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Seismic Investigation on the Effect of Surface Structures and Twin Tunnel on the Site Response in Urban Areas

Seyed Abolhasan Naeini, Saeideh Mohammadi

Abstract**—**Site response has a profound effect on earthquake damages. Seismic interaction of urban tunnels with surface structures could also affect seismic site response**.** Here, we use FLAC 2D to investigate the interaction of a single tunnel and twin tunnels-surface structures on the site response. Soil stratification and properties are selected based on Line. No 7 of the Tehran subway. The effect of surface structure is considered in two ways: Equivalent surcharge and geometrical modeling of the structure. Comparison of the results shows that consideration of the structure geometry is vital in dynamic analysis and leads to the changes in the magnitude of displacements, accelerations and response spectrum. Therefore it is necessary for the surface structures to be wholly modeled and not just considered as a surcharge in dynamic analysis. The use of twin tunnel also leads to the reduction of dynamic residual settlement**.**

Keywords**—**Superstructure, tunnel, site response, surcharge, interaction.

I. Introduction

When a fault ruptures, seismic waves move through hundreds of kilometers of bedrock to arrive at the site location. Then they normally propagate through less than a hundred meters of the softer soil to reach to the ground surface. Thus, the upper soil layer plays an important role in the determination of ground movement and acceleration that is known as the site effect [1]. The site effect problem was at the center of scientist's attention since the early days of the 20th century. They evaluated the effect of the site and depth of alluvial layers of the site on the alteration of seismic wave properties [2]. These evaluations continue at present and after the occurrence of a new earthquake around the world, a lot of researches are conducted on the effects of the site on the severance of the earthquakes. An example of the site effect on the earthquake damages was observed in the 1985 Mexico City earthquake with a magnitude of 8.1 that caused mild destructions at its epicenter (Pacific coast) but ruined Mexico City at the distance of 350 km [3]. On the other hand, rapid urban development leads to the construction of urban tunnels for transport. Passage of tunnels under the surface structures and utilities prompted the changes in the site conditions and hence alteration of the dynamic response of surface structures.

S. Abolhasan Naeini is Professor in Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran (phone: +982833901125; e-mail: Naeini_h@ikiu.ac.ir).

Saeideh Mohammadi is PhD Candidate of Civil Engineering, Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran, (e-mail: Saeideh.mohammadi68@gmail.com).

Although in most analyses, the effect of the superstructures is considered as an equivalent surcharge [4], static analysis show modeling the structure geometry is important. Since the stiffness of the superstructure is considered in this case, stress and displacement fields would be closer to the actual values [5], [6]. The effect of consideration of superstructure geometry is not studied in dynamic analysis sufficiently; therefore, two cases of equivalent surcharge and modeling the structure geometry in dynamic analyses of the interaction of superstructure with tunnel are investigated here. The effect of the construction of a single tunnel and twin tunnels are also reviewed. For this purpose, the soil properties and location and geometry of the tunnel are selected based on Line No. 7 of the Tehran subway.

II. Soil Parameters

According to the subsurface investigation in the project site, the ground in the studied area has two layers. The used parameters of Mohr-Coulomb model for these two layers are presented in the following table [7]:

TABLE I
Used Constitutive Model Parameters in the Analysis

ν	E (kN/m^2)	Dilation Angle (deg)	Friction Angle (deg)	Cohesion (kPa)	Density (kN/m^3)	Layer
0.3	6000	3	33	15	1.84	ET2
0.32	4000	3	33	30	1.90	ET 3

III. Assumption

Nowadays, the use of numerical methods through professional software is very popular in geotechnical engineering. Here version 7 of FLAC software is used. The constitutive model parameters are selected according to Table I. Due to the validity for most soils, simplicity, presentation of a clear physical perception for the soil behaviour, low parameters required and easy extraction of parameters from geotechnical reports, the Mohr-Coulomb model is used here.

For consideration of initial conditions of stress and strain, all models are equilibrated under their weight and then the weight or geometry of the structure is applied in the model. For the application of the equivalent weight, it is assumed that the building is residential and the equivalent weight of each storey is 10 kPa. For modeling the geometry of the structure, the beam element that is one of the available structural elements in software is used. This element has bending and axially behavior that makes it suitable as a structural beam or a column modeling. Dimensions of this element are selected based on the ordinary dimensions and distances of beams and columns in residential buildings. After this stage, the tunnel is excavated. The tunnel diameter is 9.16 m and is located at a depth of 15 m from the surface. For the twin tunnels case, the diameter is selected in such a way that the area of single and twin tunnels becomes equal. The center-to-center distance of twin tunnels varies from 1D (tunnel diameter) for attached tunnels to 2D for the farthest case. Twin tunnels are considered axisymmetric with regard to the CL of the superstructure. Finally, the seismic load is assigned to the model and the site response consisting of accelerations, displacements and response spectrum is determined and compared for different scenarios. For dynamic analysis, Tabas earthquake acceleration time history with a 7.6 magnitude, horizontal peak acceleration of 0.828 g and dominant frequency of 1.318 Hz are used. To save the analysis time, the frequency content above 10 Hz is filtered before the assignment of the load to the numerical model and baseline correction of time history is performed. The dimensions of meshing elements are selected so that the wave could transmit through the element. Model boundaries should be placed at a distance that has no effect on the model behavior. This distance is determined by sensitivity analysis. At last, the length and width of the model and the mesh size become 200 m, 65 m and 1 m, respectively. To consider semi-infinite space in the static mode, two vertical boundaries are assumed to be roller supported and the bottom boundary is restricted in both x and y directions. In the dynamic mode, seismic wave reflects to the model after hitting the boundaries and creates chaos in the model, hence the boundaries are considered as a free-field boundary and seismic excitation is applied on the bottom boundary. Fig. 1 shows the model dimensions and Fig. 2 depicts the created model in the case of a single tunnel. The used acceleration time history is shown in Fig. 3.

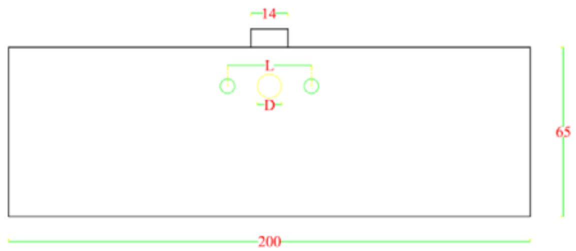

Fig. 1 Geometrical dimensions of the model

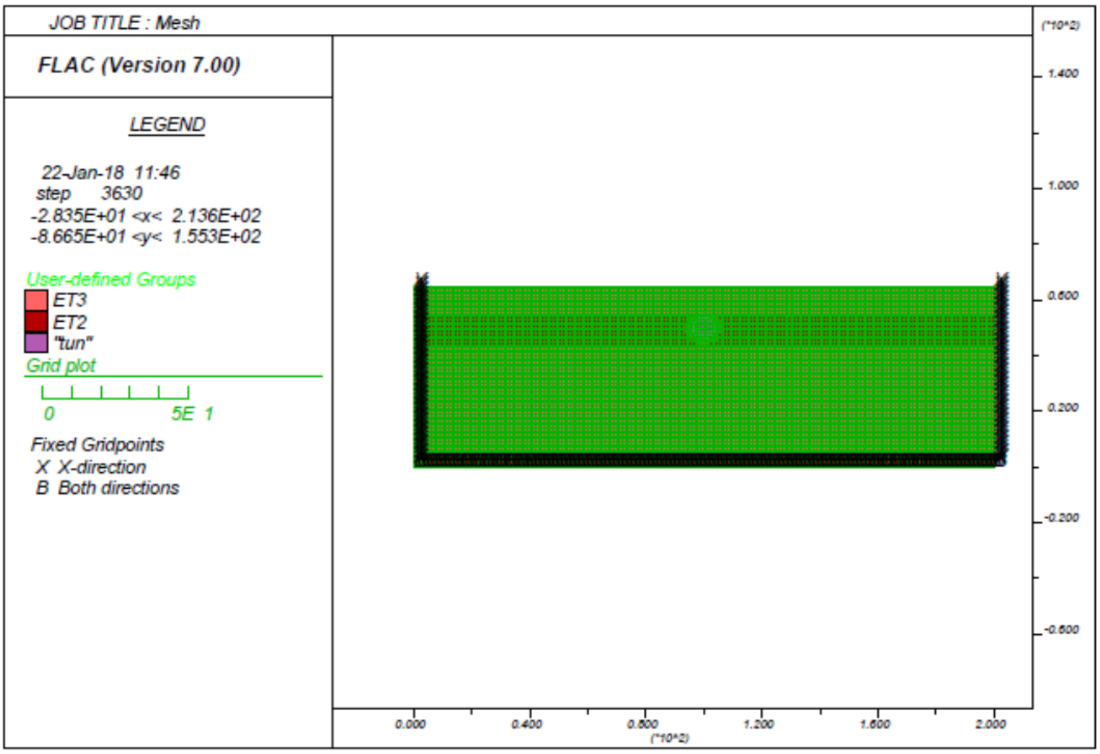

Fig. 2 Geometry of the created model in the case of a single tunnel

The inherent damping of the soil is important, while a dynamic load is applied and should be considered in the dynamic analysis. This damping is due to the movement of soil particles during the earthquake vibrations. Since when shear strain increases during the earthquake, soil stiffness decreases and its damping increases, the hysteresis damping of FLAC is used for the simulation of this case. Shear modulus versus shear strain and damping versus shear strain curves are selected from the proposed curves in reference books considering the depth and the type of the soil of the site [8]. Moreover, in the dynamic analysis of the soil, it becomes necessary to calculate small strain shear modulus and assign it to the soil according to the following relationship [9].

$$G_0 = 7000 * p^{0.5} * \frac{(2.17 - e)^2}{1 + e} \quad (1)$$

e is the soil porosity, p is the average effective stress and G_0 is small strain shear modulus. For the implementation of this relationship in the software, FISH language is used [10]. Consequently, the software is able to calculate the variation in shear modulus and damping based on the shear strain level at any moment of loading.

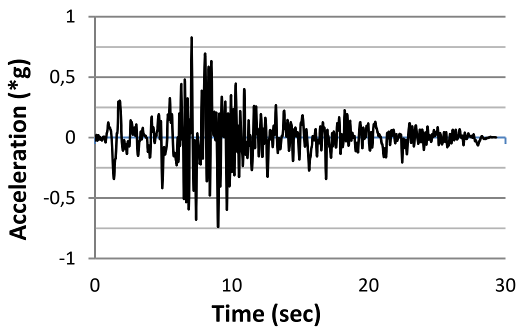

Fig. 3 Tabas earthquake accelerogram used in the analysis

IV. Discussion

In this section, the results are analyzed. In order to investigate the effect of tunnel-superstructure interaction, the equivalent load and geometry of a 3-storey building are considered. It is supposed that the single tunnel and twin tunnels have the same surface area and depth. The center-to-center distance of the twin tunnels varies from 1D to 2D. In the following, peak ground acceleration, surface residual displacements and response spectrum of the surface are investigated in different conditions.

A. Single Tunnel Case, Comparison of Equivalent Load and Superstructure

Here it is assumed that the single tunnel center is aligned with the foundation center. The analyses are carried out in two cases of 30 kPa equivalent surcharge load and consideration of beam element for modeling structure geometry. Results are compared in three parts:

- *Peak ground acceleration (PGA) and tunnel crown acceleration:*

The generated peak acceleration in the center of superstructure and the tunnel crown is presented for the two mentioned cases, as in Fig. 4. It is seen that when the structural elements are used to model the geometry, the PGA and the crown acceleration decrease considerably compared to the case when the equivalent load is applied. The reason for this might be the effect of structural stiffness and the change of the natural period of the site due to that it leads to the increase of damping and decrease of acceleration. But when the surcharge is modeled, the spread area of plastic points is limited to the corner of the loads that leads to the decrease of damping and increase of acceleration in the center of the foundation. Moreover, when the tunnel is close to the surface, the superstructure stiffness affects more the tunnel crown behaviour. When superstructure is modeled, the PGA reduces 50% compared to the equivalent load case. The rate of this reduction in the tunnel crown is about 37% .

- *Ground displacement*

The residual settlement of ground for different cases is compared and presented in Fig. 5. It is seen that like the trend observed in static analyses, modeling the structure stores leads to a considerable decrease of settlement compared to the equivalent surcharge case. The reason for this might be the significant effect of structural stiffness. The settlement decreases at the rate of 64%.

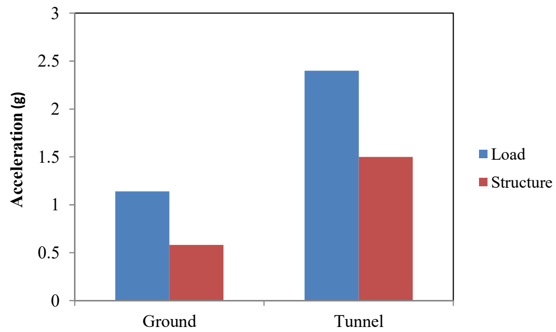

Fig. 4 Comparison of peak accelerations at the ground surface and at the tunnel crown

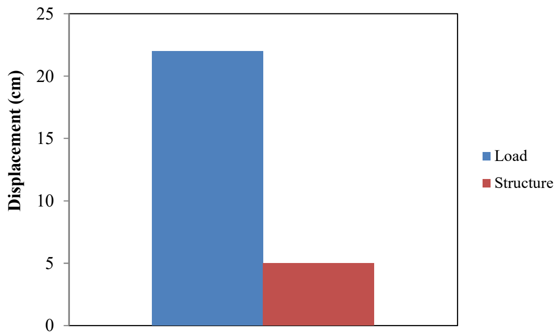

Fig. 5 Comparison of the residual settlement of the ground

- *Spectral acceleration of the ground*

The response spectrum is one of the most beneficial and important tools for the identification of strong ground motions properties. In fact, it shows the maximum response of a system against a specific input as a function of natural frequency (or natural period) and damping ratio. Generally amplitude, frequency content and the duration of displacement all affect the spectral values. Here, the acceleration response spectrum for the intended ground considering critical damping of 5% is investigated. Since most damages in an earthquake occur in a period range of 0 to 10 seconds, this period range is studied in the response spectrum.

Response spectrum for the application of surcharge and modeling the geometry of superstructure are compared in Fig. 6. It is observed that the spectral acceleration of modeling the geometry of superstructure is always less the equivalent surcharge. In other words, consideration of superstructure stiffness leads to the reduction of calculated applied force to the superstructure and feasibility of its design.

B. Comparison of Single and Twin Tunnels

In this section, the structure geometry is taken into account and the effect of single and twin tunnels with the same area and variable center to center distances on the response spectrum is studied.

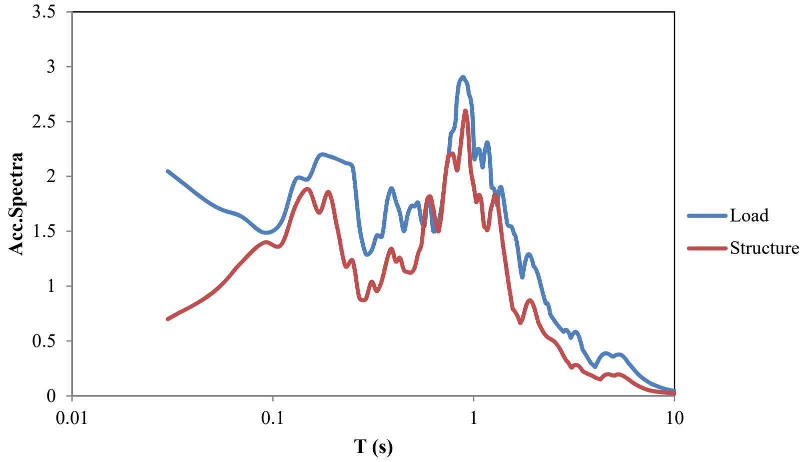

Fig. 6 Response spectrum of acceleration for surcharge and modeling superstructure

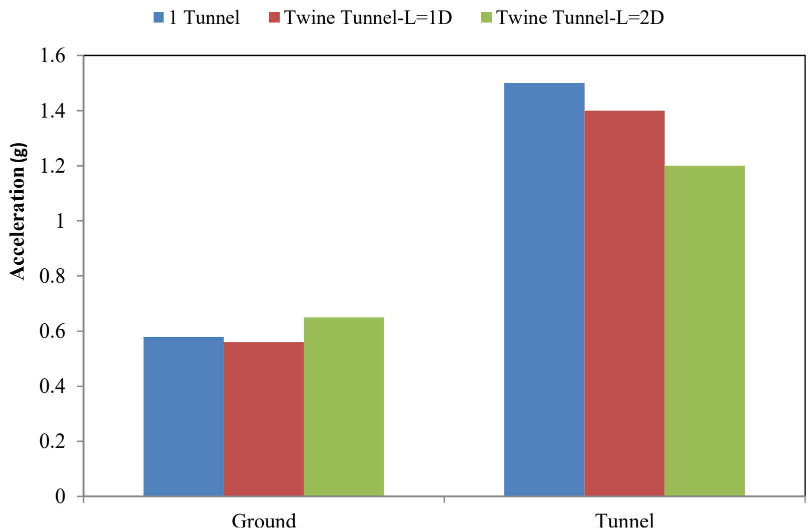

Fig. 7 Comparison of peak acceleration at the ground surface and at the tunnel crown of the single tunnel and the twin tunnels

- *Peak acceleration at the ground surface and the tunnel crown*

Peak acceleration at the ground surface and the tunnel crown is presented in Fig. 7 in different cases. By conversion of the single tunnel to two attached tunnels with the same surface area, peak ground acceleration decreases a little, but when the center-to-center distance increases, peak acceleration at the ground surface increases as well.

When center-to-center distance increases, the effect of excavated volume and the change in the stiffness of the media on the superstructure becomes less. Change in the stiffness of the media due to the excavation could lead to the increase or decrease of ground surface acceleration and in this case, it is seen that the ground surface acceleration increases. In the case of attached tunnels, since the excavated surface area is the same and the two tunnels are attached, the surface response is practically the same as the single tunnel.

By conversion of the single tunnel to twin tunnels and when the distance of the tunnels increases from each other, the acceleration at the tunnel crown decreases. Reduction of excavation surface area for each tunnel compared to the single tunnel and reduction of reciprocal interaction of tunnels when the center-to-center distance increases is the reason for this. In other words, twin tunnels are more stable than the single tunnel.

By conversion of the single tunnel to twin tunnels, when the center-to-center distance increases from 1D (attach tunnels) to 2D, ground surface acceleration decreases 3% and increases

12%, respectively. In the same scenario, the acceleration at the tunnel crown decreases 6% and increases 20%, respectively, compared to the single tunnel.

- *Displacement at the ground surface*

The residual settlement at the ground surface is shown for the single tunnel and twin tunnels in Fig. 8. It is seen that the conversion of the single tunnel to two attached tunnels increases the settlement at the center of the superstructure that is due to the interaction and the accumulation of settlements of the tunnels. When center-to-center distance of twin tunnels increases, the interaction of the two tunnels on each other decreases and ground surface settlement reduces. This might be due to the reduction of the effect of excavated volume on the superstructure when the distance of the tunnels from the center of the superstructure grows. It is observed that the settlement of the superstructure in two cases of attached twin tunnels and center-to-center distance of 2D compared to the single tunnel increases 20% and decrease 43%, respectively.

- *Spectral acceleration of ground surface*

Spectral acceleration is compared for two cases of the single tunnel and twin tunnels in Fig. 9. It is seen that the resulted spectral accelerations are almost identical for the three analyses and the studied factors have no effect on this case.

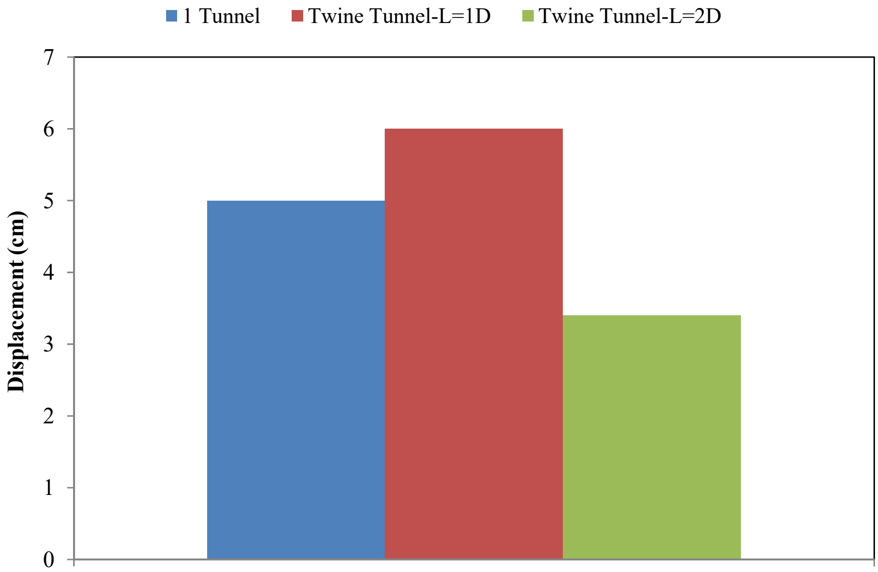

Fig. 8 Comparison of residual settlement of ground surface in single and twin tunnels cases

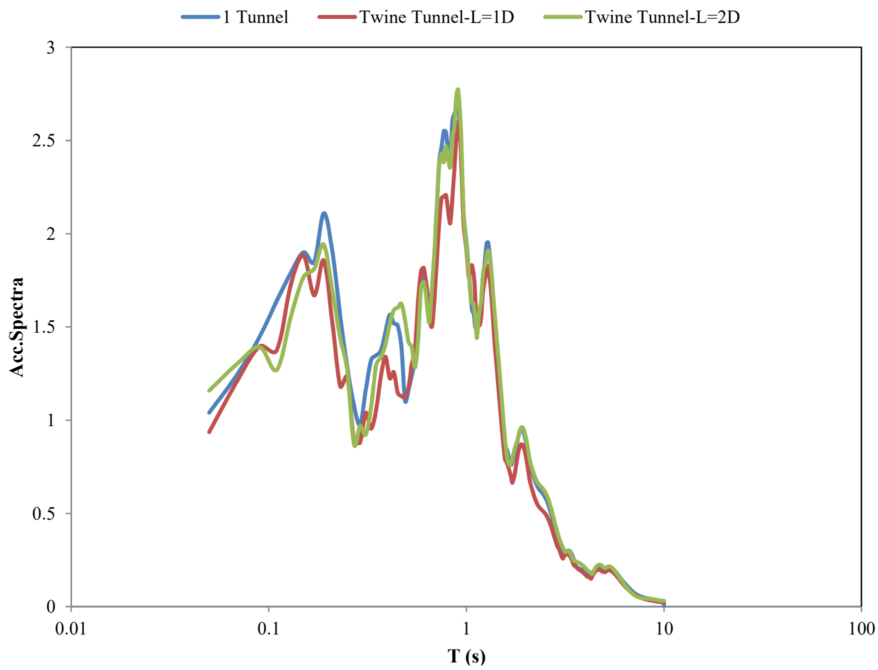

Fig. 9 Comparison of acceleration response spectrum for the single tunnel and twin tunnels

V. CONCLUSIONS

In this study, the effect of the equivalent surcharge and structure geometry on the site response is investigated in the presence of the tunnel. Two cases of a single tunnel and twin tunnels are also compared. Soil properties and tunnel geometry are considered according to the Line No. 7 of Tehran subway. It is observed that when the geometry of the structure is modeled, the site response is different from when the equivalent surcharge is applied. The peak ground acceleration and residual displacements are considerably lower when structure geometry is modeled compared to when an equivalent surcharge is applied. The spectral accelerations obtained from the modeling of the superstructure are less than the equivalent surcharge case. Twin tunnels increase dynamic stability of tunnels and reduce residual settlement. Based on the obtained results, consideration of structure geometry is necessary to examine the interaction of tunnel-superstructure, especially in the determination of residual displacement.

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