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EXPERIMENTAL EVALUATION OF SEISMIC SITE RESPONSE OVER AND NEARBY UNDERGROUND CAVITIES (STUDY OF SUBWAY TUNNEL IN CITY OF KARAJ, IRAN)*

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Abstract– The effect of underground cavities in site seismic response was studied over the subway tunnels that are under construction in the city of Karaj, using ambient noise measurements as well as numerical modeling. The idea for this research comes from the observation of differences in experimental site transfer function, calculated on more than 100 locations of the city, for the areas near the under construction subway tunnel, compared with other parts of the city. In the present study a series of multi stations ambient noise measurements at 11 test sites across the tunnel were performed to evaluate the effect of the tunnel on seismic site response. This paper shows the results of these measurements as well as the result of a numerical modeling for one of the locations. The results show that the site effect in areas near the tunnel are affected by tunnel and vary based on dimension of excavation and distance from tunnel axis.

Keywords– Seismic site response, subway tunnels, Karaj, Iran

1. INTRODUCTION

The effect of surface and subsurface irregularities is one of the well known local site effects that may affect the ground surface motion and numerous studies have been developed on the effect induced by valleys and topographies. Despite these large numbers of studies, understanding and quantifying the effects of underground irregularities, such as buried cavities or tunnels, is still at a research stage. Similarly, the identification and characterization of either natural or artificial subsurface obstacles, such as cavities or petroleum reservoirs, constitute a challenging issue for geophysical subsurface investigations [1].

On the other hand, almost all of the researches that have been previously carried out in this topic are of analytical calculation or numerical modelling type [1-3]. There have been only a few experimental efforts in characterizing the effect of the subsurface cavities on seismic ground motion by Lombardo and Rigano [4, 5] and Sgarlato et al [6].

The present paper deals with evaluation of local seismic response related to the presence of subway tunnels in the city of Karaj (Iran) in the framework of a comprehensive research project of the local seismic hazard studies in this town. This city, with a population near to 3 million is situated 25 km west of Tehran and adjacent to some active faults, capable of creating an earthquake with magnitude greater than 7.

A subway network, consisting of 5 lines with a total length of 72 Km (Fig. 1) is under construction by the municipality of the city that covers considerable area of the city and can affect the seismic site

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response, at least for the localities up to or near the tunnels. In order to study the seismic site response near these tunnels a series of experimental ambient noise measurements and numerical modeling are considered for some sites along line 2 of this subway network, for which the excavation is completed.

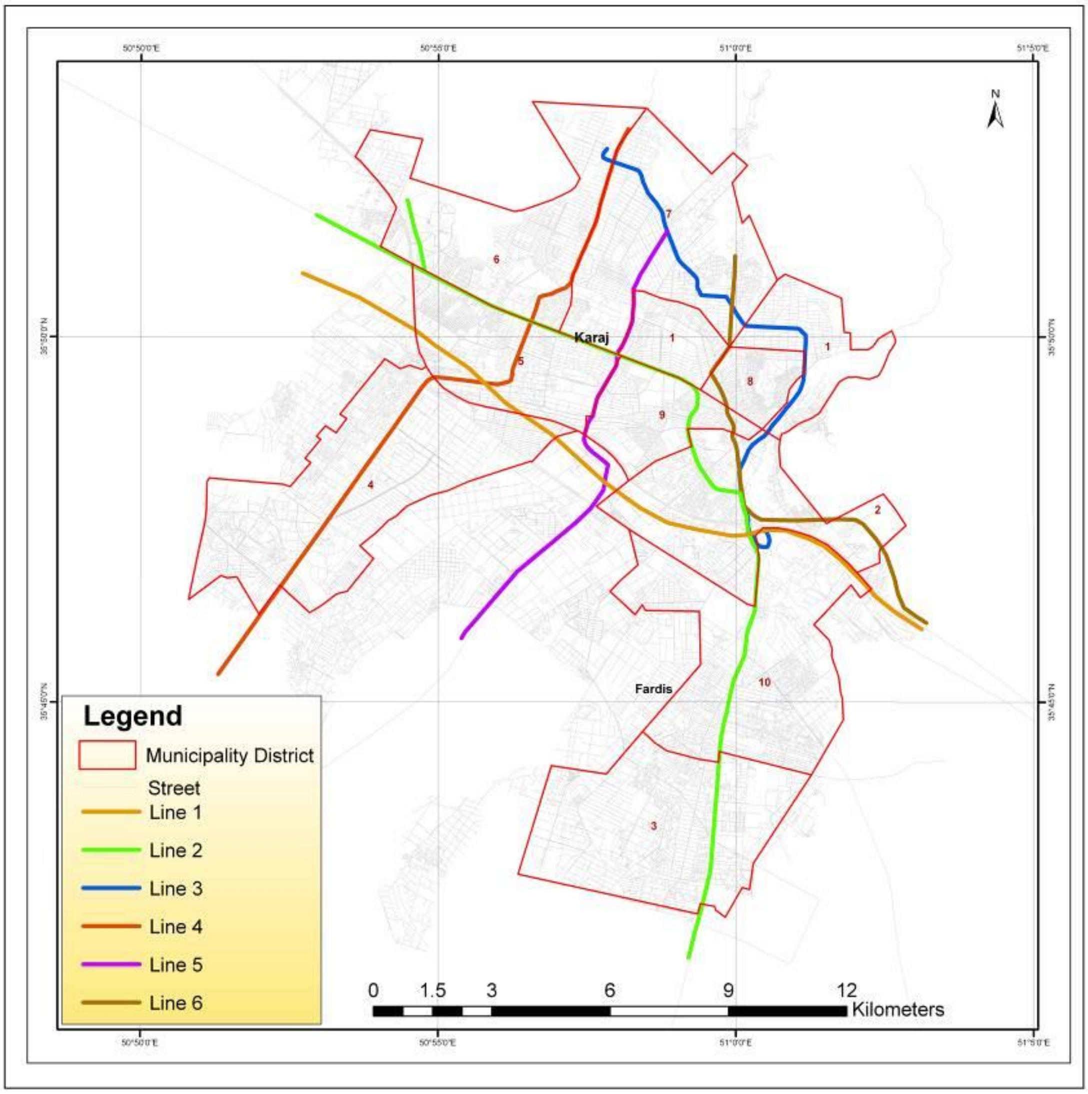


Fig. 1. Karaj Municipality districts and under construction subway plan

2. GEOLOGICAL AND GEOTECHNICAL SETTING

Karaj is located on Plio-Quaternary alluvial deposits of a very large piedmont, which is bordered by the southern slopes of the Alborz Mountains in the north of the city. There are also some minor hills in the south-western part of the city.

There is a general decreasing trend in grain size of alluvial deposits from north to south, as well as east to west. This decreasing trend is in accordance with the increasing distance from the northern mountains and Karaj River; however, there are some anomalies such as the existence of a silty-sandy surface layer at the northern foothills. Figures 2 and 3 show the surface geological map of the area and a geological section along the subway line 2.

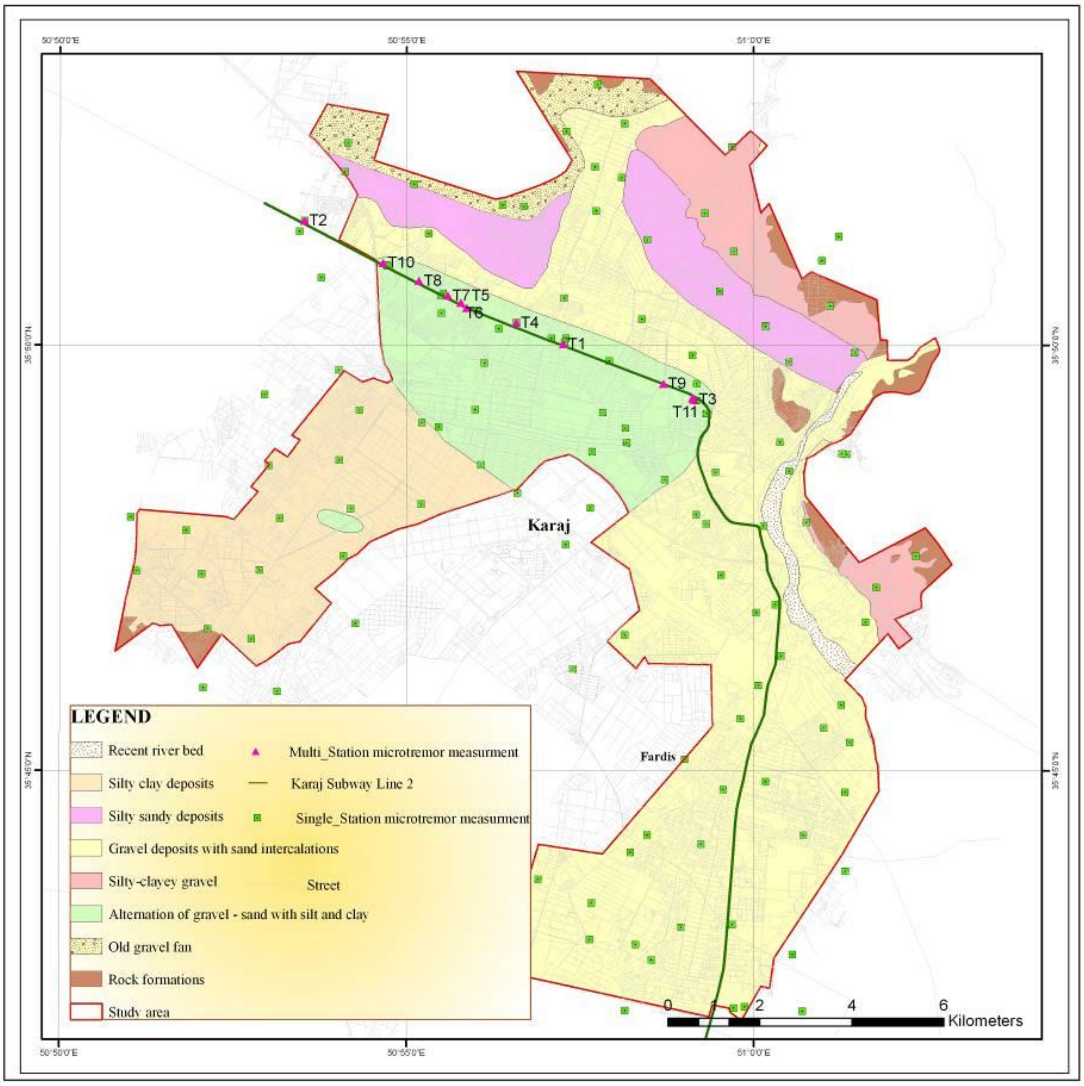


Fig. 2. Surface geological map of the city and location of experimental measurement along the subway tunnel (line 2)

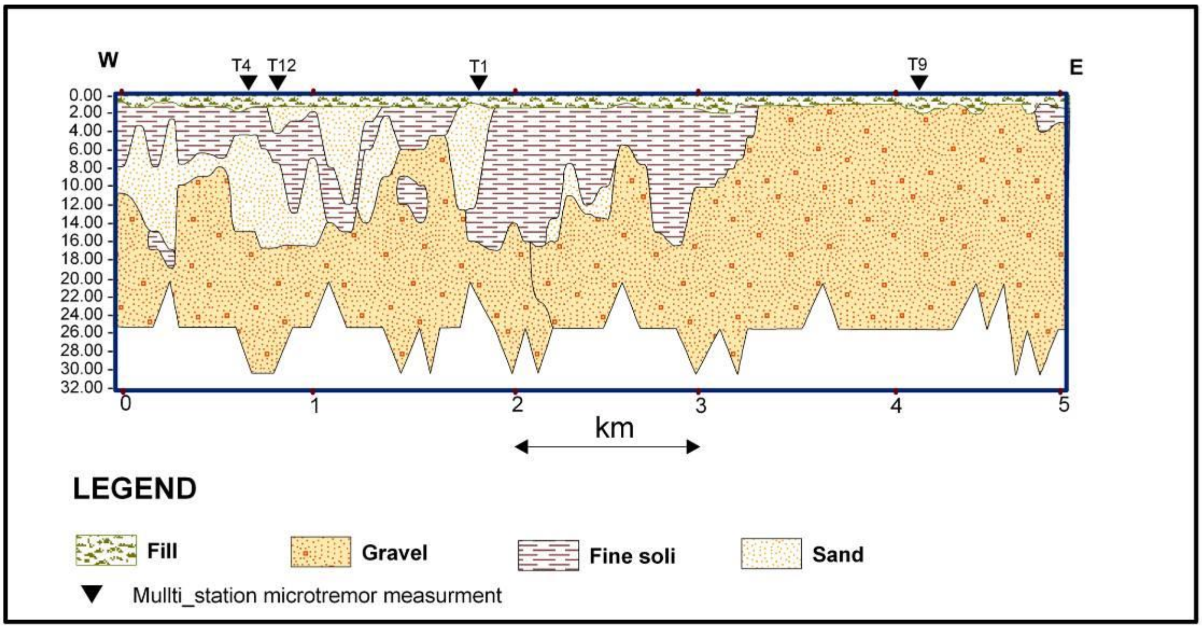


Fig. 3. Surface geological cross section along a part of the studied subway tunnel

The mentioned geological situation is based on direct observation of active excavations and boreholes drilled for subway construction and other constructional projects within the city. The depth of these observations is limited to the maximum depth of drillings (not more than 60 meters); however, the geological evidence proposes much greater thicknesses for Karaj alluvial deposits. A depth of 150 to 400 meters has been proposed for geologic bedrock in different parts of the city, based on Geological interpretation, some electrical resistance and ambient noise array measurements [7].

The geo-seismic measurements at 33 locations of the city show that shear wave velocity exceeds from 700 m/s in the central part of the city for the near surface layers (down to 30 meters) but remains less than 500 m/s at south-western and south-eastern zones (Fig. 4).

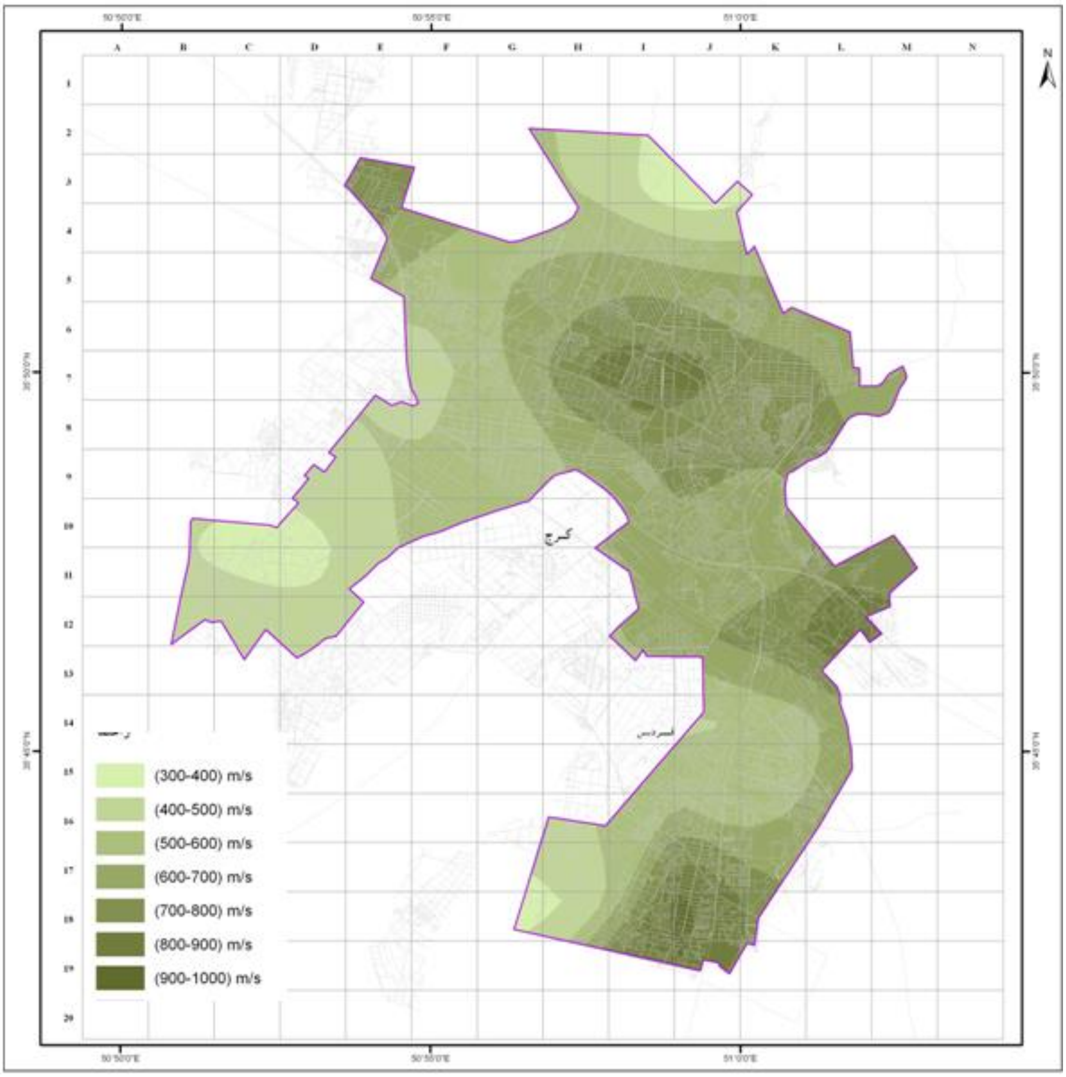


Fig. 4. Shear wave velocity (Vs) of Karaj city for depth 30 m, obtained from refraction seismic measurement at 33 localities of the city (Haghshenas et al. 2013)

Despite such condition of shear wave velocity the results of horizontal/vertical spectral ratio on single station ambient noise measurements (H/V) at more than 120 locations show that resonance frequency of the soil profile tends to decrease toward the central part of the city. In addition, for most of the measured locations the resonance frequencies are lower than or around 1 Hz. Figure 5 shows the map of resonance periods, obtained during the Karaj microzonation studies [7].

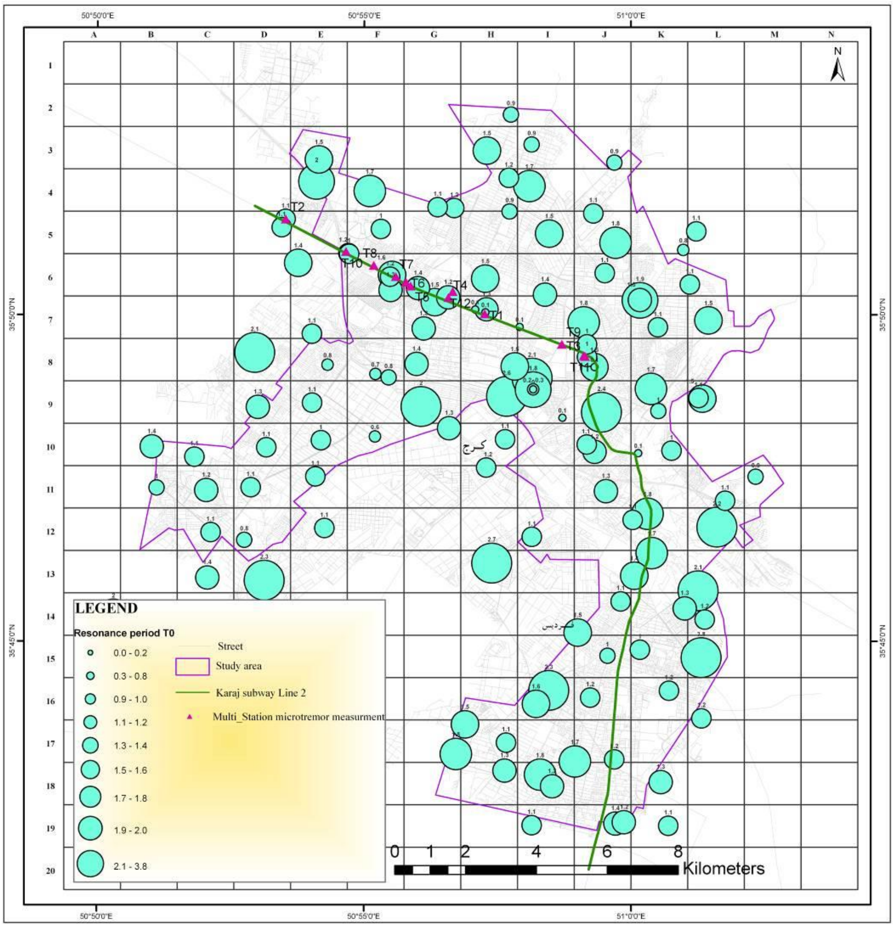
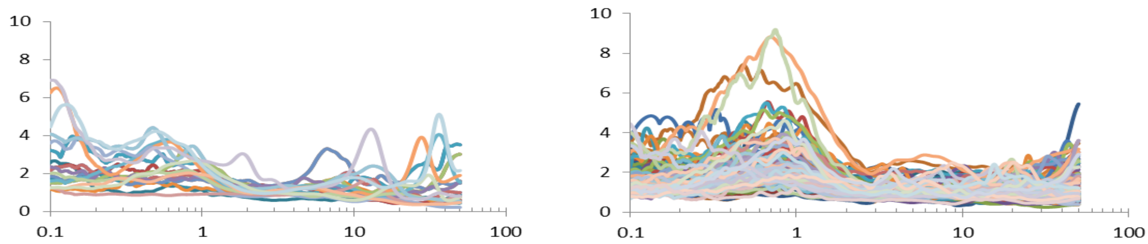


Fig. 5. The resonance periods obtained from single station microtrmor measurements and H/V spectral rations calculation. The map was prepared based on first peak, observed on H/V curves

This disagreement between frequency of resonance and near surface geological and geotechnical condition of the studied area can be attributed to the existence of a deep impedance contrast (geological bedrock for example) at the base of very thick alluvial deposits having a shear wave velocity with gradient increment. The same condition has been previously reported for Tehran at 25 Km east of Karaj [8].

For the stations measured near the subway tunnel, in addition to this low frequency peak, another peak is seen on H/V curves in higher frequencies (around 10 Hz), that does not exist in other parts of the city (Fig. 6). So it seems that the existence of the underground cavity alters the seismic response of the ground surface.



(a) (b)

Fig. 6. Average of H/V spectral ratio for data recorded in distance less than 150 m from the tunnel axis (a) and data recorded in other part of the city with distance farther than 150m form the tunnel axis (b)

These changes in H/V behavior for the areas near to the tunnel convinced us to perform some multi station measurements across the tunnel to investigate how the underground openings can affect the site response.

3. MULTI STATIONS DATA ACQUISITION

The multi-station microtrmor measurements have been performed in 11 locations (Fig. 2) over the subway tunnel with the aim of experimental evaluation of the effect of underground cavity on the site response. Each test includes the installation of one or more seismological stations at the base of the tunnel and some stations on the ground surface at different distances from the tunnel axis (0, 40, and 100 meters). The numbers of surface stations were different from one test to another test due to the availability of the instruments.

The measured sites include different types of tunnel shapes and dimensions that can be classified into 4 general shapes (Fig. 7). Table 1 and 2 show the site characteristics in each location. For 2 locations (T3 and T9 on Fig. 2) we had the opportunity to perform the measurements in 2 different stages of excavation that enabled us to compare the site response based on tunnel dimension.

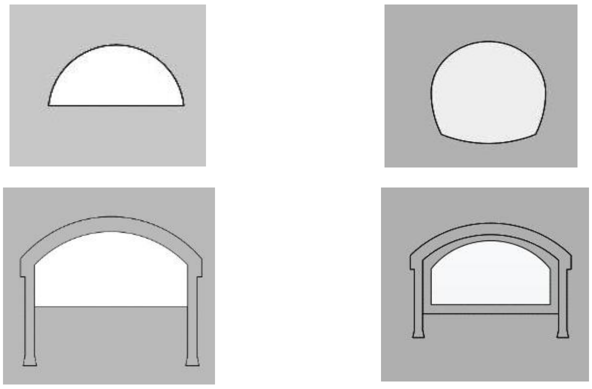


Fig. 7. Schematic of 4 general type of measured tunnels, (up-left: Top Tunnel, 4.2m height, 9.69m width; up-right: Rectifier, 7.55m height, 21.6m width; down-left: Toe Horse , 8.37m height, 7.78m width; down-right: Complete Station , 10.2m height, 16.2m width)

The seismological equipment includes Guralp broad band velocimeters (CMG-6TD) with 1-3 hours of recording time. The sampling frequency is 100 samples per second.

Table 1. Characteristics of measuring sites and the name of reference stations for each site

Name	Base stations	Tunnel shape	Over burden (m)	Tunnel hight(m)	Tunnel width(m)	Soil type to 40 meter depth
T1	T1B1	top tunnel	10.6	4.2	9.69	Near surface: CL; in Depth: GC, SC
	T1B2	top tunnel	10.6	4.2	9.69	
	T1B3	toe horse	10.6	7.78	9.69	
T2	T2B1	toe horse	9.4	7.78	9.69	CL-ML
	T2B2	top tunnel	9.4	4.2	9.69	
	T2B3	top tunnel	9.4	4.2	9.69	
T3	T3B2	toe horse	15.5	7.78	9.69	GP,GW with cementation
	T3B3	Rectifier	10.25	7.55	21.6	
T4	T4B1	top tunnel	7.5	4.2	9.69	Near surface: CL in Depth: SC,SM
	T4B2	complete station	7.5	10.2	16.2	
T5	T5B1	top tunnel	11	4.2	9.6	SP-SM
T6	T6B1	toe horse	11	7.78	9.69	SP-SM
T7	T7B1	toe horse	11	7.78	9.69	SP-SM
T8	T8B1	toe horse	10.8	7.78	9.69	SP-SM
T9	T9B1	toe horse	15.5	7.78	9.69	GP,GW with cementation
	T9B2	complete station	12	10.2	16.2	
T10	T10B1	toe horse	9.5	7.78	9.69	SM
	T10B2	top tunnel	9.5	4.2	9.69	
T11	T11B1	top tunnel	10.8	4.2	9.69	Near surface: SP-SM, in Depth: GP-GM

Table 2. Name of out tunnel stations and their distance from tunnel axis for each site

Name	Base Station1	Name of surface stations and distance to tunnel axis (m)	Base station2	Name of surface stations and distance to tunnel axis (m)
T1	T1B2	T1S1, 0	T1B1,T1B3	T1S1, 25
		T1S2, 40		T1S2, 65
		T1S3, 93		T1S3, 118
		T1S4, 127		T1S4, 152
T2	T2B3	T2S1, 0	T2B1,T2B2	T2S1, 30
		T2S2, 40		T2S22,70
		T2S3, 80		T2S3, 120
		T2S4, 132		T2S4, 160
		T2S5, -145		T2S5, -115
		T2S6, -185		T2S6, -155
T3	T3B2	T3S1, 0	~	~
		T3S2, 40	~	~
		T3S3,105	~	~
	T3B3	T3S6, 0	~	~
		T3S7, 40	~	~
		T3S8, 100	~	~
		T3S9, 150	~	~
T4	T4B1	T4S1, 50	~	~
		T4S2, 90	~	~
		T4S3, 110	~	~
	T4B2	T4S4, 0	~	~
		T4S5, 40	~	~
		T4S6, 100	~	~
		T4S7, 160	~	~
T5	T5B1	T5S1, 40	~	~
		T5S2, 100	~	~
T6	T6B1	T6S1, 40	~	~
		T6S2, 120	~	~
T7	T7B1	T7S1, 40	~	~
		T7S2, 100	~	~
T8	T8B1	T8S1, 40	~	~
		T8S2, 100	~	~
T9	T9B1	T9S1, 0	~	~
		T9S2, 40	~	~
	T9B2	T9S3, 0	~	~
		T9S4, 40	~	~
T10	T10B1	T10S1, 50	~	~
	T10B2	T10S1, 50	~	~
T11	T11B1	T11S1, 40	~	~
		T11S2, 100	~	~

4. DATA PROCESSING AND RESULTS

Like the single station measurements all the multi station ambient noise data were processed using H/V technique [9,10,11] and also by spectral ratio of surface station to base stations (site/reference spectral ratio, SSR) method considering the in-tunnel stations as references.

Some steps of calculation were performed using the Geopsy software package (see the http://www.geopsy.org for information about this package). The stationary time windows of 40-60 sec length were selected using anti-triggering algorithm.

a) Site/Reference spectral ratio for multi stations measurements

As it concerned multi station measurements, the different spectral ratios between the stations, installed on the surface and reference stations, installed at the base of tunnel were calculated and compared based on geotechnical condition, tunnel dimension and distance from tunnel axis. In the following sections the results of these comparisons are presented and discussed. The spectral ratios were obtained by dividing the Fourier spectra of corresponding components of the surface station by base stations as well as the ratio of H/V spectral ratio at surface and base station. The H/V spectral ratios were used in order to eliminate the effect of local noises that may affect the spectral amplitude for surface stations, compared to base stations.

1. Effect of geotechnical condition: As Table 1 shows, a wide variety of soil profiles from fine grain relatively soft soils to coarse grain dense soils have been measured during the present study. As the geotechnical condition can also affect the site response we compare the spectral ratios in 2 test sites, T1 and T9, with clear different geotechnical condition. Site T1 is a site with predominant fine grain clayey soils in a 15 meter upper part, over the coarse grain gravely soils, while site T9 consists principally of cemented coarse grain materials (see the geotechnical section on Fig. 3). Spectral ratios of these 2 sites are compared on Fig. 8. For site T9 the results are shown for 2 tunnel shape toe-horse and complete station that have been measured during 2 different stages of excavation.

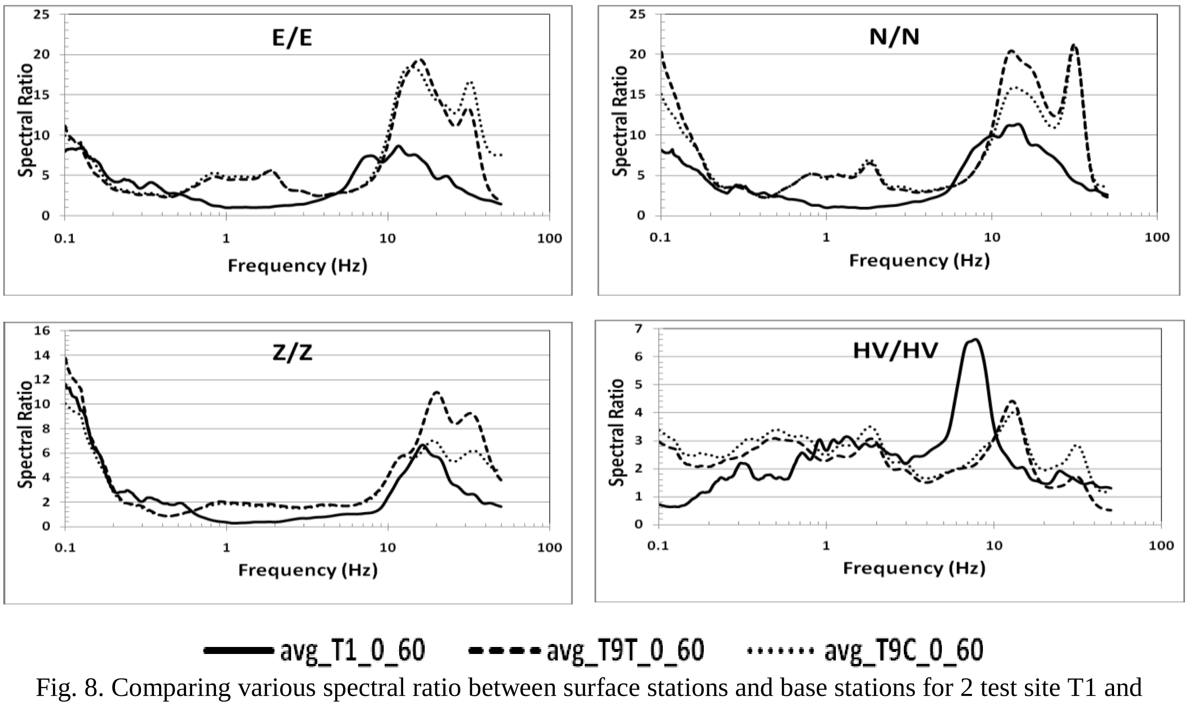


Fig. 8. Comparing various spectral ratio between surface stations and base stations for 2 test site T1 and T9 with clear different geotechnical profiles. The surface station spectra are averaged between to station, installed at distance 0 to 60 meters from tunnel axis. For T9, 2 series of measurement on toe-horse shape (T9T) and complete station (T9C) were used.

As can be seen, despite the clearly different soil profiles, the spectral ratios show a peak at frequency ranges around 10 Hz for both of these two sites. In addition, the amplification ratios are significantly higher for site T9 with dense coarse grain materials, while a contrariwise result is expected. Considering this comparison as well as overall H/V spectral ratios for the city it can be concluded that this peak for the sites near the subway tunnel is not related to geotechnical condition.

2. The effect of tunnel dimension: In order to study the effect of tunnel dimension on the site response, we first compare the spectral ratios for 2 test sites T3 and T9, for which we have microtremor measurement at 2 different stages of excavation, 1st measurement on toe-horse tunnel shape and 2nd one when the tunnel has been enlarged to rectifier for T3 and complete station for T9. The results are presented in Fig. 9. For site T3 a clear augmentation of spectral ratio can be observed with tunnel enlargement, while for site T9 the curve is significantly similar.

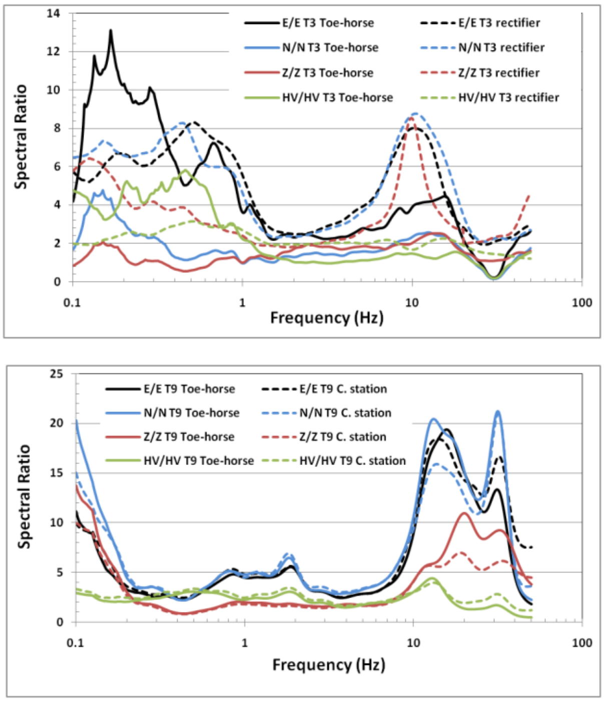


Fig. 9. Variation of spectral ratios with tunnel enlargement from toe-horse to rectifier at site T3 (up) and from toe-horse to complete station at site T9 (down)

Regarding these discrepant results and the fact that most of our measurements were performed on top-tunnel and toe-horse sections, in the next step we compared the average spectral ratios for these two types of sites. Figure 10 shows the spectral ratios, averaged on all the stations measured a different distances from the tunnel axis for these two types of tunnel shape. The results show general increasing trend of surface/base spectral ratios for the tunnel section with greater dimension (toe-horse).

3. The effect of distance from tunnel axis: Figure 11 shows the average spectral ratios for north-south component of all the measurements based on distance from tunnel axis. As it can be observed, the measurements over the top of the tunnel show the maximum value of amplification ratio that decrease with distance from tunnel axis. The maximum value in frequency range 4 to 20 Hz is extracted for all the 3 components (Fig. 12) and classified into 4 categories, based on distances from tunnel axis (Fig. 13). All of these observations indicate decreasing amplification with increment of distance from tunnel axis. As referred in previous sections it seems that the effect of Tunnel disappeared after the distances larger than 150 meters and, for the single station measurements, performed all over the city, far from the subway tunnel any amplification in high frequency can be observed.

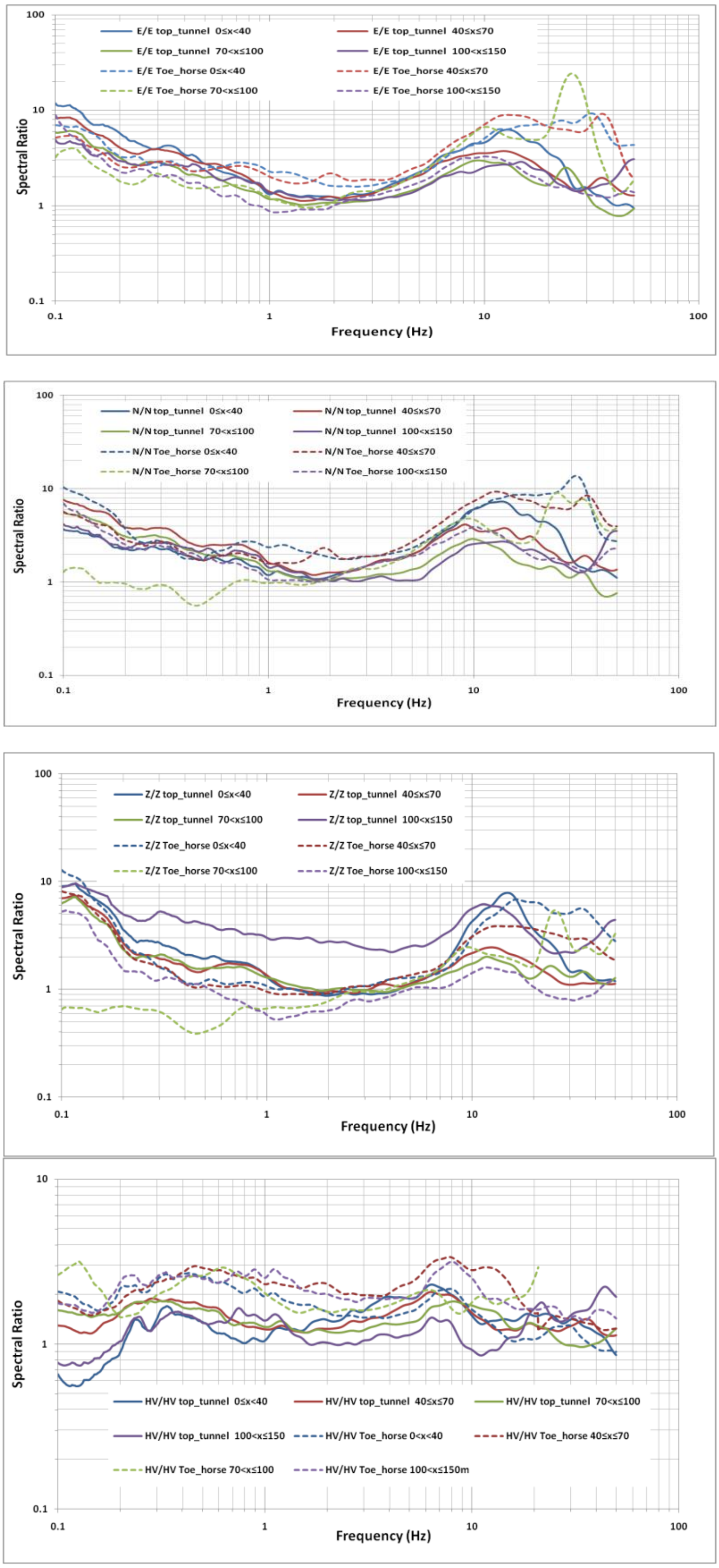


Fig. 10. Comparison of spectral ratios averaged on various distances from tunnel axis for all the stations measured around the top-tunnel and toe-horse tunnel shape showing the general increasing trend of spectral ratios for stations around toe-horse sections

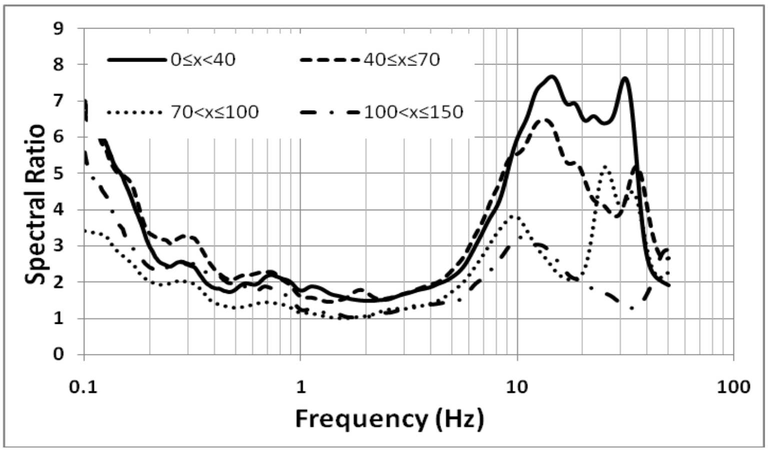


Fig. 11. Average spectral ratio for north-south component of all the measurements, classified based on distance from tunnel axis

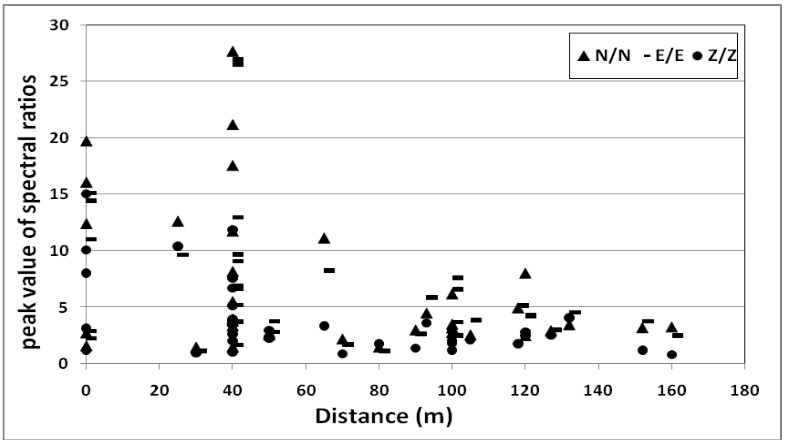


Fig. 12. Peak value of average spectral ratios of all the measurements, extracted for frequencies between 4 to 20 Hz, based on distance from tunnel axis

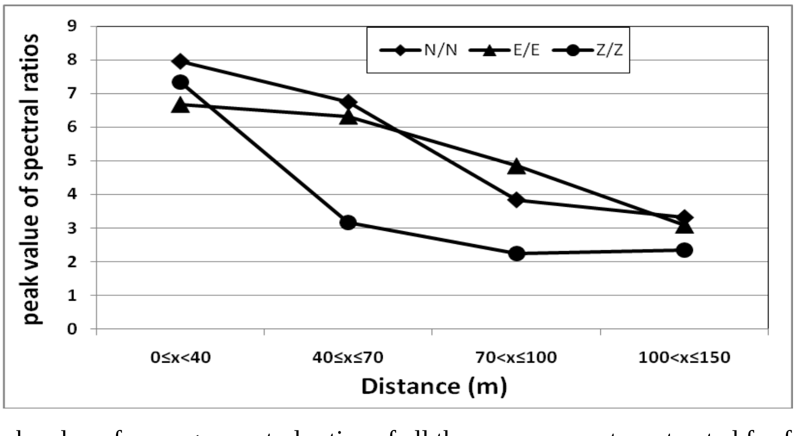


Fig. 13. Peak value of average spectral ratios of all the measurements, extracted for frequencies between 4 to 20 Hz, classified based on distance from tunnel axis

5. COMPARISON WITH NUMERICAL MODELLING

In order to compare the result of experimental measurement with numerical modelling the FEM numerical modelling applied for test site T1 is abbreviated here with N1 to distinguish between the numerical results and experimental one. A model with 200*400 meters dimensions in finite zone and 100*200 meters dimension in infinite zone was considered (Fig. 14). 100 seconds of recorded ambient noise was selected as input motion. This time history was extracted from a temporary seismic station installed for 2 months on bedrock in Karaj during the earthquake geotechnical microzonation of this city [7]. The model response was calculated for some points at the base of the tunnel and some points at ground surface as shown in Table 3. The spectral ratios between surface points and base points were calculated and are compared in the following paragraphs.

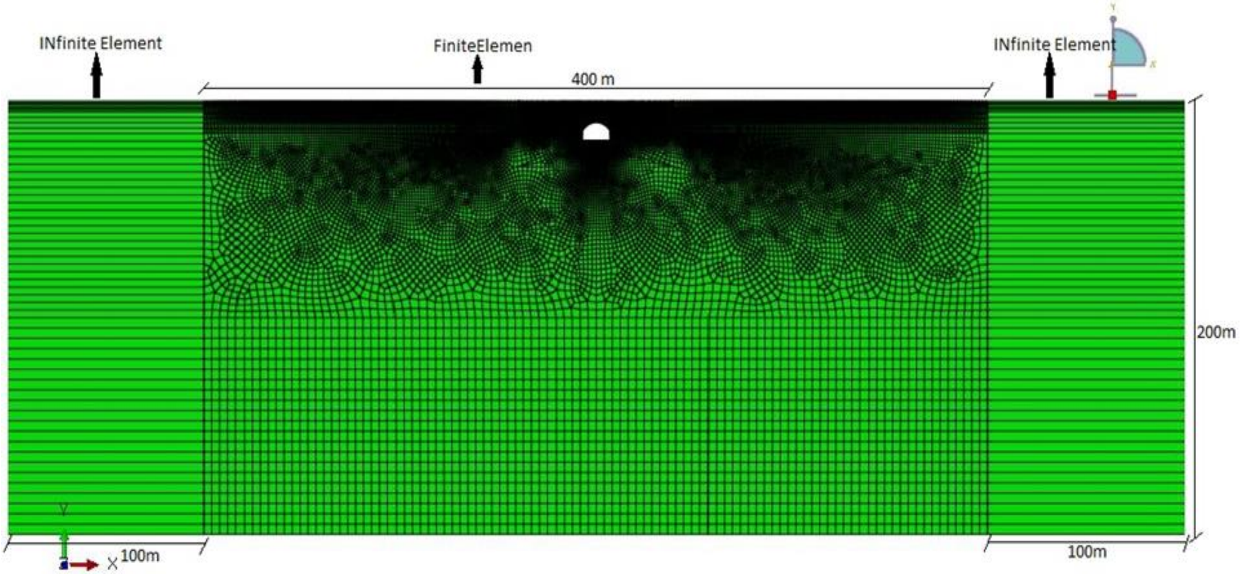


Fig. 14. Configuration of the model used for numerical modelling

Table 3. Name and characteristic of calculated nodes in numerical modelling

Tunnel type	Surface nodes	Base nodes	Distance of surface nodes to axis (m)
Toptunnel	N1S1	N1B1	0
	N1S2		40
	N1S3		93
	N1S4		127
Toehorse	N1S5	N1B2	0
	N1S6		25
	N1S7		40
	N1S8		65
	N1S9		93
	N1S10		118
	N1S11		127
	N1S12		152

Figures 15 and 16 compare the spectral ratios respectively for two categories of tunnel dimensions (top-tunnel and toe-horse) and distance to tunnel axis. As can be seen, the trend of variation is similar as in experimental results, that means the amplification ratios increase with enlargement of tunnel and decrease with distance to tunnel axis. Nevertheless the amplification frequencies are not exactly the same as experimental measurements (Fig. 17). For both methods some peaks for frequencies around 10 Hz are seen, however, there is another peak for numerical modelling around 2 Hz, though this peak is not extracted by experimental data. In addition, the amplification ratio obtained from experimental data is significantly higher than numerical modelling for peak of 10 Hz.

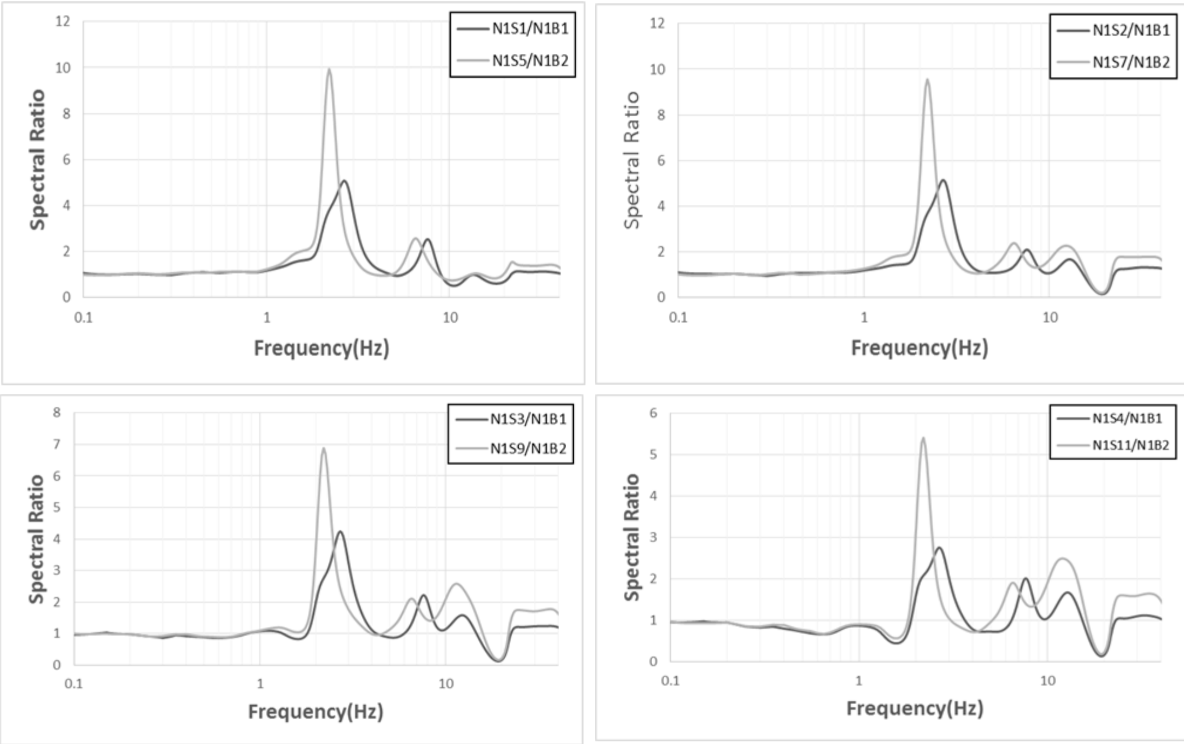


Fig. 15. Comparison of the surface/base spectral ratios obtained by numerical modelling in two cases of tunnel dimension; top-tunnel (black curves) and toe-horse (gray curves); for different distance from tunnel axis; top of tunnel (up-left), 40 meters (up-right), 93 meters (down-left) and 127 meters (down-right)

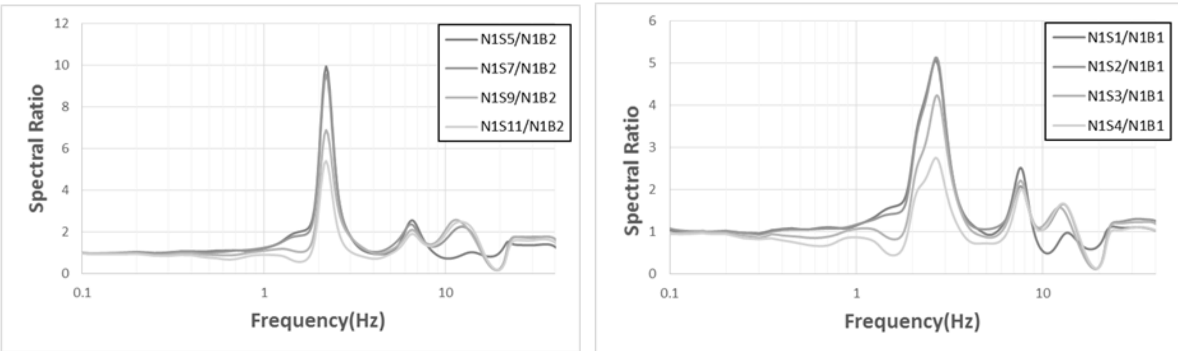


Fig. 16. Variation of spectral ratios obtained from numerical modelling based on distance from tunnel axis; in case of top-tunnel (left) and toe-horse (right)

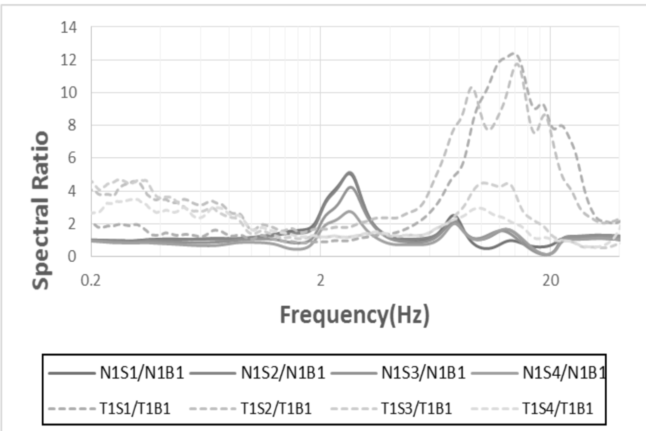


Fig. 17. Comparison of numerical and experimental result for test site 1 and tunnel shape toe-horse

6. CONCLUSION

Numerous single station microtremor measurements, performed in the framework of Earthquake geotechnical microzonation of the city of Karaj show the changes of H/V spectral ratio behaviour for the area near the under-construction subway tunnel in comparison with the area far from the tunnel. In order to investigate whether this variation is related to the effect of the tunnel a series of multi station measurements have been conducted in 11 test sites across the tunnel and the various surface/base spectral ratios were obtained. The results show that despite a general trend of low frequency (0.8 Hz) amplification detected by single station H/V ratio in different parts of the city this trend is changed significantly for the area located around the subway tunnel. For these areas the multi station SSR method revealed amplification in high frequency ranges (around 10 Hz) where its amplitude depends on tunnel dimension and distance from tunnel axis. This amplification is higher for the station installed just above the tunnel or at a distance lower than 40 meters from the tunnel axis and decreases for farther distances.

FEM numerical modelling for one of the locations confirms the existence of this high frequency amplification but shows another peak in lower frequencies (around 2 Hz).

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