The Research of Influence of Above Building on Tunnel Dynamic Response

LI Xue-hong, LIANG Chen, XU Xiu-li, LI Zhi-Jun

College of Civil Engineering, Nanjing Tech University, Nanjing, China
1301718902@qq.com

Abstract. Based on finite element software ABAQUS, by using equivalent viscous-spring artificial boundary element combine wave motion input, a series of two-dimensional plane strain models of above building-soil-tunnel were built to study the influence of above building on tunnel dynamic response. The dynamic nonlinear effects of soils are considered by using equivalent linear method. Three seismic input with different spectrum characteristics were used here as input motion. Results show that the influence of above building is negligible. The dimension of above building, spacing between structures and the buried depth of tunnel are the important factors of the interaction system, in contrast, the stiffness of above building have small influence degree.

1. Introduction

In densely populated urban areas, tunnels and other underground structures are often passing beneath high-rise buildings or they are located close to them. The existence of these structures may create complex interaction effects with the underground structures usually referred as “city effects”.

In view of this phenomenon, both domestic and overseas scholars have made the research. Fang-jie li [2] analyzed the height of the above frame structure with different influence on underground station. The results show that the existence of ground structure has an important influence on the seismic response indexes such as the relative displacement of underground structure and the internal force of the nodes. The method based on vibration input of Huai-feng wang [3] sets up the two-dimensional plane strain model of ground structure - earth - underground station structure, analyzing the influence of surface building height, building rigidity and foundation depth and so on. Guo-bo wang [4-5] made a preliminary analysis by establishing the calculation model of a tunnel - soil - surface frame structure interaction system and discussing the influence of seismic response on the underground structure. Kyriazis Pitilakis [6] simplified the surface structure into a single degree of freedom, analyzing the influence of different ground structure layout on tunnel dynamic response. The result shows that the existence of ground structure strongly influences the relationship between flexibility ratio F and pressure ratio R.

The existing research in considering the above structure, usually does not consider the role of structure foundation, and the above structure foundation due to more close to the underground structure, the underground structure effect cannot be ignored. Therefore, this article established considering pile group foundation frame structure and the analysis model of the tunnel on the ground, using the finite element software ABAQUS, through between soil - tunnel and soil - the surface structure setting reasonable contact to consider the dynamic action of soil-structure, studies systematically the influence
of factors such as rigidity, mass, structure spacing and tunnel depth of the above building to the earthquake response of the tunnel. It provides the reference for site selection and seismic design of underground tunnel structure.

2. Finite element model
The above building takes a 3 span and 12 storey frame structure. The height of each layer is 3.6m, the length of the building is 20m and the width is 15m, the span of both sides is 6m, the middle span is 3m, the beam section is 0.25×0.60m, the column section is 0.60×0.60m; the pile foundation is arranged according to the pile distance with 3m, the diameter of the pile foundation is 0.6m, the pile length is 20m, and the layout of the pile foundation is shown as Figure 1. The tunnel is a circular tunnel with equal cross section. The outer diameter of the tunnel is 6.15m, the inner diameter is 5.85m, and the thickness of the tunnel is 0.3m.

\[
E_{ep} = \frac{E_P A_p + E_S A_s}{A}
\]

In the formula (1), A_p is the area of pile section, A_s is the area of soil in the wide range of the pile, A is the sum of A_p and A_s, E_P is the elastic modulus of the pile, and E_s is the elastic modulus of soil in the wide range of pile.

The finite element model as shown in Figure 2, the width of the calculation area is 160m, the distance from the arch bottom to the bedrock is 40m, the vertical distance from the vault to the ground surface is defined as h, and the minimum distance between the tunnel and the pile foundation is defined as B.
2.1 Calculation parameters

In order to eliminate the influence of soil layer factors, the homogeneous soil layer is adopted here and the nonlinear characteristic of soil is considered by the equivalent linearization method. The constitutive model of soil is simulated with the Davidenkov model. The Davidenkov model is described by the formula (2) and the formula (3).

\[ G_{\text{max}} = 1 - \left( \frac{\gamma_d}{\gamma_0} \right)^{2B} \]  \hspace{1cm} (2)
\[ \lambda = \lambda_{\text{min}} + \lambda_0 \left( 1 - \frac{G}{G_{\text{max}}} \right)^\beta \]  \hspace{1cm} (3)

In the formula (2) and formula (3): \( \gamma_0, A, B, \lambda_0 \) and \( \beta \) are the fitting parameters related to soil properties, the value of the soil refer to the Chen Guoxing soil sample test, \( \lambda_0 = 0.175 \), \( \lambda_{\text{min}} = 0.0183 \), \( \gamma_0 = 3.1 \times 10^{-4} \), \( A = 1.17 \), \( B = 0.43 \), \( \beta = 0.94 \).

In calculation of soil parameters, shear wave velocity of is 140 m/s, density is 1900 kg/m\(^3\), poisson's ratio is 0.35. The C30 concrete are considered for the above frame structure and the pile foundation, modulus of elasticity is 30 Gpa, density is 2500 kg/m\(^3\), poisson's ratio of 0.2. Tunnel lining structure uses C50 concrete, the elastic modulus is 35 Gpa, density is 2500 kg/m\(^3\), the poisson's ratio is 0.2.

2.2 Model boundary and seismic wave input

The equivalent viscoelastic artificial boundary were used here to simulate the model boundary. The stiffness and damping value of equivalent viscoelastic artificial boundary element are as the formulas (4) and (5):

\[ \tilde{E} = \alpha_N h \frac{G_{\text{el}} (1+\phi)(1-2\phi)}{R} \]  \hspace{1cm} (4)
\[ \tilde{\eta} = \frac{\rho R}{2G_{\text{el}}} \left( \frac{\varphi N}{\alpha_T} + \frac{\varphi p}{\alpha_N} \right) \]  \hspace{1cm} (5)

In formula (4) and (5); \( h \) is the sickness of equivalent viscoelastic artificial boundary element; \( G_{\text{el}} \) means equivalent modulus of rigidity of the i layer of soil which can be got from the shear strain of the corresponding layer of soil; \( R \) is the distance from wave source to artificial boundary; \( c_{\text{si}} \) and \( c_{\text{pi}} \) respectively represents equivalent shear and compression wave velocity; \( \tilde{\varphi} \) is the equivalent poisson ratio whose values are as the formulas (6):

\[ \tilde{\varphi} = \begin{cases} \frac{\alpha^2}{2(\alpha-1)} & \alpha \geq 2 \\ \frac{\alpha}{2(\alpha-1)} & \alpha < 2 \end{cases} \]  \hspace{1cm} (6)

In formula (6), the value range of \( \alpha = \alpha_N/\alpha_T \), \( \alpha_T \) and \( \alpha_N \) can be referred to literature[11], set \( \alpha_N = 1 \) and \( \alpha_T = 0.5 \).

Taking vertical plane wave as incident seismic wave, the loads applied on artificial boundaries can be expressed by displacements and velocities of input wave, which makes the earthquake easy to input. The equivalent joint load can be expressed as formulas (7):

\[ F_B(t) = \tau_0 (x_B, y_B, t) + C_B \omega_0 (x_B, y_B, t) + K_B \omega_0 (x_B, y_B, t) \]  \hspace{1cm} (7)

In formula (7): \( \omega_0 \) is the displacement field of artificial boundary; \( \omega_0 \) is the corresponding speed field; \( \tau_0 \) is the stress field caused by the displacement field \( \omega_0 \).

2.3 The contact between structures

Penalty function method were used here to consider the interaction between soil and pile. to achieve the dynamic contact model in ABAQUS method is to use "hard contact " in normal, tangential contact with coulomb friction model, the friction coefficient of 0.4. Assuming that there is no slip phenomenon between the tunnel and the soil. The displacement of the earth contact surface always satisfies the coordination condition, and no separation occurs, than use the Tie Main from contact unit to simulate.
2.4 Input waves

Three seismic waves with different spectrum characteristics are selected. Kobe wave, Chichi wave and Northbridge wave are selected as incident waves. The peak acceleration of three waves is adjusted to 0.3g, and the seismic dynamic holding is 30s. The acceleration time history curve and acceleration response spectrum are shown in Figure 3.

3. The influence of the existence of the above building on the earthquake response of tunnels

This part mainly analyses the influences of the presence or absence of the above building on the seismic response of the tunnel, which includes the influences on the relative deformation and the stress of the tunnel structure.

3.1 Relative deformation of the tunnel

Under the influence of lateral seismic waves, the underground structure is deformed by the compression of the surrounding soil layers, as shown in Figure 4. This paper uses the horizontal relative displacement of top and bottom of the arch as an indicator to measure the dynamic response of underground structures.
reaches 34.5%. And the second is the kobe wave which reaches 27.5%, and the chichi wave being the smallest which is 13.7%.

3.2 stress of the tunnel

The layout of the main analysis point of the tunnel is shown in Figure 6, where θ is 45°. And AR1~AR8 respectively correspond to the top, left spandrel, left arched waist, left arched foot, bottom, right arched foot, right arched waist and right spandrel of the tunnel. Figure 7 shows the comparison of the stress peaks at the eight monitoring points of the tunnel with or without the above structure under the action of three seismic waves (tunnel depth is 2m). In condition 1, there is no above building, while in condition 2 there is an above building.

From Figure 7, it can be seen that the presence of the above building has noticeable impact on the overall stress peak of the tunnel structure. The reflection of seismic waves between structures leads to the change in the structural dynamic response. When there is an above building, the force distribution form of the original tunnel structure does not change, the maximum value appears at the spandrel and arched waist of the left and right of the tunnel, and the stress peak still distributes as “X”. The stress at each location of the tunnel increases when there is an above building in comparison with no above building. Under the action of kobe wave, the peak stress of the tunnel increases from 2.29 MPa to 2.69 MPa. And the stress changes the most at the spandrel of the tunnel, which increase by 1.31 MPa. Under the action of the northbridge wave, the peak stress of the tunnel increases by 0.25 MPa, and the stress increases by 0.96 MPa at the right spandrel of the tunnel which is considered as the largest increase. Under the action of the chichi wave, the peak stress of the tunnel increases by 0.31 MPa, and the stress increases by 0.65 MPa at the left spandrel of the tunnel which is seen as the largest increase.
4. Analysis of the influence of main parameters of above building on tunnel

In order to provide reference for seismic design of tunnels, main factors that may affect the seismic response of tunnels are analysed which mainly include: the distance between the building and the tunnel, the stiffness of the building, the volume of the building, etc.

4.1 Impact of the location of the above building

The interactions between adjacent structures occur under the action of earthquake, and the reflection of seismic waves between adjacent structures leads to changes in the structural dynamic response. And construction between structures directly affects the strength of interaction. Therefore, it is necessary to analyse the influence of the distance from the tunnel to the building on the dynamic response of the tunnel. 12-story frame structure that mentioned above is considered as the above building with the width which equals to 15m (W = 15m). The minimum distance between the pile foundation and the tunnel is defined as the distance B. Conditions that B=2m, 8m, 16m...40m are analysed. At the same time, four different site soils are considered. Parameters are shown in Table 1.

Table 1 Soil parameters

| soil   | A    | B    | Vₙ(×10⁻⁴) | β     | λ₀/λ (%) | λₘ₀/λ (%) | Gₘₐₓ/MPa | Poisson ratio μ |
|--------|------|------|------------|-------|----------|-----------|-----------|------------|
| Soil 1 | 1.17 | 0.43 | 3.1        | 0.94  | 17.5     | 1.83      | 36        | 0.35       |
| Soil 2 | 1.08 | 0.46 | 3.0        | 1.09  | 18.4     | 1.91      | 40        | 0.3        |
| Soil 3 | 1.01 | 0.47 | 3.4        | 1.10  | 18.5     | 0.94      | 53.5      | 0.25       |
| Soil 4 | 0.93 | 0.50 | 4.1        | 1.29  | 21.5     | 1.15      | 70        | 0.2        |

The shear wave speeds of the four soil layers are obtained according to the formula G=pc²; Vₙ=140m/s, 145m/s, 164m/s, and 187m/s. Figure 8 shows the variation of the relative displacement at the top and the bottom of arch at different spacing in the four ground soils. And the longitudinal axis is the ratio of relative displacement when there is no above building.

![Figure 8 Relative displacement ratio with spacing](image)

It can be seen from Figure 8 that the relative deformation of the tunnel gradually decreases with the increase of the spacing. When the width of the above building is 15m, the spacing reaches 30m, that means, when L/W (spacing/building width) = 2, the existence of the above building has negligible impact on the dynamic response of the tunnel. The softer the soil layer is, the more obvious the influence of spacing on tunnel seismic response is. When the spacing is 2m, the influence rate of clay layer in Kobe wave condition reaches 27.6%, while that in sandy soil reaches 23.7%. The other two seismic waves have similar rules.

4.2 The influence of the stiffness of the above building

In order to analyse the influence of the stiffness of the above building, the soil with an equivalent shear wave velocity of 140m/s is taken as the ground soil. The depth of tunnel is 2m, and the distance between pile foundation and tunnel is 2m. Multiplying the concrete elastic modulus E of the building by 0.5, 0.75, 1, 1.25, and 1.5 to simulate the different stiffness of the building. The calculated horizontal relative displacement time history curve and the maximum principal stress contrast are shown in Figure 9 and

![Figure 9](image)
figure 10. And it can be seen that the influence of the stiffness of the above building on the dynamic response of the tunnel is not significant. With the decrease of the stiffness of the above structure, the interaction effect between the soil and the building increases, and the stress at the left and right waist and the foot of the arch increases slightly. Under the action of Kobe wave, when the stiffness of the above building is 0.5E, the maximum principal stress is 2.91MPa, and when the stiffness of the above building is 1.5E, the maximum principal stress reaches 2.47MPa. And the rules of other seismic waves are similar.

![Kobe wave](image1)

![Northbridge wave](image2)

![Chichi wave](image3)

Figure 9 Stress comparison of tunnel under different stiffness of above building

![Kobe wave](image4)

![Northbridge wave](image5)

![Chichi wave](image6)

Figure 10 Horizontal relative displacement of tunnel under different stiffness of above building

4.3 The influence of the volume of the above building

The previous studies show that the impact of changes in building stiffness on the seismic response of tunnel structures is not significant. Therefore, when studying the influence of the volume of the above structure, the effect of changes in structural stiffness on the dynamic response of the structure is ignored as the number of storey floors change. The seismic response of tunnel structure is comparatively analysed when the number of above buildings is 6, 12 and 18. Table 4 and Table 5 show the maximum peak stress of the tunnel under the three kinds of seismic wave conditions. Figure 11 and Figure 12 present the stress of the tunnel and horizontal relative displacement. From Table 4, Table 5, Figure 11 and Figure 12, it can be seen that with the increase of the number of above buildings, the seismic response of the tunnel structure is significantly affected. The stress at the left and right waist and the foot of the arch increases obviously. Under the action of Kobe wave, when the number of above building floors reaches 18, the maximum main stress of the tunnel reaches 3.22MPa, which increases by 0.53MPa compared with the number of 12 and the increase rate reaches 19.7%. In comparison with the number of 6, the maximum principal stress increases by 0.75MPa and the increase rate is 30.3%. The horizontal relative displacement of tunnel structures is also influenced significantly. Under the action of kobe, the maximum relative displacement of tunnel structure reaches 28.52mm when the above building reaches 18 floors, which increases by 5.8mm in comparison with that with 12 floors and the increase rate is 25.5%. While in comparison with 16 floors, the maximum relative displacement of tunnel increases and the rate increases by 31.1%. The other two seismic waves have similar rules.
5. Conclusions  
(1) The above structure has a noticeable effect on the dynamic response of the tunnel, which leads to the increase of stress and deformation of the tunnel. When the distance between the building and the tunnel is 2m, the influence of the frame structure with 12 stories on the tunnel stress reaches 17.82%, and that on the relative displacement of the tunnel reaches 34.5%.

(2) When the distance between the above building and the tunnel is different, the degree of influence on the earthquake response of the tunnel is also different. That means the larger the distance, the smaller the impact. When the ratio of distance to building width reaches 2, the interaction between the two can be ignored. In addition, the softer the soil, the more obvious the influence of spacing on the seismic response of the tunnel.

(3) The stiffness of the above building has a little influence on the tunnel. Only when the stiffness of the superstructure is small, the stress of the tunnel increases slightly. Because the enhancement of the interaction between the building and the soil has obvious impact on the dynamic response of the tunnel.

(4) The volume of the above building is an important factor that affects the dynamic response of the tunnel. The greater the volume, the greater the degree of influence on the dynamic response of the tunnel. When the number of storeys of the above frame structure is 18, the stress and deformation of the tunnel increases by 20%-30% compared with when the number of storeys is 6.

(5) When the tunnel with a shallow depth penetrates a large building, the interaction among building-soil-tunnel is the most obvious, and attention should be paid to the seismic performance of the tunnel under such engineering conditions.

References
[1] Plilakis K,Tsinidis G.Performance and seismic design of underground structures in earthquake geotechnical engineering design [M],[s.l.]:Springer International Publishing,2014:279-340.
[2] Li Fangjie, Zhao Fenxin, Zhang yushan, You Hongbing. Influence of relative position of ground structure on seismic response of underground structure of subway[J].China Earthquake, 2010, 26 （2）:201-209(in Chinese)
[3] Wang Huafeng, Lou Menglin, Chen Xi, Zhai Yongmei. Influence parameters of adjacent structure on dynamic response of underground structures[J].Journal of Tongji University.
2012,40（12）1773-1777(in Chinese)

[4] Wang Guobo, Wang Yaxi, Chen Bin, Yu Yanli. Analysis of seismic response factors of tunnel-soil-surface structure interaction system[J]. Chinese journal of rock mechanics and engineering, 2015 (in Chinese)

[5] Wang Guobo, Yu Yanli, He Wei. Preliminary analysis of seismic response of near frame structure interaction system under tunnel ground surface[J]. Journal of geotechnical engineering, 2014 (in Chinese)

[6] Kyriazis Pitilakis, Grigorios Tsinidis, Andera Leanza, Michele Maugeri. Seismic behavior of circular tunnels accounting for above ground structures interaction effects[J]. Soil Dynamics and Earthquake Engineering, 2014

[7] Wang Li, Zhen Gang. Comparison of pile-soil interaction between pile and raft foundation by finite element simplified models[J]. China Civil Engineering Journal, 2007, 40: 308-313 (in Chinese)

[8] Chen Guoxin, Liu Xuezhu, Zhu Dinghua, Experimental study on dynamic shear of newly deposited soils in the south of Yangtze River in Jiangsu[J]. Journal of underground space and Engineering, 2007, 3(4): 745-750. (in Chinese)

[9] Chen Guoxin Geotechnical seismic engineering[M]. Bei Jin: Science Press, 2007 (in Chinese)

[10] Liu Jinbo, Du Yinxin, Yan Qiushi. Implementation of viscoelastic artificial boundary and ground motion input in general finite element software[J]. Journal of disaster prevention and mitigation engineering, 2007, 27: 37-42. (in Chinese)

[11] Du Dongshen, Wang Shuguang, Liu Weiqin, Li Weiwei. Effects of ground motion spectrum characteristics on response and damage of isolated structures[J]. Journal of Vibration and Shock, 2015, 34 (20) : 203-213 (in Chinese)