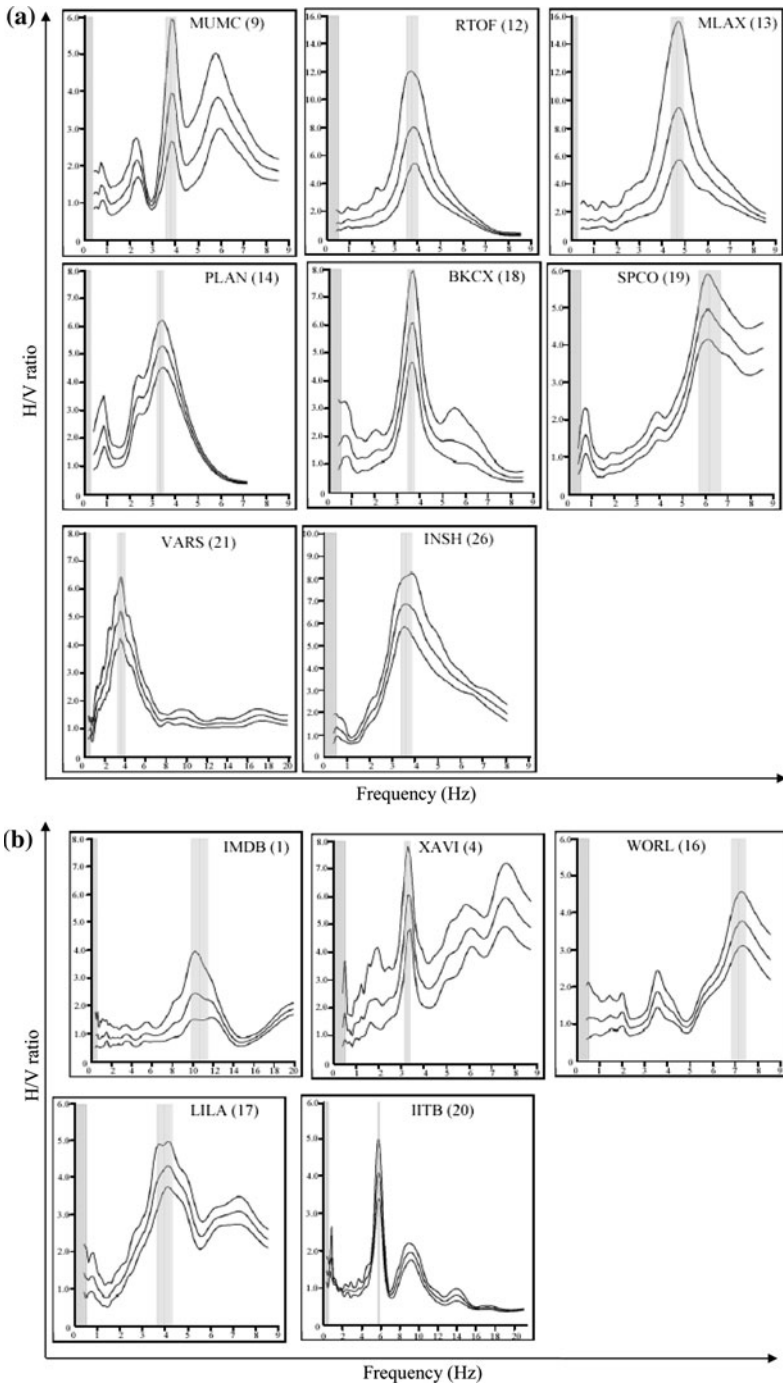


Fig. 7 **a** Plots of H/V ratios with mean and standard deviation at sites on alluvium. **b** Plots of H/V ratios with mean and standard deviation at sites on alluvium (1 and 4) and hard rock (16, 17 and 20). **c** Plots of H/V ratios with mean and standard deviation for hard rock sites

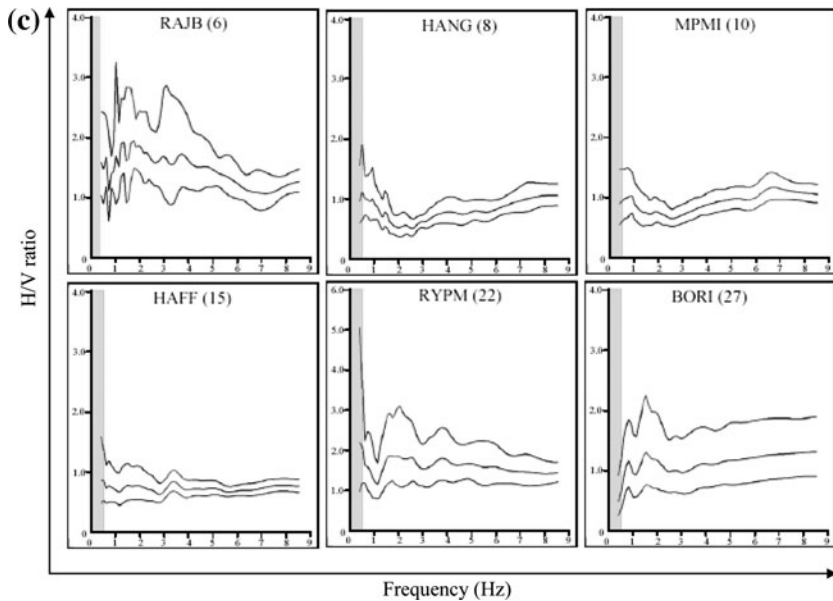


Fig. 7 continued

8 Discussion

A significant portion of south Mumbai comprises of reclaimed land, which today is indistinguishable from the original basaltic islands. The lithological map of Mumbai (Fig. 2) shows large tracts of land covered with alluvium that could be reclaimed land or underlain by the basaltic islands. Several pockets of the terrain classified as hard rock are also covered with variable thickness of weathered layer which has the potential to amplify the ground motion. The reclaimed parts of Mumbai are expected to be underlain by a thick layer of soft weathered material in contrast to the hard rock found on the original islands. Thus, significant amplification is expected at sites on reclaimed land, while hard rock regions should show little amplification unless covered with alluvium or weathered soil.

Superpositioning the antique and present day maps of Mumbai (Fig. 8) enables approximate demarcation of reclaimed and original basaltic islands (Table 2). It is observed from Fig. 8 that with the exception of sites 1 and 4, which fall under alluvium covered islands, all the other sites on alluvium fall under reclaimed areas. However, the antique map is not to scale and hence additional information would be required to validate these observations. In the absence of borehole data, the site responses provide supporting evidence for the presence of thick alluvium cover as expected in reclaimed areas. The site responses (Fig. 7a) at the alluvium covered sites 9, 12, 13 and 14 in south Mumbai are distinctly different from those (Fig. 7c) on the original basaltic islands (e.g., sites 6, 8, 10 and 15) with the former exhibiting clear peaks of resonance frequency with significant amplification unlike the latter. Importantly, the resonance frequencies of peak amplification consistently fall in a narrow frequency range of 3.3–4.6 Hz. Similarly, in north Mumbai, the sites covered with alluvium i.e., sites 18, 21 and 26, also show distinct peak amplitude in the frequency range 3.6–3.9 Hz consistent with those observed over alluvium

Table 1 Peak amplitude and the corresponding resonance frequency obtained from H/V ratios for sites exhibiting peak amplification

Site no.	Site	Resonance frequency f_o (Hz)	Peak amplitude A_0
1	IMDB	10.5	2.5
4	XAVI	3.3	6.1
9	MUMC	3.9	4.0
12	RTOF	3.8	8.0
13	MLAX	4.6	9.6
14	PLAN	3.3	5.3
16	WORL	7.1	3.7
17	LILA	4.0	4.2
18	BKCX	3.6	6.1
19	SPCO	6.2	4.9
20	IITB	5.9	4.0
21	VARS	3.8	5.2
26	INSH	3.6	6.7

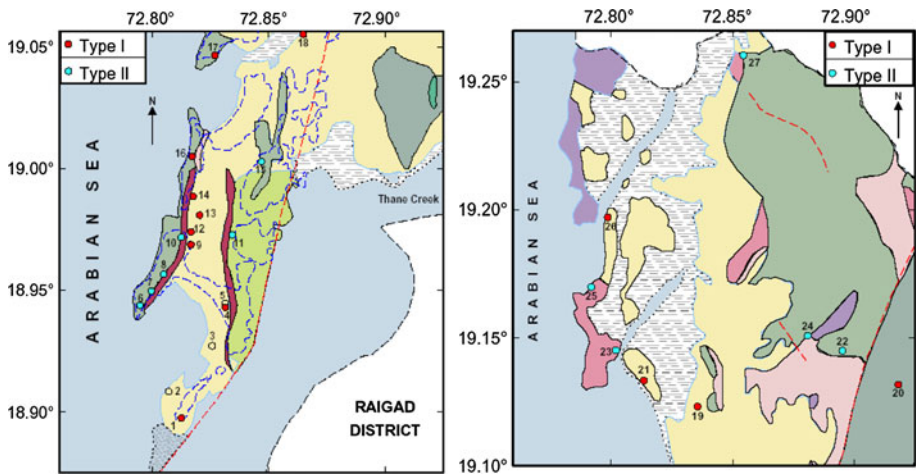


Fig. 8 Classification of sites based on peak amplification into Type 1 indicating amplification and Type 2 indicating absence of amplification. *Open circles* indicate sites (2, 3 and 5) where the site responses did not satisfy the stability criteria

covered areas in south Mumbai. In contrast, the sites e.g., 22 and 27 in north Mumbai show typical hard rock response with negligible amplification (Fig. 7c). Significant amplification observed at sites on alluvium suggests the presence of thick sediments as expected over reclaimed areas. The site responses validate the observations made from the maps and enable discriminate reclaimed sites from hard rock sites with negligible soil cover.

However, there are exceptions when hard rock sites are covered with thick weathered zone e.g., sites 1 and 4 lying on alluvium covered islands and sites 16, 17 and 20 falling in the region classified as hard rock, which show clear resonance frequency of amplification in a wide range of frequencies 3.3–10.5 Hz (Fig. 7b). The difference in frequencies of peak amplification can be related to variations in the sediment thickness based on the empirical

Table 2 Classification of sites based on site response

Type	Sites	Remark
I	MUMC(9), RTOF(12), MLAX(13), PLAN(14), BKCX(18), SPCO(19), VARS(21), INSH(26), IMDB(1), XAVI(4)	Sites located on alluvium covered reclaimed land Sites located on alluvium covered basaltic islands
	WORL(16), LILA(17), IITB(20)	Sites located on basaltic flows with thick top soil
	II	RAJB(6), MHLL(7), HANG(8), MPMI(10), BYCU(11), HAFF(15), RYPM(22), MADH(23), AAMC(24), DANA(25), BORI(27)

formula (Ibs-von Seht and Wohlenberg 1999), which has been successfully utilized to estimate the sediment thickness in Rhine embayment, Germany. Although the relation between peak frequency and sediment thickness may not be valid in the study area for estimating the sediment thickness, it can still be qualitatively used to study the variations in the sediment thickness. Thus, reclaimed areas characterized by low resonance frequencies 3.3–4.6 Hz have thicker sediment overlying the basement in comparison with hard rock areas with thick soil cover where the resonance frequencies are higher. The variations in resonance frequency of peak amplification can be used in addition to site amplification as a criterion in distinguishing between reclaimed land and hard rock with soil cover. For example, the site 17 (LILA) that is classified as hard rock is characterized by a resonance frequency of 4 Hz and amplification of 4.2 similar to that observed over reclaimed areas. These observations suggest that site 17 is underlain by a thick soil cover over a hard rock. However, as the site lies on the margin of the islands, it falls in the category of shallow accretionary land and there is a strong possibility of it being a reclaimed site. Most site responses exhibiting clear single peaks also show large amplification, which conforms to a uni-model of a thick sedimentary sequence overlying a basement. The sites exhibiting more than one peak suggest a bi-model in which there could be two different layers of varying properties overlying the basement. A few sites appear to conform to a bi-model where a second peak of amplification is observed at frequencies lower than the peak resonance frequency, however, the stability criteria are not fulfilled.

9 Conclusions

The site amplification together with the corresponding resonance frequency proves to be useful discriminants in identifying and demarcating reclaimed areas. The reclaimed areas in Mumbai are characterized by resonance frequencies in the range 3.3–4.6 Hz corresponding to clear single peaks of significant amplification (>4) on the H/V curves. These observations imply large velocity contrasts across a sharp discontinuity consistent with a uni-model of a single layer of alluvium overlying a basement rock. In contrast, the H/V curves devoid of clear peak amplification are observed at sites lying on the original basaltic islands and the mainland comprising of basaltic flows with negligible soil cover. The hard rock sites with soil cover exhibit amplification in a wide range of dominant frequencies suggesting significant variations in soil thicknesses and properties. The present pilot study provides the basic information about the site amplification and the associated resonance

frequencies at several sites in Mumbai that are critical inputs in preparing the seismic hazard maps for Mumbai.

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