Effect of Underground Structures on Free-Field Ground Motion during Earthquakes

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SUMMARY:
In order to develop underground structures such as subways, metro tunnels and other buried facilities in big cities, the dynamic interaction of these structures and their environment should be considered. Previous studies based on series solution in frequency domain showed that, in existence of a tunnel, the free-field motion of surrounding soil is amplified during design earthquakes. This amplification should be applied to vicinal structures above or around the tunnel. In order to study this important phenomenon more accurately, the effect of a road tunnel on free-field motion will be studied in this paper. The Niyayesh-Sadr tunnel with 14 meter span and its environmental conditions will be used as a case study. This tunnel with 3.5 kilometres long is located in north of Tehran which connects Niyayesh to Sadr highway. The tunnel is excavated by MULTI DRIFT method in a sedimentary alluvium. The results of the static stress distribution will be used in evaluating dynamic material properties. The dynamic time history analysis to design earthquake excitation will be done by numerical methods and the ground response amplitudes will be evaluated. In the numerical model, the quiet boundary conditions will be used in order to prevent wave reflection. The effect of geotechnical conditions will also be considered in sensitivity analysis. Results show that when the tunnel is located in ground, the acceleration time histories are amplified at surface

Keywords: Road Tunnel, Free-Field Motion, Earthquake, Amplification

1. INTRODUCTION

The effect of the construction and existence of underground structures, such as metro tunnels, stations and underground facilities on free field space and also on above ground has been examined thoroughly in the past, focusing mainly on the resulting surface settlements. However, these studies are performed by numerical methods and also the effects of presence of tunnel which embedded in an elastic half-space are investigated. In previous studying, the effect of stress release during construction and also that the presence of a traffic tunnel with actual shape in occurrence of real earthquake with time history acceleration are neglected.

In this subject, Pao and Mow (Pao and Mow, 1973) studied the diffraction of SH elastic waves and dynamic stress concentration by a circular cylinder embedded in an ideal infinite space. Later, other researcher (Datta & El-akily, 1978, Wong et al., 1985) considered the scattering of elastic waves by a cylindrical cavity in a semi-infinite medium. Dravinski (Dravinski, 1982 & 1983) presented a detailed literature review on the scattering of elastic waves by subsurface irregularities, while Lee and co-workers undertook a systematic study to analyze, the scattered wave field induced by either a cavity or a tunnel under plane SH waves incidence (Lee, 1977, Lee, 1979) and to SV and P incidence (Lee & Karl, 1992, Lee & Karl, 1993). Finally, the interaction effects between surface (e.g. canyon or valley) and subsurface cavities/tunnels and their influence on surface ground motion were studied in (Lee et al., 1999). Nevertheless, many other researchers (e.g. Lee and Trifunac, 1979, Manoogian & Lee, 1996, Manoogian, 1998, Lee & Karl, 1992, Barros & Luco, 1993 and 1994, Lee et al, 2001, Mitra et al., 2007) have examined analytically the effect that the presence of a circular underground structure

on the surface ground motion. In all these literatures, the result show an amplification on surface and free field space due to existence of tunnel or cavities in earthquake.
In this study, the effect of Niyayesh-Sadr Tunnel on behaviours of surface ground near this site during an earthquake in respect of free field condition are investigated. In the present work, the problem is treated numerically, with the aid of the available Finite Difference code.

2. EVALUATION AND SPECIFICATION OF THE CASE STUDY

For connecting the Niyayesh highway to Sadr highway, two tunnels in north and south parts with approximately 3.5 kilometres long are predicted in north of Tehran. Each tunnel in section in whole length contains 3 traffic lines with 3.5 meter width and 2.5 meter emergency line and 1 line for sidewalk.

2.1. Structural and excavation characteristic of tunnel

The cross section of the tunnel has a horseshoe shape with invert beam as shown in Fig 1. The tunnel has a width of 18 m and height of 12 m. The excavation and lining of main tunnel support will be carried out using MULTI DRIFT method, combing a horizontal and vertical operation sequence. In this method partial driving and sufficient face support with shotcrete is required to provide safe tunnelling conditions.

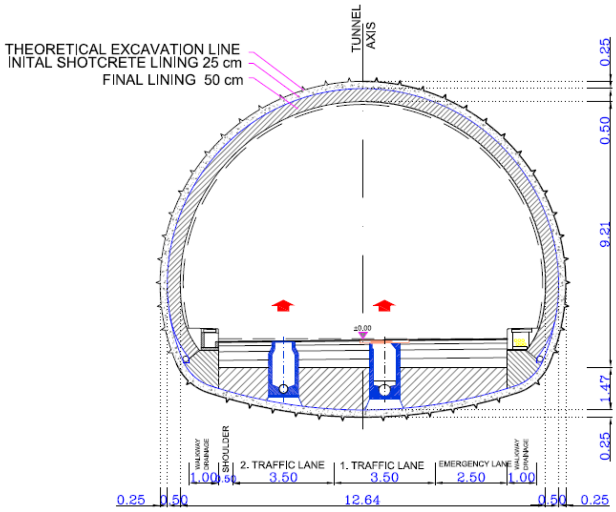

Figure 1. Cross section of main tunnel (TETCO, 2011)

As shown in Fig 1, 25 centimetre shotcrete lining with reinforcement layer will be used for initial support and also 50 centimetres in cast reinforcement concrete will be used for final lining.
The construction sequences are performed in 6 steps for each tunnel which is shown in Fig 2.

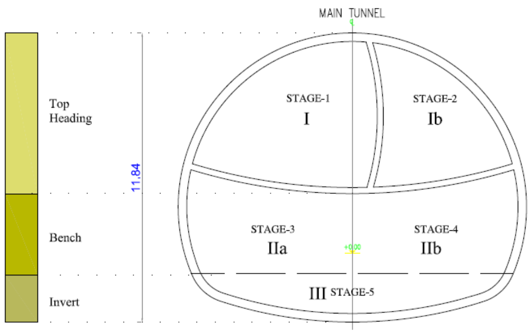

Figure 2. Excavation stages of main tunnel support (TETCO, 2011)

The main tunnels in north and south parts are located under Mahyar & Nahid Street respective. In most part of these streets, buildings are constructed or are going to be constructed. The project level is varies form -11 to -30 in long. In this study assume that the overburden of this tunnel is equal to 11m. This overburden is minimum and critical for this study. Fig 3 shows the profile of this tunnel in critical cases.

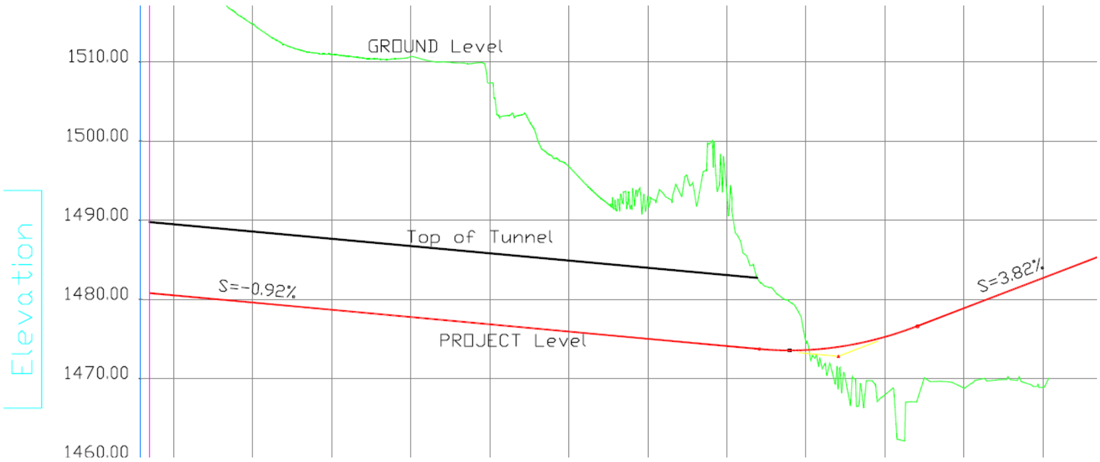

Figure 3. Profile of tunnel in lowest overburden location (TETCO, 2011)

In this study, cast in place concrete with related properties are assigned to model to simulate final lining. It assumed that, during an earthquake, initial linings are not contributed and all forces are imposed to final linings. Table 1 shows the structural parameters related to final lining which are used in this analysis.

Table 2.1. Structural parameters

Parameter	Value
Final Lining thickness	50 cm
Yang module of concrete	2.5 e7 kN/m2

2.2. Geotechnical properties of soil

In general, the site medium are contain stiff sandy gravel and compact sand with little silt and clay. These soils contain 5% to 50% fines. In addition in some layer silt and clay are observed. The geotechnical parameters used in the analysis are based on table 2.2. In this study assume that all soil in depth is same and then 1 layer is introduced as bellow. In initial support analysis, short time properties of soils are used. In all boreholes, the water levels are under construction zone then the properties of material in unsaturated case are introduced to model. For seismic analysis, dynamic properties of soil are used.

Table 2.2. Geotechnical parameters (TETCO, 2011)

parameter	Unite weight *kN/m^3*	Bulk module *MN/m^2*	Shear module *MN/m^2*	Angle of friction *Deg.*	Cohesion *kN/m^2*	Passion ratio
Static analysis	18	1.04E2	3.49E7	33	50	0.3
Dynamic analysis-Original	18	9.72E2	6.48E2	36	20	0.3
Dynamic analysis-weak soil	18	4.86E2	3.24E2	25	10	0.3

3. NUMERICAL ANALYSIS PROCEDURE

In this study an available finite difference package, which is capable of doing dynamic analysis of soil-structure interaction, has been implemented. Since it is planned to investigate the impact of a tunnel construction on the response of the surface motion, three different cases have been taken into account:

I) in the first case, the seismic analysis of the ground surface before excavating the underground tunnel in free field case has been done. then, the time history acceleration of surface are calculated.
II) In the second case, the dynamic analyses of the surface under the same accelerographs are performed, while the underground tunnel has already been built (Fig .4). In this case the acceleration of reference points are calculated. To study the impact of the underground tunnel on the seismic behaviour of the surface, the rresults of case I and II are compared with each other.
III) In the third case, the material properties of soil reduce to weak soil and same analysis are performed to show the behaviour of soil properties on ground motions. These properties are compatible with other parts of this project. In weak soil, all properties of soil like bulk module and shear module are selected as half of original one. With this variation, the shear wave velocity which is imposed to bottom of model as shear stress is also reduced.

The behaviours of the Tunnel and soil layers are assumed linear elastic and elastoplastic Mohr-Coulomb, respectively. The mechanical and physical properties of material used in modelling are presented in Table 1 for soil layers and in Table 2 for the final tunnel concrete lining. The geometry of the model and mesh generation which is used in static and dynamic analysis are shown in Fig 4.

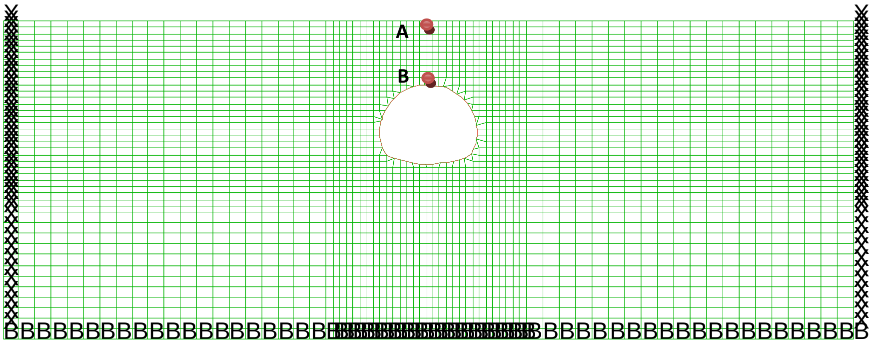

Figure 4. Geometry of model and mesh generation with target points

In the static analyses, the boundary conditions at the end of the model are hinged support and at the sides of the model are roller supports. The boundary conditions applied at the artificial boundaries were a) lateral dashpots to minimize wave reflections and achieve free-field conditions, b) absorbing boundaries at the bottom i.e. normal and shear dashpots of coefficient c= ρ CsVs (Kramer, 1996) to represent the effect of radiation damping and c) a stress boundary of amplitude τxy=-2 ρ CsVs at the bottom to simulate the velocity caused by earthquake. In this relation, variation of Vs during the time is obtained from acceleration by integration. The factor of 2 in the above relation corresponds to the fact that half of the input energy is absorbed by the viscous boundary, while in the above relations Cs is speed of S-wave propagation through medium, ρ is the mass density and Vs the seismic particle velocity. Despite the existence of a vertical plane of symmetry, the full model was used due to the limitations of the numerical code with respect to lateral dashpots. In this study, the effects of damping of materials are neglected.

4. DYNAMIC ANALYSIS PROPERTIES

For dynamic analysis of model, component horizontal LOMA PRIETA GILROY acceleration is chosen. The Loma Prieta earthquake occurred on October 17, 1989. It had a moment magnitude of 6.9 and a surface wave magnitude of 7.1. The duration was 15 to 20 seconds and peak acceleration of 4 m/s^2. A strong-motion seismograph gave an acceleration reading of 0.64 g near the source. The time history acceleration on bed rock is modified with base line correction. In Fig. 5, the corrected time acceleration with related velocity and displacement are shown.

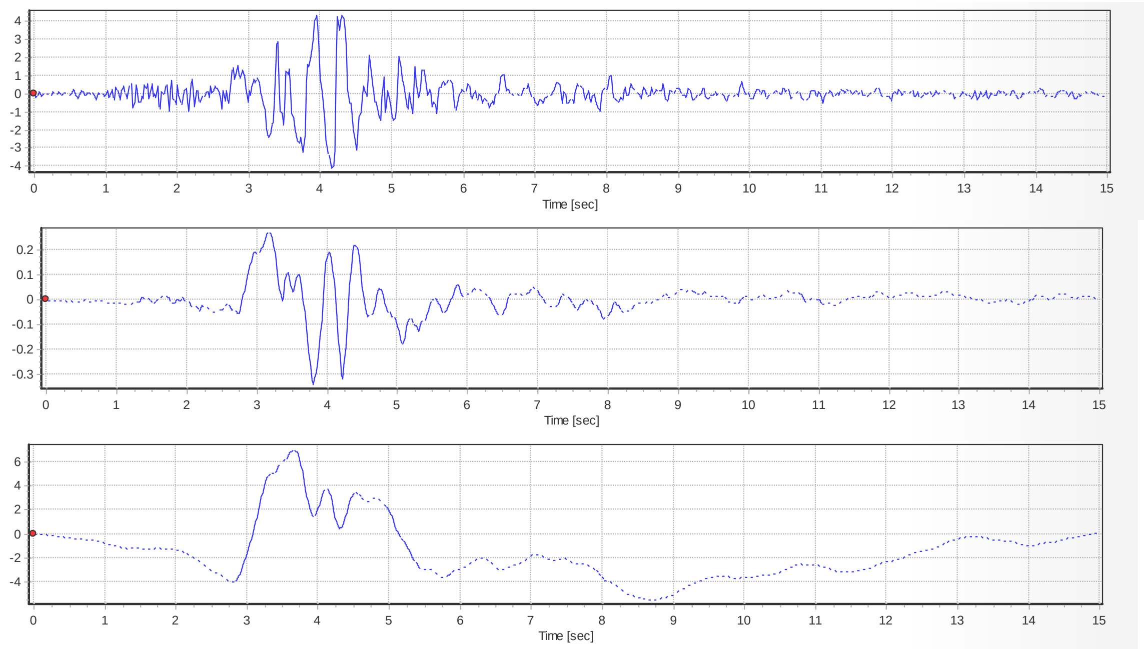

Figure 5. The corrected acceleration with velocity and displacement related to Loma Prieta earthquake

In this study assume that, this original acceleration is applied to base of model and no scale is needed. For control of selected time history, the displacement and velocity of it are calculated by seismosignal. These charts are shown in above Fig. and also just the first 15 second of this time history is selected for analysis. It can be seen the displacement is 0 at 15 second.

Other subject which has more effect on result of dynamic analysis is shear wave velocity of soil. This parameter is directly related to shear module. In this study based on downhole tests which are performed in different location of site, this velocity is selected as 600 m/s^2. The dynamic shear module which also has correlation with this velocity is selected for surrounding soil.

5. RESULTS OF NUMERICAL SIMULATION

In this part the result of numerical dynamic analysis are shown in two parts. In the first part the result of dynamic analysis in free field condition and also soil tunnel interaction with original soil properties are shown together. The time history acceleration in surface and surrounding of tunnel are compared in both cases. These accelerations which computed at target points are shown in Fig. 6. The differences of peak acceleration in positive and negative values are also listed in table 5.1.

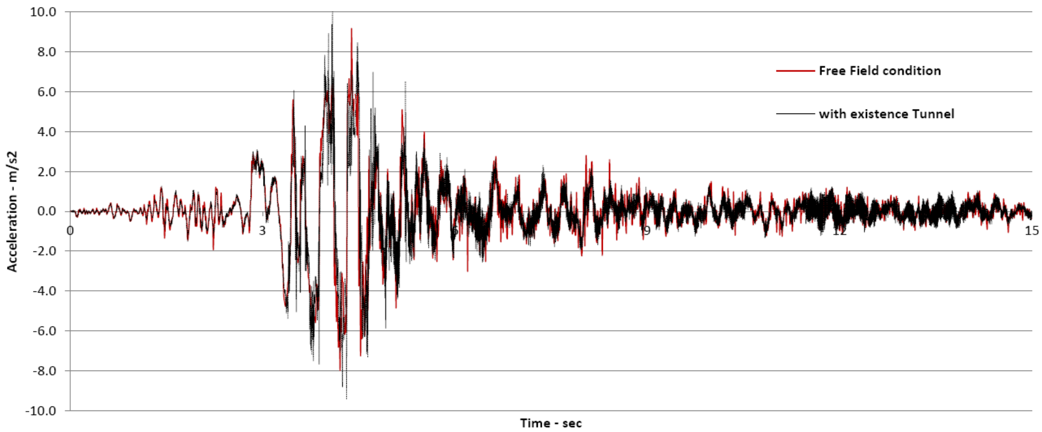

Figure 6. Computed acceleration time history at selected target point in surface (Point A)

Table 5.1. The induced maximum and minimum acceleration of surface in absence and existence of tunnel

m/s^2	Free Field	Existence of tunnel	Difference, %
Peak acc, neg.	7.95	9.40	18.33
Peak acc, Pos.	9.15	10.05	9.70

As Fig. 6 and Table 5.1 shown, in point A (at surface), existence of tunnel modify the behaviour of surface. It means that when the tunnel is located in ground, the acceleration time histories are amplified. In this target point and for this situation peak ground acceleration is amplified about 18% for negative values of time history. To investigation more on these results, the other target point which is located above tunnel in medium is selected and acceleration time history again obtains in this point. Fig. 7 and table 5.2 are presented these results.

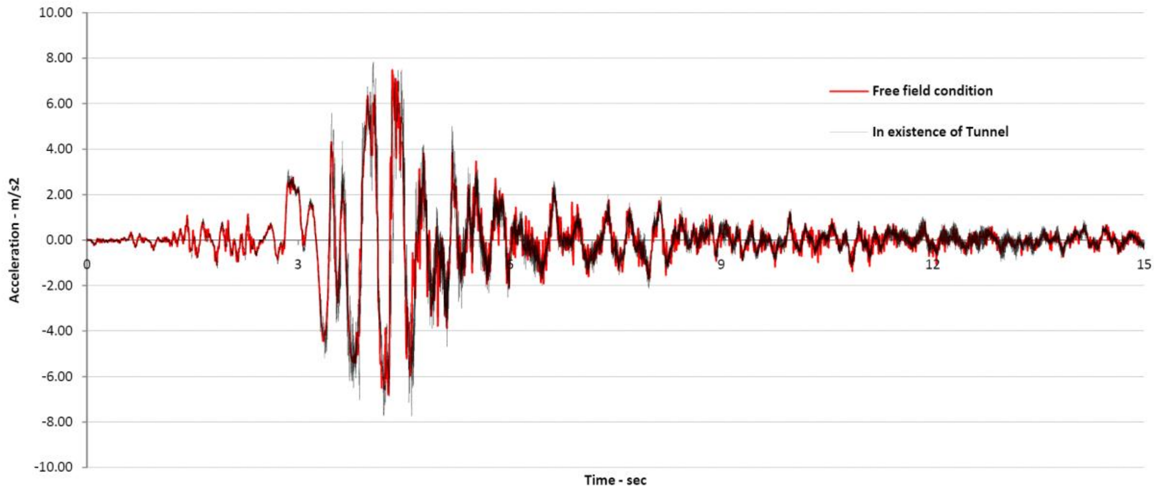

Figure 7. Computed acceleration time history at selected target point at top of tunnel (point B)

Table 5.2. The induced maximum and minimum acceleration of soil at top of tunnel in absence and existence of tunnel

m/s^2	Free Field	Existence of tunnel	Difference, %
Peak acc, neg.	-6.80	-7.73	13.60
Peak acc, Pos.	7.45	7.82	5.05

In this new target point, also the previous result can be seen. In this point the amplification of acceleration is less that point A, it means that the existence of tunnel has more effect on surface rather that lower level in soil. This phenomenon is related to wave reflection due to existence of tunnel. In absence of tunnel, the shear waves going up to surface and then reflected due to incidence to surface and came back to medium. When tunnel is located in this way, the shear waves are trapped in tunnel and also in distance of tunnel and surface which caused more complicated response and amplified the accelerations. This fact can also observe in viscous stress (τ_{xy}) on surface due to an earthquake in presence of tunnel. These dynamic responses versus time are presented in Fig.8 in these two different cases.

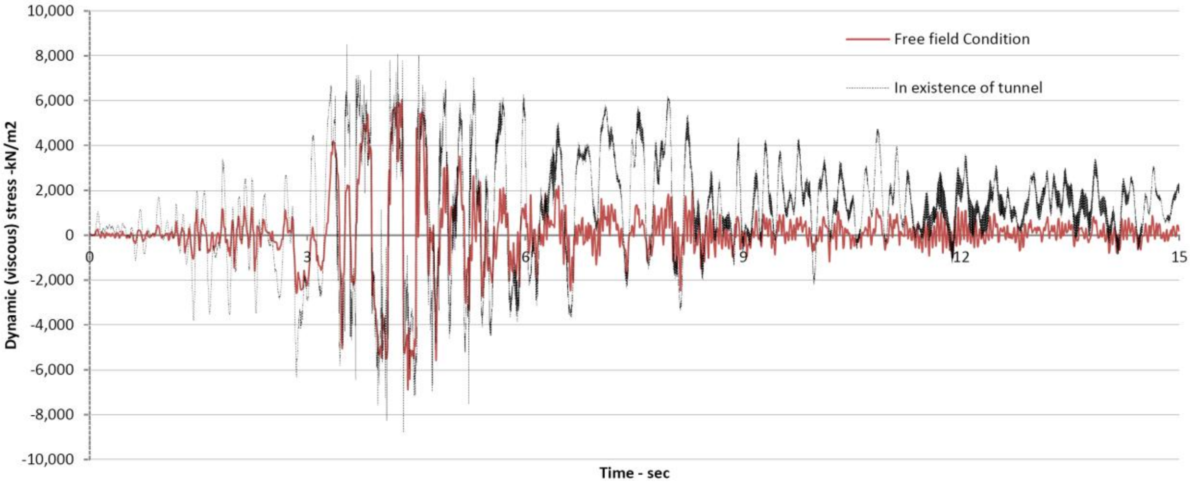

Figure 8. Computed Dynamic stress time history at selected target point in surface (Point A)

The amplification of these stresses are observed clearly which indicate that presents of tunnel has significant effect on surface response. In most cases, the peak ground acceleration which is used for design of surface structures are selected by codes. In these codes the effects of tunnel are not considered then in urban area where the tunnels are passed in way, above buildings should design based on corrected peak ground acceleration based on existence of tunnel. In addition, some facilities like pipelines and tank storage are subjected to higher seismic force due to existence of tunnel.
For more investigation, colour contour diagrams of dynamic stress near tunnel in both cases are shown. The disturbance of medium due to presence of tunnel is significant in Fig. 9. In respect of free field model, tunnel model has higher dynamic stress around tunnel. These counters are related to end of time.

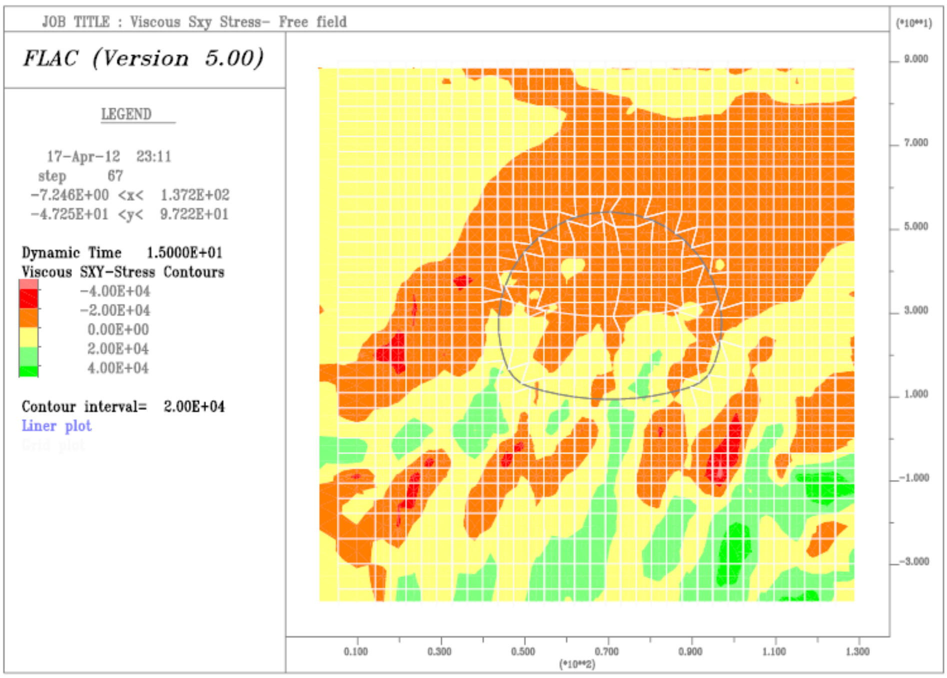

Figure 9. Dynamic stress contour in t=15 sec, free field model

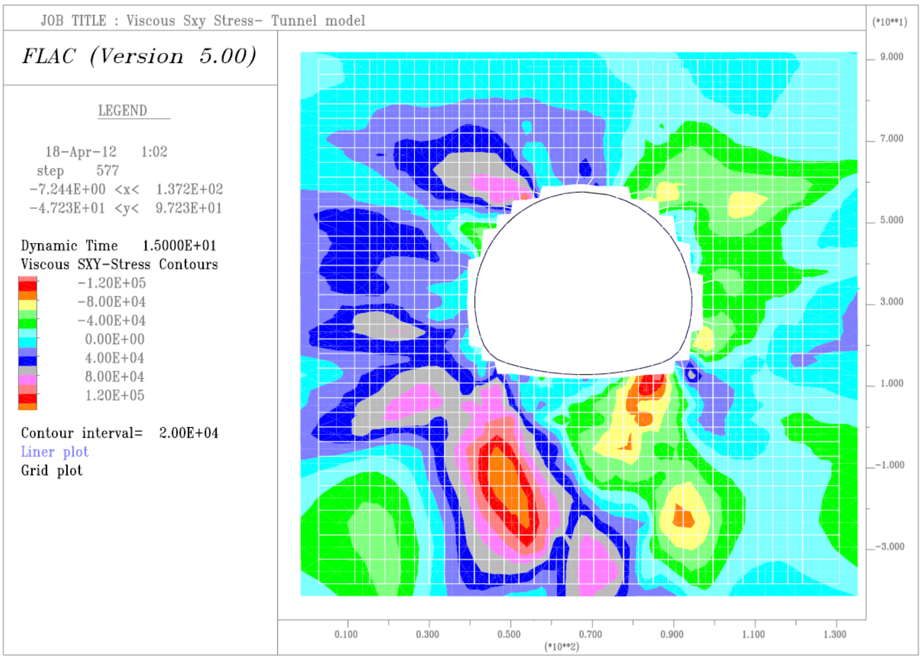

Figure 10. Dynamic stress contour in t=15 sec, Tunnel model

In second part, these analyses are performed on new model with weak soil properties to show the effect of geotechnical conditions on amplification of acceleration in adjacent of tunnel.

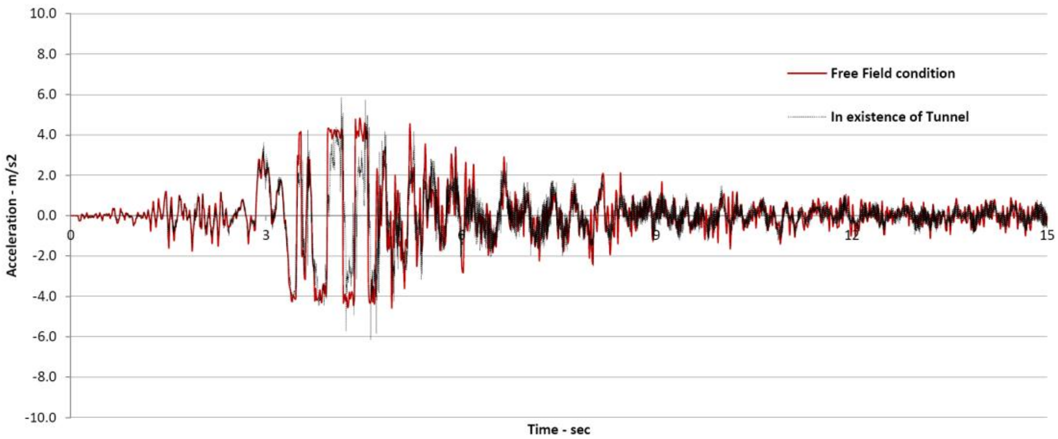

Figure 11. Computed acceleration time history Point A in weak soil

Table 5.3. The induced maximum and minimum acceleration of surface in absence and existence of tunnel in weak soil

m/s^2	Free Field	Existence of tunnel	Difference, %
Peak acc, neg.	4.55	5.84	21.46
Peak acc, Pos.	4.81	6.13	34.70

In respect to original soil properties, the weak soil shows better this phenomenon. It means that in weaker soil, the amplification of acceleration is more than harder. In urban area especially in alluvial bed, effect of tunnel can cause critical situation in peak ground acceleration which it is used for design. In this special case, the peak acceleration at surface amplifies up to 34%. It needs more care to use peak acceleration for design base on codes.

This difference can be seen in Dynamic stress as Fig 12. This Fig shows higher difference in peak and most of the times.

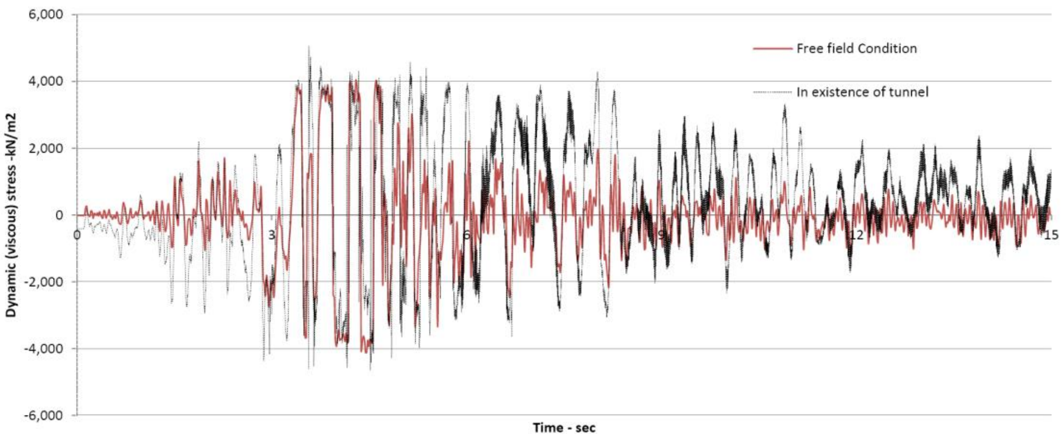

Figure 12. Computed Dynamic stress time history at Point A in weak soil

6. CONCLUSIONS

In order to extract preliminary criteria identifying the cases when the presence of an underground structure like tunnels can or cannot be neglected in the design of a surface structure, all results were evaluated via combined plots of time history acceleration values. The different values in case I and II which indicated the amplification of acceleration are also presented in tables. The results show that presence of tunnel modifies the behaviour of surface. In this analysis, the peck acceleration on tunnel models are increased approximately which means that when the tunnel is located in ground, the acceleration time histories are amplified at surface. Likewise dynamic stress around tunnel is also shown amplification. In respect to original soil properties, in weaker soil, the amplification of acceleration is more than harder one. Totally, it can be proposed that in urban area, in adjacent underground structure like tunnels, the peak ground acceleration should be chosen from dynamic analysis in presence of tunnel instead of using codes.

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