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THE IMPACT OF SUBWAY TUNNELS ON THE SEISMIC RESPONSE OF OVERLAYING STRUCTURES

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Abstract. The seismic response of structures overlaying soil strata has been extensively studied. Also, numerous studies can be found in the literature regarding the deformations imposed on structures during the excavation of tunnels in suburban areas. However, the impact of the presence of a tunnel on the seismic response of overlaying structures has drawn very limited attention.

The goal of this study is to examine the considerable influence that the existence of a tunnel has on ground acceleration, as well as to point out the limits of parameters, such as the tunnel depth and the horizontal distance of a structure from the axis of the tunnel, beyond which the difference in ground acceleration cannot be neglected.

The corrected accelerograms of the Athens(Greece), Kobe(Japan) and Duzce (Turkey) earthquakes are used in this investigation. The geotechnical data has been drawn from the drillings that took place during the construction of the subway in Athens. For the Athens earthquake two approaches were applied. In the first approach the soil stratum with the tunnel were modeled as a linear system with the finite element software called Plaxis. In the second approach the part of the soil stratum over the bedrock and up to a distance of 2.5 m below the lower part of the tunnel were modeled with software capable to account for nonlinear soil behavior, while the upper part including the tunnel were modeled as a linear system using Plaxis. The second approach is considered as more realistic especially for the latter two seismic excitation cases.

The results of this study showed that the presence of the shallow tunnels considerably modify the surface ground motion within a range that depends on their geometrical characteristics. Even though this is a limited study, the results clearly indicate that the phenomenon should be considered when : i) evaluating the anticipated seismic behavior of overlaying structures, ii) deciding on strengthening measures in order to protect structures with inferior strength, iii) specifying the design spectra of new buildings to be constructed in the vicinity of such tunnels and iv) making decisions regarding relocation of a tunnel to be constructed.

INTRODUCTION

In recent years there have been considerable advances on techniques of bored tunnel construction in any type of ground. This has led to a plethora of tunnelling projects being instigated, frequently in urban areas, in order to deal with increasing traffic congestion problems. As a consequence, there is respectable international interest in predicting the impact that tunnels have on the behaviour of overlaying and neighboring structures.

Even though the presence of tunnels in urban environments, such as low-depth subway tunnels is very common in countries with high seismicity, there are indeed very few studies reported in the literature on this topic. It should be noted that many of the overlaying structures are old and in many cases constructed without seismic provisions. The influence of the presence of a subway tunnel on the seismic response at the ground surface supporting a structure is investigated in this study.

This paper summarizes the methodology adopted to predict the critical area around a tunnel, depending on its depth, where the acceleration from an earthquake is increased due to the presence of the tunnel.

ANALYSIS PROCEDURE

Firstly, the soil profile is specified.

The soil profile has been obtained from the drillings during the construction of the metro at a location of central Athens. The soil profile with the corresponding characteristics is shown in *Figure 1*.

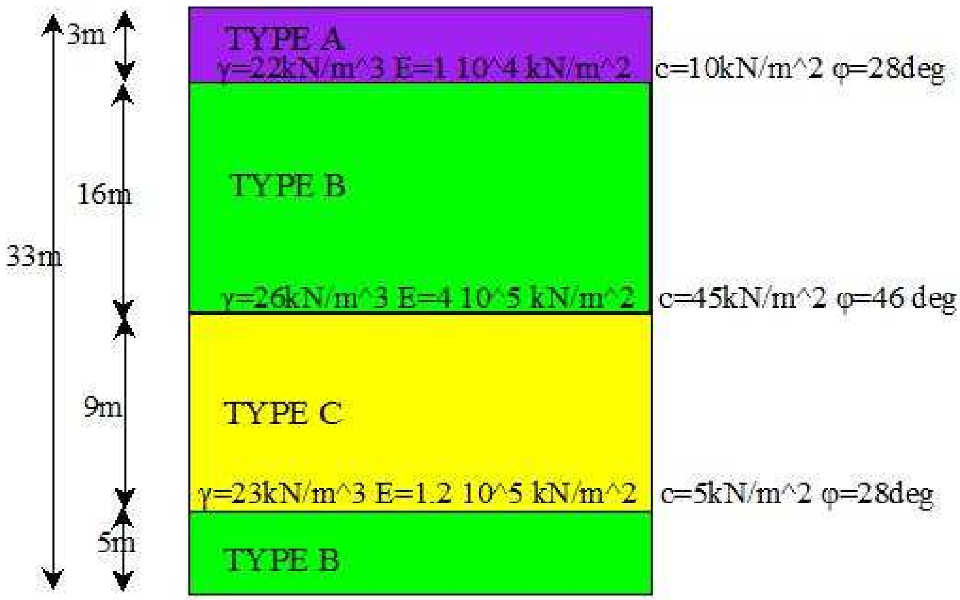

Figure 1 – The soil profile and characteristics

Where:

γ: bulk density, E: Young's modulus, c: effective cohesion, φ: effective internal angle of friction.

Ground motions for three well-known earthquake records were used, i.e. the Athens, the Kobe and the Duzce earthquakes. All records present near source directivity phenomena ([3], [4]). The earthquake records were used as is described in the following: For the Athens earthquake two approaches were applied. In the first approach the soil stratum with the tunnel were modeled as a linear system with the finite element software called Plaxis ([1], [5]). In the second approach the part of the soil stratum over the bedrock and up to a distance of 2.5 m below the lower part of the tunnel were modeled with software capable to account for nonlinear soil behavior, while the upper part including the tunnel were modeled as a linear system using Plaxis. The second approach is considered as more realistic. The models used in these approaches are dedicted in figures 2a, 2b and 3. Specifically, *figure 2a* :shows the model using Plaxis for the linear analysis of the soil stratification with the tunnel, *figure 2b* :shows the finite element mesh of the model using Plaxis, *figure 3:* shows the soil strata model using the Shake2000 ([2]) for the lower part and Plaxis for the upper part that includes the tunnel.

In all cases a tunnel with a diameter of 2.5 m is used.

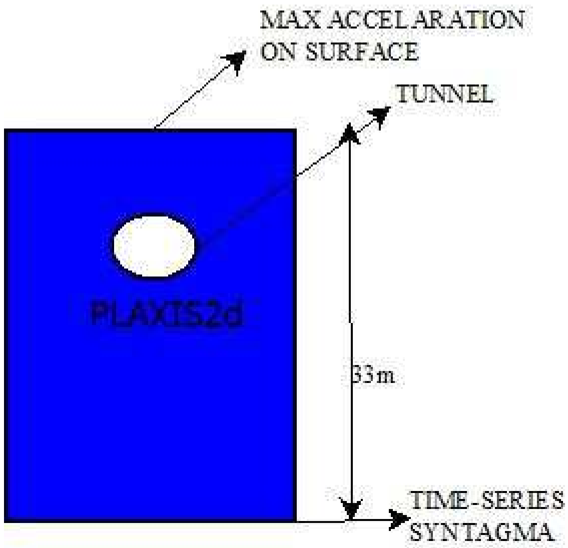

Figure 2a – Plaxis Model

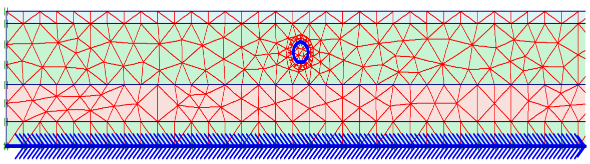

Figure 2b – The finite element mesh of Plaxis model

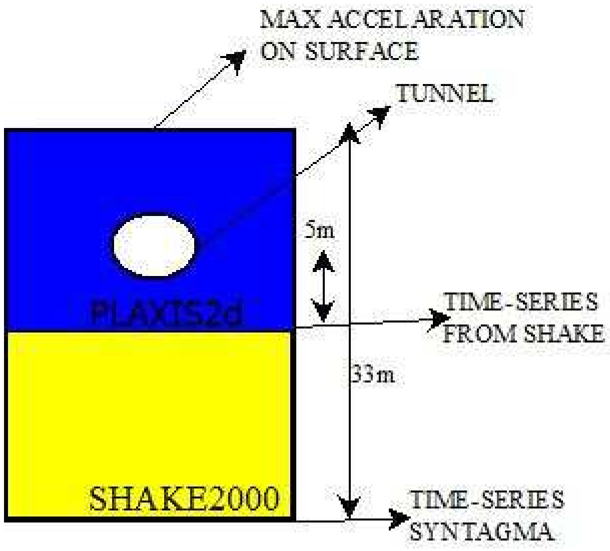

Figure 3 – Shake2000 & Plaxis model

Figures 4, 5, 6 show horizontal accelerations of the records at Syntagma (Athens) 1999, Kobe (Japan) 1995 and Duzce (Turkey) 1999 respectively.

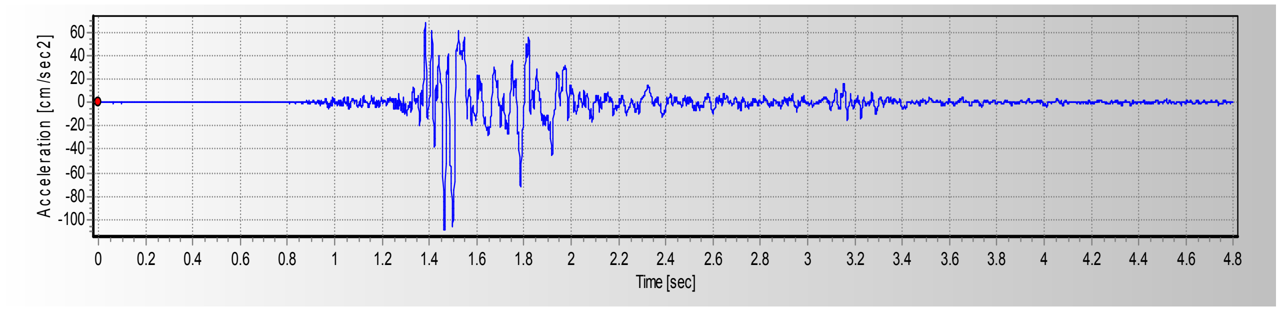

Figure 4 – Syntagma (Athens) 1999 earthquake record on the bedrock,

maximum acceleration : 1.08 (m/s^2) , estimated effective acceleration (EDA) : 0.37 (m/s^2)

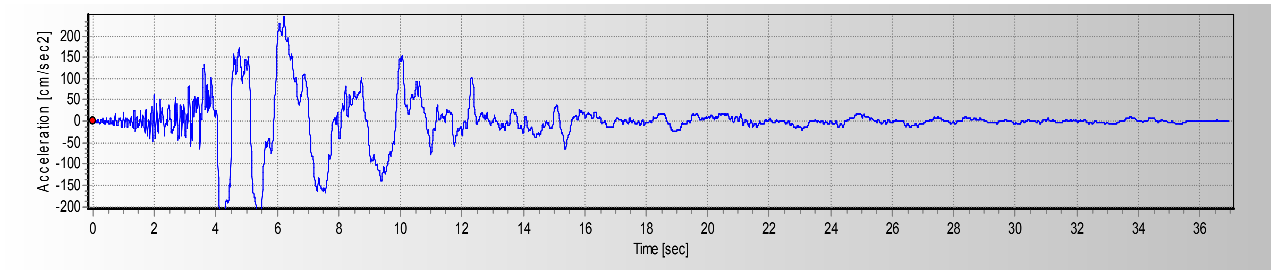

Figure 5 – Kobe (Japan) 1995 earthquake record on the bedrock,

maximum acceleration : 3.09 (m/s^2) , estimated effective acceleration (EDA) : 3.09 (m/s^2)

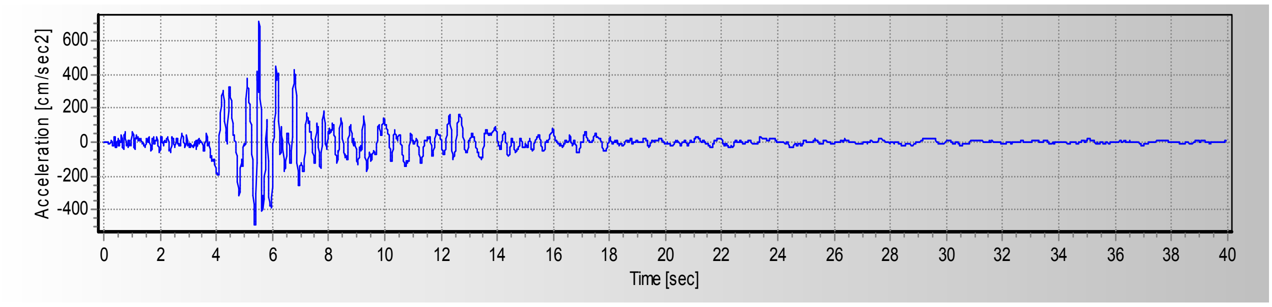

Figure 6 – Duzce (Turkey) 1999 earthquake record on the bedrock,

maximum acceleration : 7.14 (m/s^2) , estimated effective acceleration (EDA) : 5.99 (m/s^2)

The locations where the response of all analyses for the models of both approaches have been calculated are showed in *figure 7*.

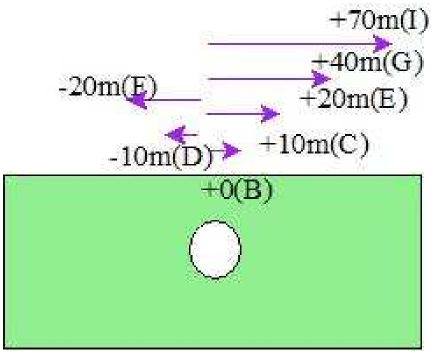

Figure 7 – Locations where ground acceleration values are calculated.

In the following all the results of the analyses are given in a table form for the locations presented in figure 7 and for each case of tunnel depth. In Tables 1a, 2a, 3a, 4a, 5a, 6a and 7a the results from the first method using Plaxis are showed, while in Tables 1b, 2b, 3b, 5b, 6b and 7b the results from the second method using Shake2000 & Plaxis are presented.
Red ink is used to point out when the increase of surface acceleration exceeds a limit of 5%.

POINT B	PLAXIS		Percentage
Dist.: 0	notunnel	**tunnel**	Increase (%)
depth=5	2.1708	3.054	40.69
depth=10	2.1708	2.515	15.86
depth=15	2.1708	2.411	11.07
depth=20	2.1708	2.39	10.10
depth=25	2.1708	2.34	7.79

Table 1a – Results from Plaxis model

POINT B	SHAKE		Percentage
Dist.: 0	notunnel	**tunnel**	Increase (%)
depth=5	1.44	1.66	15.47
depth=10	1.44	1.57	9.13
depth=15	1.44	1.456	1.46
depth=20	1.44	1.432	-0.21
depth=25	1.44	0.00	0.00

Table 1b – Results from Shake & Plaxis model

Athens earthquake 1999

The horizontal distance from the tunnel center is taken as 0 m.

POINT C	PLAXIS		Percentage
Dist.: 10	notunnel	tunnel	Increase (%)
depth=5	2.905	3.443	18.52
depth=10	2.905	3.229	11.15
depth=15	2.905	3.004	3.41
depth=20	2.905	3.002	3.34
depth=25	2.905	2.446	-15.80

Table 2a – Results from Plaxis model

POINT C	SHAKE		Percentage
Dist.: 10	notunnel	tunnel	Increase (%)
depth=5	1.88	2.12	13.01
depth=10	1.88	2.04	8.90
depth=15	1.88	1.865	-0.59
depth=20	1.88	1.801	-4.00
depth=25	1.88	0.00	0.00

Table 2b – Results from Shake & Plaxis model

Athens earthquake 1999

The horizontal distance from the tunnel center is taken as 10 m.

POINT E	PLAXIS		Percentage
Dist.: 20	notunnel	tunnel	Increase (%)
depth=5	3.3488	3.879	15.83
depth=10	3.3488	3.696	10.37
depth=15	3.3488	3.68	9.92
depth=20	3.3488	3.467	3.53
depth=25	3.3488	3.432	2.48

Table 3a – Results from Plaxis model

POINT E	SHAKE		Percentage
Dist.: 20	notunnel	tunnel	Increase (%)
depth=5	2.03	2.21	8.91
depth=10	2.03	2.15	5.56
depth=15	2.03	2.103	3.49
depth=20	2.03	2.096	3.15
depth=25	2.03	0.00	0.00

Table 3b – Results from Shake & Plaxis model

Athens earthquake 1999

The horizontal distance from the tunnel center is taken as 20 m.

POINT G	PLAXIS		Percentage
X.Θ.: 40	notunnel	tunnel	Increase (%)
depth=5	2.898	3.014	4.00
depth=10	2.898	3.021	4.24
depth=15	2.898	3.00	3.45
depth=20	2.898	3.054	5.38
depth=25	2.898	2.765	-4.59

Table 4a – Results from Plaxis model

POINT G	SHAKE		Percentage
X.Θ.: 40	notunnel	tunnel	Increase (%)
depth=5	1.77	1.81	2.66
depth=10	1.77	1.80	1.87
depth=15	1.77	1.698	-3.80
depth=20	1.77	1.805	2.27
depth=25	1.77	0.00	0.00

Table 4b – Results from Shake & Plaxis model

Athens earthquake 1999

The horizontal distance from the tunnel center is taken as 40 m.

POINT I	PLAXIS		Percentage
X.Θ.: 70	notunnel	tunnel	Increase (%)
depth=5	1.5423	1.675	8.60
depth=10	1.5423	1.678	8.80
depth=15	1.5423	1.60	3.94
depth=20	1.5423	1.607	4.20
depth=25	1.5423	1.467	-4.88

Table 5a – Results from Plaxis model

POINT I	SHAKE		Percentage
X.Θ.: 70	notunnel	tunnel	Increase (%)
depth=5	1.21	1.24	2.15
depth=10	1.21	1.20	-0.74
depth=15	1.21	1.209	-0.25
depth=20	1.21	1.211	-0.08
depth=25	1.21	0.00	0.00

Table 5b – Results from Shake & Plaxis model

Athens earthquake 1999

The horizontal distance from the tunnel center is taken as 70 m.

Noticing the results showed in the tables above one could make the following remarks: In Table 1b (location B) it is observed that ground acceleration after the construction of a tunnel is increased by 15.5% : when the tunnel depth is 5m, by 9.1% : when the tunnel depth is 10m and less than 5% : when the tunnel depth is more than 10m. In Table 2b (location C) the increase is 13.0% when the tunnel depth is 5m, 8.9% when the tunnel depth is 10m and less than 5% when tunnel depth is more than 10m. In Table 3b (location E) the ground acceleration is increased because of the tunnel presence by 8.9% when the tunnel is located 5m below the surface, by 5.6% when it is located 10m below the surface and by less than 5% when it is located more than 10m below the surface. Finally, in Tables 4b (location G) and 5b (location I) the increase is less than 5% for any case of tunnel depth.

For the Kobe and Duzce earthquake records the combined method is used.

The results for the Kobe analysis are showed in a table form while red ink is used to point out when increase of surface acceleration exceeds the limit of 5% (Tables 6, 7, 8, 9).

POINT B	SHAKE		Percentage
Dist.: 0	notunnel	**tunnel**	Increase (%)
depth=5	1.56	1.90	22.24
depth=10	1.56	1.77	13.43
depth=15	1.56	1.654	6.30
depth=20	1.56	1.587	1.99
depth=25	1.56	0.00	0.00

Table 6 – Results from Shake&Plaxis model

POINT C	SHAKE		Percentage
Dist.: 10	notunnel	tunnel	Increase (%)
depth=5	1.72	2.10	22.13
depth=10	1.72	1.98	14.75
depth=15	1.72	1.865	8.30
depth=20	1.72	1.789	3.89
depth=25	1.72	0.00	0.00

Table 7 – Results from Shake&Plaxis model

Kobe earthquake 1995

The horizontal distance from the tunnel center is taken as 0 m for Table 6 and 10m for Table 7.

POINT E	SHAKE		Percentage
Dist.: 20	notunnel	tunnel	Increase (%)
depth=5	2.03	2.21	8.91
depth=10	2.03	2.15	5.56
depth=15	2.03	2.103	3.49
depth=20	2.03	2.096	3.15
depth=25	2.03	0.00	0.00

Table 8 – Results from Shake&Plaxis model

POINT G	SHAKE		Percentage
Χ.Θ.: 40	notunnel	tunnel	Increase (%)
depth=5	1.77	1.81	2.66
depth=10	1.77	1.80	1.87
depth=15	1.77	1.698	-3.80
depth=20	1.77	1.805	2.27
depth=25	1.77	0.00	0.00

Table 9 – Results from Shake&Plaxis model

Kobe earthquake 1995

The horizontal distance from the tunnel center is taken as 20 m for Table 8 and 40m for Table 9.

Table 6 (location B) shows that ground acceleration after the construction of a tunnel is increased by 22.2% when the tunnel depth is 5m, 13.4% when the tunnel depth is 10m, 6.3% when the tunnel depth is 15m and less than 5% when the tunnel depth is more than 15m. In Table 7 (location C) the increase is 22.1% when the tunnel depth is 5m, 14.7% when the tunnel depth is 10m, 8.3% when the tunnel depth is 15m and less than 5% when the tunnel depth is more than 15m. In Table 8 (location E) the ground acceleration is increased by 8.9% when the tunnel depth is 5m, by 5.6% when it is 10m and by less than 5% when it is more than 10m. Last, in Table 9 (location G) the increase is less than 5% regardless of the tunnel depth.

The results for the Duzce analysis are showed in a table form (Tables 10, 11, 12, 13), while red ink is used to point out when increase of surface acceleration exceeds the limit of 5%

POINT B	SHAKE		Percentage
Dist.: 0	notunnel	**tunnel**	Increase (%)
depth=5	1.79	2.13	19.06
depth=10	1.79	1.95	9.22
depth=15	1.79	1.821	1.79
depth=20	1.79	1.787	-0.11
depth=25	1.79	0.00	0.00

Table 10 – Results from Shake&Plaxis model

POINT C	SHAKE		Percentage
Dist.: 10	notunnel	tunnel	Increase (%)
depth=5	1.72	2.10	22.13
depth=10	1.72	1.92	11.73
depth=15	1.72	1.835	6.56
depth=20	1.72	1.789	3.89
depth=25	1.72	0.00	0.00

Table 11 – Results from Shake&Plaxis model

Duzce earthquake 1999

The horizontal distance from the tunnel center is taken as 0 m for Table 10 and 10m for Table 11.

POINT E	SHAKE		Percentage
Dist.: 20	notunnel	tunnel	Increase (%)
depth=5	1.65	1.85	12.09
depth=10	1.65	1.77	6.83
depth=15	1.65	1.675	1.27
depth=20	1.65	1.664	0.60
depth=25	1.65	0.00	0.00

POINT G	SHAKE		Percentage
Χ.Θ.: 40	notunnel	tunnel	Increase (%)
depth=5	1.67	1.71	2.82
depth=10	1.67	1.70	1.98
depth=15	1.67	1.698	1.98
depth=20	1.67	1.705	2.40
depth=25	1.67	0.00	0.00

Table 12 – Results from Shake&Plaxis model *Table 13 – Results from Shake&Plaxis model*

Kobe earthquake 1995

The horizontal distance from the tunnel center is taken as 20 m for Table 12 and 40m for Table 13.

In Table 10 (location B) the ground acceleration is increased because of the tunnel presence by 19.0% when the tunnel is located 5m below the surface, by 9.2% when it is located 10m below the surface and by less than 5% when it is located more than 10m below the surface. Table 11(location C) shows that increase of acceleration is 22.1% when the tunnel depth is 5m, 11.7% when the tunnel depth is 10m, 6.6% when the tunnel depth is 15m and less than 5% when the tunnel depth is more than 15m. In Table 12 (location E) the acceleration is increased by 12.1% when the tunnel depth is 5m, by 6.8% when the tunnel depth is 10m and by less than 5% when the tunnel depth is more than 10m. In table 13 (location G) the increase is less than 5% for any case of tunnel depth.

CONCLUSIONS

- In general, in Plaxis2d higher acceleration results were obtained in comparison with the ones from the combined Shake2000&Plaxis2d models. This difference is attributed to the fact that Shake accounts for nonlinear soil behavior
- The impact of the tunnel presence on the ground acceleration could be considerable, since the ground surface acceleration can be increased even by 22%.
- As the horizontal distance of the foundation of a structure from the tunnel center and the tunnel depth increase, the influence of the presence of the tunnel on the acceleration at the surface diminishes.
- When the horizontal distance from the tunnel center is 20m or less and the tunnel depth is 5m, the increase of the ground acceleration ranges from 7% to 22%. Furthermore, when the horizontal distance from the tunnel center is 20m or less and the tunnel depth is 10, the increase of the ground acceleration ranges from 5% to 15%.

The results indicate that the presence of the tunnel should be considered when the following two conditions are present:

- ***1st Condition***: Tunnel depth must be less than 10 meters.
- ***2nd Condition***: Horizontal distance from the tunnel center must be less than 20 meters.

Those conclusions were drawn from the analyses based on specific data (the soil profile from central Athens, Athens, Kobe and Duzce earthquakes, tunnel diameter 5.0 m).

Even though the conclusions are based on limited results, they clearly indicate that the impact of the tunnel presence on ground acceleration should be taken into consideration when:

i) specifying the design spectra of structures to be built at the area near the subway tunnel.
ii) selecting strengthening measures in order to strenghten structures that are vulnerable.
iii) deciding on the location of a tunnel to be constructed.
iv) evaluating the anticipated seismic behavior of overlaying structures.

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