Seismic Waves Scattering Impact through Tunnel Excavation on Adjacent Monuments Subjected to Far Field Earthquakes

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ARTICLEINFO

Abstract

Studying the effect of seismic wave scattering has attracted extensive attention due to tunnels prominent role in the past couple of decades. A seismic wave, meeting the tunnel, can generate scattering which, in most cases, may raise damages in adjacent structures. In this study, using Finite Element Method (FEM), the effect of seismic wave scattering in far field has taken into consideration. The twin tunnels of Shiraz subway system is selected as case study in this research and three far field seismic waves was selected for time history analyses. Investigating the normal mode (before tunnel construction) in comparison to the excavation mode (after tunnel construction) enables calculating the effect of displacement, in adjacent structures. The analysis results show there is significant difference between before and after tunnel construction (Pvalue<0.05). By the way influence of constructing a tunnel on adjacent surface structures is very important for tunnel design.

1. Introduction

As a seismic wave impact the various surface irregular like holes or underground structures, because of the dissimilarity between the characteristics of the initial medium and the existing underground irregular media, part of the wave changes direction while the other part propagates through the medium. This process is called scattering. As the primary investigation, Pao et al. (1995) studied the wave diffraction around a cylindrical hole in infinite medium, in this research the wave function expansion, and derived the related stress has been calculated. Lee et al. (1982) studied the response of twin tunnel under horizontally polarized wave (SH) propagation in semi-space, based on the coordinate transformation method. Antonio et al. (2001) analyzed the three dimensional scattering with employing cylindrically shaped compound cavities in an elastic formation subjected to the broad frequency. Wang et al. (2005) evaluated dynamic stress concentration around elliptical cavities in saturated poroelastic soil under the harmonic plane waves. Esmaeili et al. (2006) worked on the dynamic response of the circular lining tunnels to plane harmonic waves. Lu et al. (2007) examined the dynamical response of piecewise circular tunnel embedded in poroelastic medium. Zhou et al. (2008) used a semi-analytical solution in order to explain the scattering of waves in an elastic half-space. Zhou et al. (2009) considered an elliptical twin tunnel embedded in a poroelastic medium and analyzed the effect of interaction between the seismic effects of two tunnels. In addition, they analyzed the behavior of plane wave scattering that created by cylindric cavities in poroelastic half-plane (Jiang et al., 2009). Bin et al. (2010) studied the dynamic response of tunnel in a under inner water pressure.

2. Research method

In the following research, Finite Element modeling (FEM) is employed to investigate the scattering phenomena. The applied software in this paper is PLAXIS 2D which is based on FEM calculation method.
and performs the dynamical analysis under far field seismic waves.

3. Case Study

The case study in this paper is part of Shiraz subway system in which the tunnel goes beneath the Zand and beside Karimkhani monuments. The constructed tunnel is situated below the ground watertable and is generally placed in silty gravel and silty clay soil. The outer diameter of the tunnel is 6.88 m and the inner diameter of this tunnel is 6 m, the dimension of the outer supported diameter, with reinforced pre-fabricated concrete segments, 6.6 m. The lining is essentially an assembly of concrete segments with 30 cm thickness and 1.4 m width. The void space (14 cm) between concrete segments and adjacent soil is injected by cement grout during TBM process. The thickness of tunnel’s over-burden from the level and the pile toe are 19 and 10 m respectively. In this study, the twin tunnel is parallel to the Zand underpass. Zand underpass has 700m length and 28 m width. It includes the upper and lower concrete slabs and in situ reinforced concrete piles as retaining walls. The wall’s height of Argekarimkhankh monuments is 12 m. Figure 1 shows a plot of Argekarimkhankh monument and Zand underpass.

4. Geology and Geotechnics

The geological profile of the case study includes 6 layers of soil with various thickness and properties. Soils are organized according to Unified Soil Classification System. The level of the ground water table is located 6.5 m below the tunnels crest. The soil properties and the material has been used in the monuments, the tunnel and the underpass property are mentioned in Table 1 and Table 2 (Afifipour et al., 2011).

![Figure 1: Relative position of twin tunnels and Zand underpass, ArgeKarimkhankh and soil layers](Afifipour et al., 2011)

| No. | Thickness (m) | Soil type | $\gamma_{sat}$ (g/cm$^3$) | $\gamma_{unsat}$ (g/cm$^3$) | $C_u$ (kg/cm$^2$) | $\phi_u$ (°) | E (kg/cm$^2$) | $V$ |
|-----|---------------|-----------|-----------------|-----------------|-----------------|----------------|-----------|-----|
| 1   | 4             | SC        | 1.9             | 1.6             | 0.3             | 33             | 325       | 0.3 |
| 2   | 3.2           | CL/ML     | 2.08            | 1.7             | 0.4             | 29             | 500       | 0.25|
| 3   | 6.7           | ML        | 2.09            | 1.68            | 0.1             | 32             | 300       | 0.25|
| 4   | 3             | CL        | 2.08            | 1.7             | 0.2             | 29             | 500       | 0.25|
| 5   | 1.8           | CL/ML     | 2.09            | 1.69            | 0.1             | 32             | 500       | 0.25|
| 6   | 21.3          | SM/ML     | 2.09            | 1.77            | 0.1             | 29             | 500       | 0.25|

Table 1: Physical and geotechnical properties of soil layers (Afifipour et al., 2011)
Table 2: Pre-fabricated segments and underpass concrete properties

| Structure                  | Model  | EA (kN/m) | EI (kNm²/m) | thickness (m) | W (kNm/m) | ν   |
|----------------------------|--------|-----------|-------------|--------------|-----------|-----|
| Pre-fabricated segments    | Elastic| 9.42e6    | 7.065e4     | 0.3          | 7.5       | 0.1 |
| Underpass concrete slab    | Elastic| 2.08e7    | 1.109e6     | 0.8          | 19        | 0.15|
| Underpass concrete pile    | Elastic| 3.12e7    | 3.744e6     | 1.2          | 28        | 0.15|
| Right wall of far arg      | Elastic| 1.32e7    | 1.198e7     | 3.3          | 49.5      | 0.3 |
| left wall of far arg       | Elastic| 1.12e7    | 7.317e6     | 2.8          | 42        | 0.3 |
| Right wall of near arg     | Elastic| 1.28e7    | 1.092e7     | 3.2          | 48        | 0.3 |
| left wall of near arg      | Elastic| 1.32e7    | 1.198e7     | 3.3          | 49.5      | 0.3 |

5. Scattering Analysis

The modeling condition is based on the plane strain condition with proper 15 triangular mesh types. The sensitivity analyze is carried out for the boundaries and the meshes and the final dimensions and mesh has been shown in Figure 2. Boundaries are selected proper situation in order to prevent the wave reflection. In refine mesh processes, we consider proper meshes due to the sensitivity around the tunnel, Karimkhani monument, and Zand underpass. According to the soil type of the case study area, special station of Chichi, Kobe, and Northridge time history seismic records are selected for far field studies. In accordance with Iran standard NO2800, Shiraz area has the relatively high risk of earthquake occurrence and the maximum earthquake acceleration should be scaled to 0.3g. The proper time for accelerographs is 20sec in which they are more critical and we can have the maximum response. Figure 3 show the employed accelerographs for far field analysis. The model of soils is Mohr-

![Figure 2: The geometrical model of the case study land](image)

![Figure 3: Acceleration of far field earthquake](image)

a) Kobe (0-20s)  
b) Northridge (5-25s)  
c) Chichi (25-45s)
6. Analyzing the Behavior of ArgeKarimkhani Monument

In order analyzing the ArgeKarimkhani monument, far field accelerographs are imposed to the structure in different directions. For studying the scattering phenomena, the control points in the structure that is further to the tunnel (A, B) and the monument that is nearer to the tunnel (C, D) are illustrated above the structure on earth. The differential displacement for each structure is investigated in various directions. Total displacement in both structures subjected to far field seismic waves of Kobe, Northridge and Chichi directed with the angle 37°, is shown in Figure 4, Figure 5 and Figure 6, Figure 7 and Figure 8, Figure 9 respectively.

Figure 4: The total displacement evaluation in the far Arg from the tunnel under the Kobe earthquake in 37° direction.

Figure 5: The total displacement evaluation in the near Arg from the tunnel under the Kobe earthquake in 37° direction.

Figure 6: The total displacement evaluation in the far Arg from the tunnel under the Northridge earthquake in 37° direction.
Figure 7: The total displacement evaluation in the near Arg from the tunnel under the Northridge earthquake in $37^\circ$ direction.

Figure 8: The total displacement evaluation in the far Arg from the tunnel under the Chichi earthquake in $37^\circ$ direction.

Figure 9: The total displacement evaluation in the near Arg from the tunnel under the Chichi earthquake in $37^\circ$ direction.

The corresponding scattering quantities due to far field seismic waves were driven in Tables 3 and Table 4. Using SPSS software and Mann-Whitney test, differential displacement amplitudes in Arge Karimkhani monument with tunnel and without tunnel construction are compared.
Table 3: The scattering in the far Arg

| Earthquake | Wave direction (degree) | Max differential seismic displacements after tunnel excavation (m) | Max differential seismic displacements before tunnel excavation (m) | Percentage of scattering (%) | P value |
|------------|-------------------------|---------------------------------------------------------------|---------------------------------------------------------------|----------------------------|---------|
| Chichi     | 0                       | 0.0485                                                        | 0.0522                                                        | -7.09                      | 0.077   |
|            | 37                      | 0.0449                                                        | 0.0463                                                        | -3.02                      | 0.00    |
|            | 45                      | 0.0453                                                        | 0.0466                                                        | -2.79                      | 0.00    |
| Northridge | 0                       | 0.0619                                                        | 0.0645                                                        | -4.03                      | 0.913   |
|            | 37                      | 0.0480                                                        | 0.0487                                                        | -1.44                      | 0.066   |
|            | 45                      | 0.0449                                                        | 0.0467                                                        | -3.85                      | 0.005   |
| Kobe       | 0                       | 0.1314                                                        | 0.1294                                                        | 1.55                       | 0.981   |
|            | 37                      | 0.1123                                                        | 0.0984                                                        | 14.12                      | 0.013   |
|            | 45                      | 0.1051                                                        | 0.0921                                                        | 14.11                      | 0.006   |

Table 4: The scattering in the near Arg

| Earthquake | Wave direction (degree) | Max differential seismic displacements after tunnel excavation (m) | Max differential seismic displacements before tunnel excavation (m) | Percentage of scattering (%) | P value |
|------------|-------------------------|---------------------------------------------------------------|---------------------------------------------------------------|----------------------------|---------|
| Chichi     | 0                       | 0.0764                                                        | 0.0635                                                        | 20.32                      | 0.00    |
|            | 37                      | 0.0417                                                        | 0.0332                                                        | 25.60                      | 0.619   |
|            | 45                      | 0.0352                                                        | 0.0328                                                        | 7.32                       | 0.00    |
| Northridge | 0                       | 0.0651                                                        | 0.0650                                                        | 0.15                       | 0.002   |
|            | 37                      | 0.0599                                                        | 0.0655                                                        | -8.55                      | 0.659   |
|            | 45                      | 0.0557                                                        | 0.0634                                                        | -12.14                     | 0.485   |
| Kobe       | 0                       | 0.0932                                                        | 0.0928                                                        | 0.43                       | 0.76    |
|            | 37                      | 0.0787                                                        | 0.0898                                                        | -12.36                     | 0.607   |
|            | 45                      | 0.0808                                                        | 0.0930                                                        | -13.11                     | 0.702   |

7. Conclusions

The effect of seismic wave scattering related to constructing the tunnel in adjacent area under far field earthquakes was studied specifically for Shiraz subway system monument the subway’s tunnel passes beneath the Zand underpass and beside ArgeKarimkhani monument. Utilizing the PLAXIS software and based on FEM analysis, simulation of the mentioned area and dynamical analysis of far field seismic waves has been carried out.

Based on the analysis of the results, the total displacement due to far field is shown in Figures 4 to 9. The scattering percentage in ArgeKarimkhani monument is mentioned in Table 3 and Table 4.

a) According to Table 3, maximum scattering percentage related to the far field study directed in an angle of 37°, in further monument is 14.12% for Kobe earthquake, and in 0°, is –

b) According to Table 4, maximum scattering percentage related to the far field study directed in an angle of 45°, in near monument is -13.11% for Kobe earthquake, and in 37°, is 25.60% for Chichi earthquake, and in 45°, is -12.14% for Northridge earthquake.

c) The maximum P-value measure in earthquake has happened in far field, for far castle monument, 0.981 and in near castle monument value is 0.76 under the Kobe earthquake in 0°.

d) In some of far fields of earthquakes, the effect of tunnel performs reversely and the percentage of scattering happens negatively. These measures
show that excavation of Shiraz tunnel causes lower drift in the Karimkhahan monument. These measures depend intensely on the earthquake frequency, the kind of structures, the distance between the structures and tunnel, the dimensions the weight of the structure.

e) The analysis results show there is significant difference between before and after tunnel construction (P-value<0.05). by the way influence of constructing a tunnel on adjacent surface structures is very important for tunnel design.

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