Structure, soil–structure response and effects of damage based on observations of horizontal-to-vertical spectral ratios of microtremors

M.R. Gallipoli\textsuperscript{a,b}, M. Mucciarelli\textsuperscript{a}, R.R. Castro\textsuperscript{c,\ast}, G. Monachesi\textsuperscript{d}, P. Contr\textsuperscript{e}

\textsuperscript{a}Di.S.G.G.-University of Basilicata, Campus Macchia Romana, 85100 Potenza, Italy
\textsuperscript{b}I.M.A.A.-CNR, C. da S. Loja, 85050 Tito Scalo (PZ), Italy
\textsuperscript{c}CICESE, Division Ciencias de la Tierra, Km 107 Carret, Tijuana-Ensenada, Ensenada, Baja California 22860, Mexico
\textsuperscript{d}INGV, Via di Vigna Murata 605, Roma 00143, Italy
\textsuperscript{e}I.A.E.A., Vienna, Austria

Accepted 11 November 2003

Abstract

The microtremor horizontal-to-vertical-spectral-ratio (HVSR) technique is widely used in the urban environment to assess the fundamental frequency response of the ground. Extensive literature exists about case histories using HVSR for microzonation in several cities, but no systematic studies have been devoted to check the presence of soil–structure interaction effects, and even less attention to study building behaviour after earthquake damage. To evaluate the above-mentioned effects, a series of experiments are reported in this article.

We first made a series of microtremor measurements on buildings and civil structures to evaluate the reliability of fundamental frequency determinations. Then, we considered several case studies to evaluate the effect of soil–structure interaction in estimates of site response in the presence of tall buildings. Finally, an experiment on the frequency change due to damage was performed. It was possible to confirm that HVSR is able to detect building fundamental modes and once known the building frequency, it is also possible to detect the presence of soil–structure interaction. Thus, once the presence of the building natural frequency is identified, it is possible to infer the site response from free field measurements. We also found that the HVSR technique is equally useful for detecting structural damage by determining the frequency shift of the buildings.

\textcopyright 2004 Elsevier Ltd. All rights reserved.

Keywords: Soil response; Soil–Structure interaction; Structure response; Microtremors

1. Introduction

Recent studies \cite{1,2} have evidenced the influence of building vibration on free field ground motion measurements. The building vibration radiates into the soil a diffracted wave field. This wave field, trapped in the foundation layer, produces a variation in frequency and amplitude of the ground motion, causing the so called site–city seismic interaction \cite{3}.

During an earthquake it is difficult to measure and separate source and site effects from that of the oscillating building. Again, it is most difficult to segregate the energy from a single vibrating building from the energy from other buildings and to separate these energies from the energy of the incident wave train. To estimate the quantity of energy that a building can release back to the soil, experiments with controlled conditions have been carried out.

Jennings \cite{4}, using forced vibration of buildings, has performed one of these experiments. Kanamori et al. \cite{5} studied the effects of high-rise buildings in Los Angeles, whose vibration was caused by the sonic boom of the Space Shuttle. Guéguen et al. \cite{6} performed a vibration experiment using a pullout test on a five-story RC-building model (scale 1:3) located in the EuroSeisTest site Volvi (GR). Similarly, Mucciarelli et al. \cite{7} describes the outcome of the recordings of free field seismic motion induced by a base isolated three storey building during a release test with 13 cm dislocation. The conclusion of these experiments confirms the importance of the interaction of building vibrations on ground motion. In an urban environment where several nearby buildings may release a noticeable quantity of energy at the same frequency, constructive
interference can be produced during an earthquake. The increase of amplitude motion will occur at the same range of frequency, thus possibly causing resonance effects on buildings located on the maximum of the interference pattern. Even if, the nearby buildings will contaminate the seismic ground motion, in microzonation studies this effect is rarely taken into account. As an example of the concern that building frequency could mask soil frequency during weak motion array operation see Tento et al. [8].

Many studies have demonstrated that the horizontal-to-vertical-spectral-ratio (HVS R) technique gives good estimates of resonance frequency of soils (for a review see Mucciarelli and Gallipoli [9]). So, in this study we use the HVS R with microtremor measurements, or Nakamura’s technique, following the scope and assumptions of Nakamura [10], the author that originally proposed the method. In general, the evaluation of the natural frequency of vibration of a building by traditional analytical methods is more uncertain than the evaluation of its static properties. For this reason, it becomes important to develop alternative approaches. The proposed procedure, essentially based on a small number of microtremors measurements on the floors of the existing building, gives a good estimation of main natural frequency of the building.

When good frequency estimates for free field sites are necessary, it is essential to evaluate them as far as possible from the range of influence of nearby structures. The influence of buildings in the determination of free field site response has been evident from HVSR functions obtained in different studies.

Another effect that may change the natural frequency of vibration is that due to the damage generated by strong motion. To study this, an experiment on a one-to-one scale building has been performed. Microtremor measurements have been taken before and after the damage, to estimate the main building frequency. It was observed that the damage produces a decrease of the natural frequency of the structure.

2. HVS R and dynamic behaviour of man-made structures

To evaluate the dynamic behaviour of buildings in seismic areas, the structures can be instrumented to record their response to a seismic input. This requires earthquake occurrence to gather data. Another possible alternative is to perform forced vibration studies, either with vibrodynes or with the snap-back approach [6,11,12]. The HVS R technique applied to weak motion from earthquakes has proven to be a reliable technique for identification of frequency response of structures like dams, for example, the Arvo and Trepidio dams, in Italy (Castro et al. [13]) and the Infiernillo dam, in Mexico (Castro et al. [14]). Microtremor HVSR can also provide a feasible and economical alternative. Nakamura [10] suggests the application of this technique for the estimation of a sort of instrumental vulnerability index. Mucciarelli et al. [15] proposed an alternative approach that takes more directly into account the importance of the input seismic spectrum. While the application of HVS R to vulnerability estimates requires further extensive validation, it is more accepted that it is a feasible technique for determining a building fundamental frequency without the need of simultaneous measurements at each floor [16]. The main expected result is the determination of the fundamental frequencies of the investigated building and of its soil foundation to determine resonance phenomena capable of compromising building stability during an earthquake. These results cannot have the complexity and the richness of information of the dynamic behaviour in the time domain obtained with a study that involves the installation of a permanent monitoring system. Nevertheless, it is very useful to be able to obtain, in the frequency domain, a faithful representation of the linear elastic behaviour. The importance of resonance between civil buildings eigenmodes and soil frequency has been investigated by Ganev et al. [17], by Mori and Asada [18], by Mucciarelli and Monachesi [19] during the Umbria-Marche earthquake, by Mucciarelli and Monachesi [20] during the Slovenia earthquake and by Mucciarelli et al. [21] for the 1998 Southern Italy earthquake. Nakamura et al. [22] and Nakamura [10] described the determination of main frequencies of vibration of cultural heritage structures using HVSR such as the Leaning Tower of Pisa and the Roman Coliseum.

3. Description of experimental measurements made on buildings

Microtremor measurements have been performed at buildings with different typology to analyse the possibility of evaluating the natural frequency of the structures. The measurements were made at each floor. Obviously on the top of the building the main frequency of the structure shown by the HVSR function is more evident than that obtained for the lower levels. For one of the structures chosen, the natural frequency had been estimated in a previous study. So, in this article we obtained an additional estimate.

In the following, two case studies will be presented to discuss the capability of HVSR technique to detect the building fundamental frequency.

3.1. Dynamic behaviour of the C.N.R. Laboratories at Tito Scalo, Italy

This is a recent, small RC frame building, with a typical antiseismic typology.

The HVSR measurements were made at three different locations inside the building (basement, first floor and second floor) and one at free field. Fig. 1a shows the amplification functions obtained for these sites. The free
field amplification function shows a main peak at about 1.5 Hz, but the structure shows a natural frequency near 3.2 Hz. The peak amplitude corresponding to the resonance frequency of the free field is present in the HVSR amplification functions at basement and other levels. In Fig. 1b the amplification rate between floors are reported. It is important to note how the amplification value increases linearly with height.

3.2. Structural dynamics of the Potenza’s University Campus, Italy

A study was performed at one block of the new campus of the University of Basilicata, namely the Faculty of Science. The construction of the building started in 1992 and it is now completed. The total volume of the building is about 100,000 m$^3$. Fig. 2 shows the longitudinal section of the building and the points where measurements were made. This building was designed and built with a seismic isolation system. All geometric and structural characteristics are known and previous studies performed on the building have been reported. The aim of the HVSR experiment was to study if it is possible to analyse with this technique the dynamic behaviour of buildings, and in particular to study how the introduction of isolators can change the building’s behaviour, since this isolator act as points of discontinuity between building and soil.

The investigated building is made of a main block, 60.50 m long and 32 m wide, with three towers that are connected at all floors with the main block, along its longitudinal side, with dynamic joints. The isolation system is placed on a one-story stiff frame basement. Due to terraced foundation, the isolation system is arranged at two different levels, in two parts of the building. One part has six storeys (north side) and the other five (southern side), with 3.40 m inter-storey height [23, 24]. The horizontal and vertical layout of this building is quite complex: in the selected solution the isolation system is placed at the second...
level above ground to reduce the free height of retaining walls and to take some advantage of the foundation. The isolation system is placed between two beam grids.

In this building HVSR microtremors measurements were performed to identify building fundamental frequencies of oscillation, how displacement rate changes between floors and if the fundamental period of the soil is affected by the buildings behaviour.

Each measurement was processed separating longitudinal amplification functions from transversal ones, where

Fig. 3. Amplification ratios at each measurement location (Fig. 1). Both longitudinal and transversal amplification functions are shown.
the longitudinal function is related with the longer side of the building. All graphs are reported to the same scale to highlight the broad order of amplification spectra. As can be seen in Fig. 2, points 5–7, where measurements were performed, are located at the same distance from the side of the building but at different levels. Likewise the sites 1–4.

In the part of the building with six floors (north side), four measurements were performed:

(a) on the beam grid where isolation system are placed upon, at site 1 (Fig. 3.1a);
(b) on the second floor at site 2 (Fig. 3.2a);
(c) on the fourth floor at site 3 (Fig. 3.3a);
(d) on the fifth floor at site 4 (Fig. 3.4a).

In the southern side of the building, where the structure has only five floors, three measurements were made:

(a) on the beam grid where isolation system are placed upon, at site 5 (Fig. 3.1b);
(b) on the second floor at site 6 (Fig. 3.2b);
(c) on the fourth floor at site 7 (Fig. 3.3b) which corresponds to the fifth floor on the northern side.

Both longitudinal and transverse components of HVSR were made at all sites. At sites 1 and 5, on the beam grid below the seismic isolation system, the response is flat in the whole frequency band (Fig. 3.1a and b). In contrast, sites 6 and 7 located in the south side of the building show a sharp peak at 2 Hz in both components, with amplification increasing with height (Fig. 3.2b and 3.3b). It is interesting to note that the longitudinal and transverse response functions of sites 2–4, on the northern part of the building, is different. The longitudinal component has a peak at 2 Hz, while the transversal component the peak is at 3.2 Hz (Fig. 3.2a, 3.3a and 3.4a).

In the longitudinal section, the dynamic behaviour of the northern side of the building (the side with six storeys) is similar to the southern side because they have an equal distribution of stiffness and consequently the main period is the same. In the transversal section the dynamic behaviour of the two parts of the building is different, the tallest section having the main peak shifted towards 3 Hz. This could be expected because the period of vibration is inversely proportional to the square root of the secant stiffness, which is, in turn, inversely proportional to the displacement [25]. Other measurements were performed along a longitudinal transect between sites 4, 7 and 8 along the fourth floor. Along the longitudinal section the building has the same dynamic behaviour. However, for the transversal section we consider it important to study how the peak is shifted and what happens at the point where there is a change of building height. It can be seen that at the southern side the amplification ratio has the main transversal peak at 2 Hz (Fig. 4a), at northern side is at 3.2 Hz (Fig. 4c) and in the central part of the whole structure is at an intermediate frequency (2.5 Hz) (Fig. 4b). In fact the rearrangement of vibration main period is attributed to the action of the isolation system. The uncoupling of translation and rotational modes of vibration tries to adjust the multimodal dynamic behaviour caused by the shape irregularities.

This base isolated building underwent a complex set of release tests, with different displacements from the zero offset position. The full set of experiments is described in Bixio et al. [24]. The dynamic response of the building was estimated by both time- and frequency-domain analyses of the acceleration time histories recorded at multiple positions all around the building. The results of those experiments pointed out the strong non-linear and amplitude-dependent
behaviour of the isolator-building system. For our purpose, there is a satisfactory agreement with the asymptotic behaviour for small displacements. The fundamental frequency of the isolated building is decreasing with oscillation amplitude: for small displacements the frequency is \(1.6 \pm 0.1 \text{ Hz}\), thus comparable with the \(2.0 \pm 0.5 \text{ Hz}\) deduced from HVSR measurements.

HVSR measurements on free field in the vicinity of the building and below the isolation system do not show any significant peak, indicating that the isolators are effective in decoupling the building from the ground.

4. Dynamic soil–structure interaction

This study was undertaken to understand how much the presence of buildings contributes to the free field measurements. In this section we address the following question: what is the radius of influence of a structure on a free field measurement? It is important to know if the fundamental mode of vibration of the ground from free field measurements near buildings is influenced by the presence of the structures. Guéguen et al. [6] and Mucciarelli et al. [7] have recently shown that, during an earthquake, the frequency of a building can be detected in free field measurements. The aim of our experiments, reported in this section, is to investigate whether microtremors can pick up this effect also.

During a microzonation study in the town of Fabriano (Italy), Tento et al. [8] showed that some of the amplification functions deduced from a reference station spectral ratio (RSSR), using weak motion recordings, could be contaminated by the vibration of the building housing the seismometers. This was inferred using the HVSR technique.

In the past only a few investigations using HVSR have been done to study soil–structure interaction. For instance, Mucciarelli et al. [26] measured microtremor H/V spectral ratio at the Hera Lacinia Column site, in the Calabria region (Italy), and they found that the first vibration mode of the column could be recognize at around 0.5 Hz. It was also found a peak at this frequency present in free field measurements made near the column with decreasing amplitude as distance increased. This peak became insignificant at a distance approximately equal to the height of the column. Interaction between frequencies of structure and soil have also been shown by Castro et al. [13] using weak motion earthquakes recorded at a dam in Southern Italy.

4.1. Macerata’s aqueduct water tower

To study the dynamic interaction between soil and structure, measurements were performed in a water tower structure in Macerata, Italy. We study how the soil–structure dynamic interaction changes with distance by taking measurements at progressive distances from the water tower. This structure was selected because there is a large free field area around it. The structure is comprised of a cylindrical stand, which is inserted at the plinth base. On the top there is a tank which is jointed at the stand with flanges and has a hydraulic capacity equal to 500 m³. The cylindrical stand is 30 m high, the basin is 10 m, thus the total height is 40 m: this is a slender structure with a heavy mass on the top.

In the water tower structure three HVSR measurements were performed (Fig. 5):

(a) at 30 m height, on the top of cylindrical stand;
(b) at 36 m height, in the middle height of basin;
(c) at 40 m height, on the top of the whole structure.

The amplification ratio at 30 m shows the main peak distributed about 0.8–1 Hz (Fig. 5). This is in a good agreement with main period computed by the designers: when the basin is full of water the main frequency is estimated at 1.27 Hz. There is another peak at about 5.5 Hz that can be caused by the mobility effect of water in the tank. This last peak is above other peaks for the measurement at 30 m height because this is the joint between the slender stand and the mass of the basin. These two parts have different mass, inertia and typology. At 36 and 40 m the amplification functions have the same performance with the main peak at about 0.8–1 Hz. Because the structure is symmetric in all directions, the amplification functions of the two components are very similar.

In free field four HVRS measurements were made (Fig. 6): at the base of the structure, and at 12, 30 and 100 m from the base. Note that at 100 m the site is at twice the height of the water tower.

For the first three measurements the behaviour of the amplification functions, in the low frequency range, is similar to the response of the structure. There is another peak at high-frequency probably related to a man-made fill. In all the measurements made, the natural frequency of the tower (peak at 1.0 Hz) is present in the site response. It has been
suggested by Gueguen et al. [3] that for a distance of at least 10 times the foundation length of the structure the influence of the structure vanishes and the measurement could be assumed as the actual free field. For the case of the tower, the foundation is about 15 m deep but unfortunately we were not able to measure at a distance greater than 150 m because of space limitations. However, the measurement made at 100 m is consistent with Gueguen et al. [3].

4.2. The Engineering Faculty Building of the Quindio University, Armenia, Colombia

The Engineering Faculty Building of the Quindio University in Armenia (Colombia) is a four floor RC building, regular in elevation and with a rectangular plan. HVSR measurements were made on all the floors, along both longitudinal and transversal directions. Two free field measurements were also made at 7 and 15 m from the building, which is 13 m high.

The results for the transverse component are reported in Fig. 7. It can be noted how the peak amplification shows a fairly regular increase with height at the same frequency (2.5 Hz). The free field measurement at a distance greater than the height of the building shows a peak at a frequency different from the measured fundamental frequency of the building, at 3.2 Hz. This observed frequency is likely due to the resonance of a layer of volcanic ashes about 30 m thick, with an average Vs velocity of less than 400 m/s [27]. The free field measurement closer to the building shows a peak at the same frequency of the building, but at an amplification level smaller than the one recorded at ground floor, indicating the presence of soil–structure interaction. The pattern for the longitudinal component is the same and it is not reported here for sake of brevity.

5. Frequency change due to damage

The HVSR has been used in the past to perform quick surveys soon after the occurrence of an earthquake to test building and soil behaviour. Examples of these are given in the articles cited in Section 1.

After a strong quake it has been found that damaged structures suffer a change in their fundamental frequency. There is a lack of HSVR data in buildings before and after earthquake damage. However, it is possible to tests...
structures subjecting them to shaking table tests. We took advantage of a structure built for studying different techniques of retrofitting in the framework of an EC-INTAS project in the laboratories of ISMES, Italy. The structure (Fig. 8) was a two storeys RC frame with masonry infills in one direction only, square plan (3 £ 3 m²) and inter-story height equal to 3 m. The model also allowed for roof and interior weight simulation by the addition of steel masses on the floors.

The aim of the test was to damage the structure, retrofit it and then shake it again with the same input that caused the damage to test the performance of the retrofitted structure. We first performed measurements on the undamaged structure at each floor. Fig. 9a shows the increase of the amplification as a function of height for the undamaged case at the resonance frequency (equal to 4 Hz) has been reported (a). These amplification values are obtained before the damage. The low graph (b) the amplification functions of e-w component of measures performed before and after damage are shown. After the damage the frequency was reduced at about 75% of the undamaged one.

6. Conclusions

The HVSR of microtremors gives a good estimation of natural building frequency. The response of the ground is strongly influenced by the proximity of structures. For the case of the water tower described earlier, for instance, the influence of the structure remains even at a distance of twice the height of the structure. This finding is very important for microzonation studies to determine site periods. Another important contribution of the HVSR method is the identification of building damage by the changes in the natural frequencies of a building before and after an earthquake. To make sure that recorded microtremors are not contaminated by energy radiation from adjacent buildings, the natural periods of some of the larger structures should be determined, so that they can be detected in the microtremor measurements of the ‘free field’, if they are present.

Acknowledgements

We are in debt with the editor of SDEE, Dr W.D. Liam Finn for his useful comments and suggestions, which help us to improve the original manuscript. We also thank the anonymous reviewers. Part of the field work was made when one of the authors (RRC) was spending his sabbatical year in the Osservatorio Geofisico Sperimentale di Macerata, Italy. We thank Dr L. Cano of Quindio University for his kind support during the stay of MRG and MM in Colombia.

References


