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Seismic Response of a Subway Station Structure Subjected to Earthquake Excitation

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ABSTRACT

The seismic performance of a large underground structure in soils became an important topic because of the severe damage to a subway station that occurred in a recent earthquake. A three-dimensional finite element model of the soil-structure interaction system was constructed using ABAQUS software. A 3D equivalent boundary element of viscous-springs was introduced based on the theory of a viscous-spring artificial boundary. The waves of the free field were used in a three-dimensional layered half space. The seismic waves were transformed into equivalent forces and were applied to the artificial boundary nodes. The equivalent forces were calculated by using a finite element model with lumped mass and the finite difference method. The open system was thus transformed into a closed-system by adding these local artificial boundaries. Seismic responses of the subway station structure were analyzed and the factors that influenced it were determined. The modal characteristics of the soil and subway station were obtained from the modal analysis. The seismic responses of the subway station structure in the horizontal and vertical directions were analyzed under SV and P waves. The corresponding responses and distribution of the internal forces were studied to determine the most vulnerable positions.

Introduction

There were some important substructures damaged recently. The most serious destruction of a subway structure was from a magnitude 7.3 earthquake in Kobe City. There were five stations and 3km interval tunnel damaged in varying degrees. The middle column of Dakai station had the most serious damage. More than half of the columns collapsed. The damage was found in two locations including bottom and top of the columns. Longitudinal cracks and oblique cracks were found on side walls. The settlement of the pavement above the station was up to 2.5m. After Kobe earthquake, researchers, such as Hashash et al. (2001), Zhou (2012) and LI(2005), greatly expanded their studies for structure-foundation dynamic interaction and foundation liquefaction. The numerical method has become an important approach in recent years. Huo (2005) studied the damage mechanism of the Dakai subway station by using the finite element software ABAQUS. He(2011) analyzed the subway station using infinite element and studied the internal force and displacement response and the influence of the soil parameters. Liu, et al. (2005) discussed the main parameters affecting the seismic response of the subway station and the tunnel using the FLUSH software. The horizontal seismic response of Chongwenmmen station was studied by Liu et al, (2008), using MSC.Marc software and THUFIBER procedure. Chen, et al. (2009) used FLAC software to analyze the earthquake response of the subway

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station. Cao,et al (2002) and other researchers found that the vertical motion could not be neglected according to their seismic analysis using a complex analysis method. Gao, et al(2001). studied the weak position of lining structure and corresponding stress and displacement under earthquake load. A constitutive soil and dynamic elastoplastic damage model of the concrete was developed for ABAQUS by Zhuang, et al, (2008). Xu, et al. (2008) established the finite element model for seismic response analysis of a double-layer subway station using software ANSYS.

Seismic wave input of the underground structure has been a complex problem for a long time. The DRM proposed by Bielak (2003) is a modular two-step FE methodology for modeling earthquake ground motion in highly heterogeneous localized with significant contrasts in wavelengths. The method separates the analysis into two sub-problems. The original semi-infinite region is truncated by outer boundary. In this proposed method is to add a special local artificial boundary and input the corresponding equivalent loading. This boundary is simplified and it can be easily applied on the model even for engineers. There have been studies about the concept and application of viscoelastic by Gu, et al. (2007). A procedure for equivalent loads on the artificial boundary has been proposed in the paper based on the finite element and difference method. The specific formula was established by integrating the shape function directly according to the different elements. The input method is easy to use. In addition, there is very little research about three-dimension models of the substructure under earthquakes due to the computation complexity. The stiffness of the huge substructures is not the same and changed in the longitudinal direction, so it is not best way to study it using the 2D model. It is important to consider how to establish and solve the computation of large-scale numerical models. We introduce the viscous-elastic artificial boundary element to induce the scale of the foundation. A three-dimensional model has been established using software ABAQUS. The effect of soil and input waves for seismic analysis of the subway station has been studied by considering SV and P waves. Conclusions about the seismic response of the subway station and the internal forces distribution of complex underground structure are presented.

Artificial Boundary Elements and the Earthquake Input

Three Dimension Equivalent Artificial Boundary Element

According to Gu's (2007) study, artificial boundary was added to the boundary to simulate the radial damping of the continuous medium. It should be noted that the radial waves did not reflect back to the limited computing area. An equivalent element was proposed for replacement of the spring-damper system. The method was to extend a layer of elements with the same type of inside elements along the normal direction. The outside boundaries of it were fixed. The accuracy of the equivalent element was verified. The equivalent shear modules, elastic modules and equivalent damping are

$$\begin{cases} \tilde{G} = hK_{BT} = 2\alpha_T h \dfrac{G}{R} \\ \tilde{E} = 2\dfrac{(1+\tilde{\nu})(1-2\tilde{\nu})}{(1-\tilde{\nu})} hK_{BN} = 2\alpha_N h \dfrac{G}{R} \cdot \dfrac{(1+\tilde{\nu})(1-2\tilde{\nu})}{(1-\tilde{\nu})} \end{cases} \qquad (1)$$

$$\tilde{\eta} = \frac{\rho R}{3G}(2\frac{c_s}{\alpha_T} + \frac{c_p}{\alpha_N}) \quad (2)$$

in which R is the distance from the wave sources to the artificial boundary; h is thickness of the equivalent element. c_s and c_p are velocities of S and P waves, respectively; G is the shear modulus of medium; ρ is the mass density of the medium; α_T and α_N are parameters. K_{BT} and K_{BN}, usually used in viscoelastic artificial boundaries, can be calculated in equation (1).

After setting the artificial boundary, the waves were be input by equivalent loading, which caused the same displacement, velocity and stress as the free wave field. The equation of the equivalent load input at a point B at the base:

$$\begin{aligned} P_{BN}(x_B, y_B, t) &= \left[\sigma(x_B, y_B, t) + C_{BN}\dot{u}(x_B, y_B, t) + K_{BN}u(x_B, y_B, t)\right]\Sigma A_i \\ P_{BT}(x_B, y_B, t) &= \left[\tau(x_B, y_B, t) + C_{BT}\dot{u}(x_B, y_B, t) + K_{BT}u(x_B, y_B, t)\right]\Sigma A_i \end{aligned} \quad (3)$$

in which P_{BN} and P_{BT} are equivalent loads of the normal and tangential directions at the node B; C_{BN} and C_{BT} equals to $\rho Rc_s/G\alpha_T$ and $\rho Rc_p/G\alpha_N$; $\sigma(x_B,y_B,t)$ are the normal stresses of node B; $\tau(x_B,y_B,t)$ is tangential stress of node B; $u(x_B,y_B,t)$ and $v(x_B,y_B,t)$ are displacement responses of node B in free field; and are velocity responses of node B free field. The equivalent loads can be calculated according to equation (3), which are needed to obtain the response of the free field.

Finite Element Model

A numerical model of wave propagation was created. According to the book written by Liao (2004), the nodes in the model were related to the neighboring elements. There was a unit element along the direction of the wave propagation. The equation of motion at one moment can be written as following:

$$m_i\ddot{u}_i + \sum_e k_i^e u^e + \sum_e c_i^e \dot{u} = P_i \quad (4)$$

in which $m_i = \sum_e\sum_j M_{ij}^e, k_i^e = \int_{V_e}(\mathrm{LN}_i)^T dLN\, dV_e, c_i^e = \int_{V_e}(\mathrm{LN}_i)^T b\, dLN\, dV_e, \rho$ is a unit of mass density. LN is one order differential of the element shape function. The calculation could be completed directly in the unit element without the total stiffness integration. For the three-dimensional case, the stiffness matrix of the cubic element can be written directly.

$$\begin{aligned} m_i &= \frac{1}{8}\rho\Delta x^3 \\ \mathrm{k}_i^e &= \frac{\Delta x E}{144(1+\nu)(1-2\nu)}[\mathrm{k}_{i1}, \cdots, \mathrm{k}_{i8}] \end{aligned} \quad (5)$$

in which ki1,…,ki8 aere 3×3 sub-matrixes related to Poisson Ratio. The accelerations were second differences of the displacements. (Substitute Eq(5) in Eq(4) to solve it.) The equations of motion of adjacent time contained only the movement in the vertical direction, which could be obtained by the neighboring nodes on the boundary of a column node displacement. The time

history of velocity and acceleration could be obtained by time history of the displacement. The equivalent load on the node could be calculated by the finite element model.
Considering the acceleration of the node B is equal to the nodes of connected element. The motion of the equation is:

$$m_B\ddot{u}_B + F_B - P_B = 0 \tag{6}$$

in which P_B is concentrated force vector on nodes of the boundary, $P_B=\{P_{Bx},P_{By}\}$, u_B is time history of velocity in free field. The time history of velocity and acceleration can be obtained by central difference method.
F_B is a force added on the node i, which is a node on the artificial boundary of the model.

$$F_B = \sum_e f_i^e = \sum_e \int_e (\mathrm{LN}_i)^T \tau dV_e \tag{7}$$

in which τ is stress vector of the element. $F_B=K_0u_{B0}$, K_0 is stiffness of element on node B. u_{B0} is time history of the displacement of node B in the free field. Eq(5) can be written as following:

$$P_B = -(m_B \ddot{u}_B + K_0 u_{B0}) \tag{8}$$

Solve the equation(7), and substitute Eq(7) in Eq(3). The equivalent load P_B can be calculated directly.

$$\begin{aligned} P_{BN}(\mathrm{x_B}, y_B, t) &= P_{By} + \left[C_{BN}\dot{u}(\mathrm{x_B}, y_B, t) + K_{BN}u(\mathrm{x_B}, y_B, t) \right]\Sigma A_i \\ P_{BT}(\mathrm{x_B}, y_B, t) &= P_{Bx} + \left[C_{BT}\dot{u}(\mathrm{x_B}, y_B, t) + K_{BT}u(\mathrm{x_B}, y_B, t) \right]\Sigma A_i \end{aligned} \tag{9}$$

According to study of Liu (2006), the earthquake wave can be input on the model according to the Eq(8), which is equivalent load added on the viscoelastic artificial boundary. The procedure is shown in Fig. 1.

There is space decoupling in lump mass method to finite element model. The accuracy and the stability of the system should be considered by controlling the ratio of the wave length and the element's dimension. The time step Δt, element dimension Δy and velocity of wave should meet the condition as following:

$$\Delta t \le \frac{\Delta y}{c} \tag{10}$$

in which c can be c_s and c_p respectively, according to considering the wave propagation of SV and P waves.

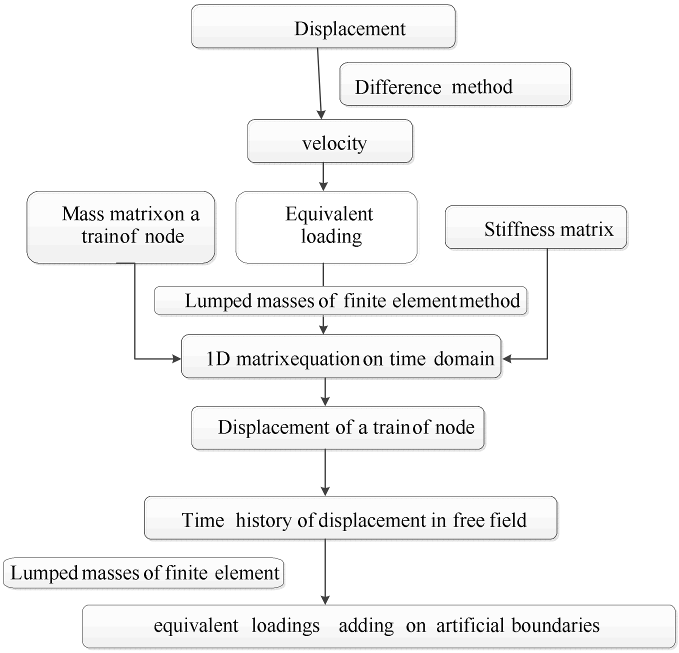
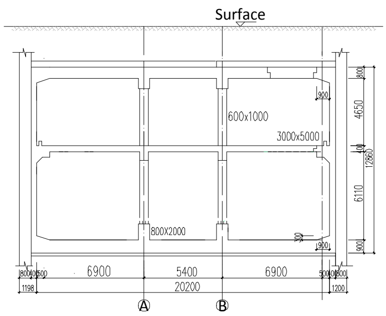


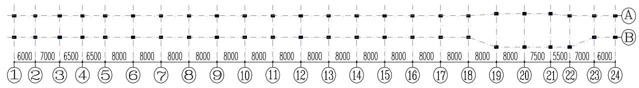
Fig. 1. The solution flowchart of equivalent loading of the nodes

Selected Case Study

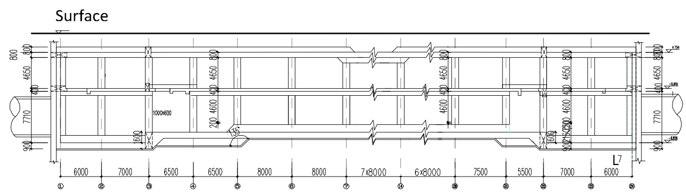
A numerical model was built of a subway station with the cross section of two columns and three spans. The structure of the station is shown in Fig. 2. There are two rows of the middle columns with 24 columns per row. The depth of the top floor of station is about 15.86m.



(a) Cross Section



(b) Arrangement of the middle columns



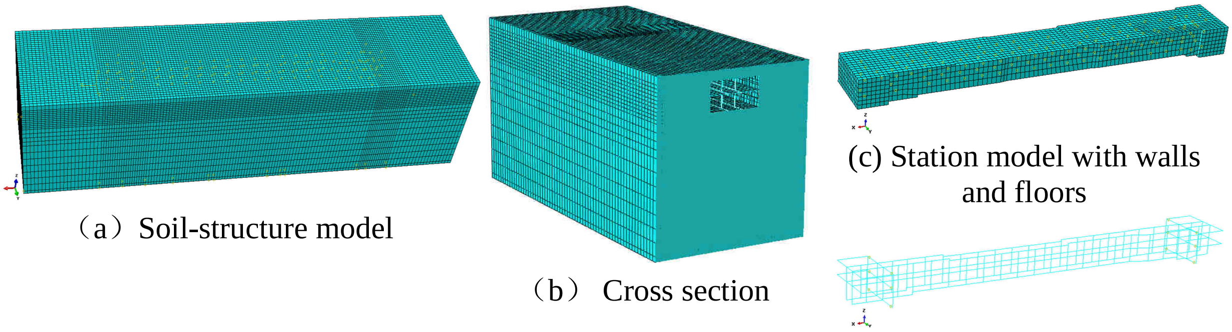
(c) Arrangement of the columns and floors in longitudinal direction

Fig. 2. Structure drawing of the railway station (unit: mm)

FEA Model and Element

A three dimensional model was established using software ABAQUS, as shown shown in Fig.3. The dimension of the model is 57.8m×252m×63.46m. The soil parameters were shown in Table

1. The station was made of C35 concrete. The soil part was discretized with an element named C3D8. There were 102,968 elements totally. The walls and floors were created with 4158 elements of type S4R. The beams and columns were simulated with 1052 elements of type B31. There were equivalent artificial boundary elements extended from a solid element of soil.



（a） Soil-structure model

（b） Cross section

(c) Station model with walls and floors

(d) Frame model of beams and columns

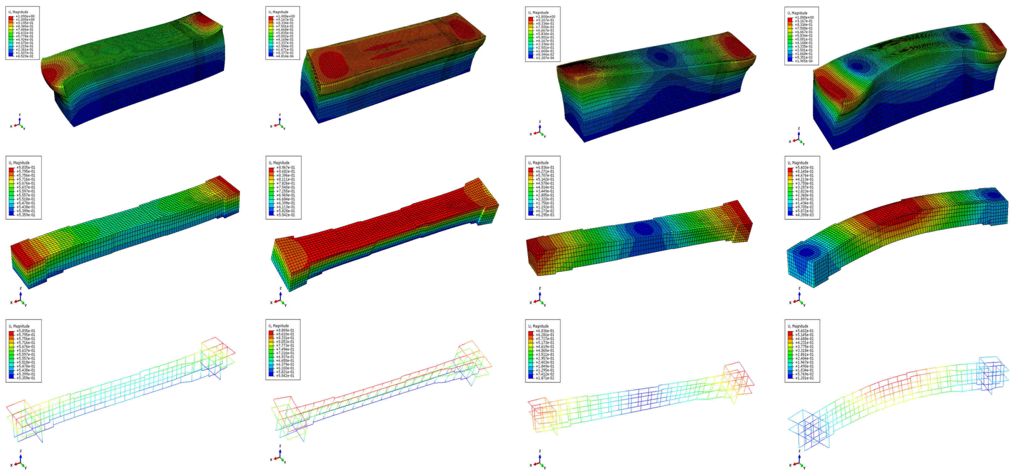
Fig. 3. FEA model of the railway station

Table.1 Parameters of soil

Thickness (m)	Mass intensity (kg/m^3)	V_S (m/s)	V_P (m/s)	Poisson's ratio
3	1700	150	280.62	0.3
13.46	1700	110	205.79	0.3
12	1650	160	299.33	0.3
15	1800	240	449	0.3
10	1900	380	710.91	0.3
10	2000	450	841.87	0.3

Mode Analysis

The open system of the soil-substructure turned into a closed system by local artificial boundary elements. It was possible to analyze the mode shape of the soil-substructure. The mode shape of the soil-structure, internal structure including wall, floor, beam and columns are shown in Fig. 4. The first six frequencies of mode are shown in Table 2. It could be seen from the figure of the mode shape that the vibration of the structure and local field were the same. The response of the underground structure was controlled by the deformation of the soil around the structure.



(a) 1st mode Longitudinal vibration

(b) 2 nd mode Transverse vibration

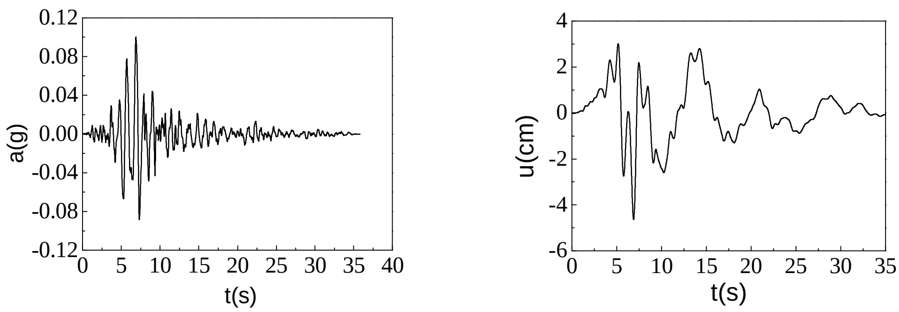
(c) 3rd mode 1st torsion

(d) 4th mode 2^{nd} transverse vibration

Fig. 4. The first four orders of natural frequencies and modes

Analysis and Results

The earthquake wave of Loma Prieta is considered in this case. The time history of the acceleration and displacement was adjusted and shown in Fig. 5. The peak value of the acceleration was 0.1g.

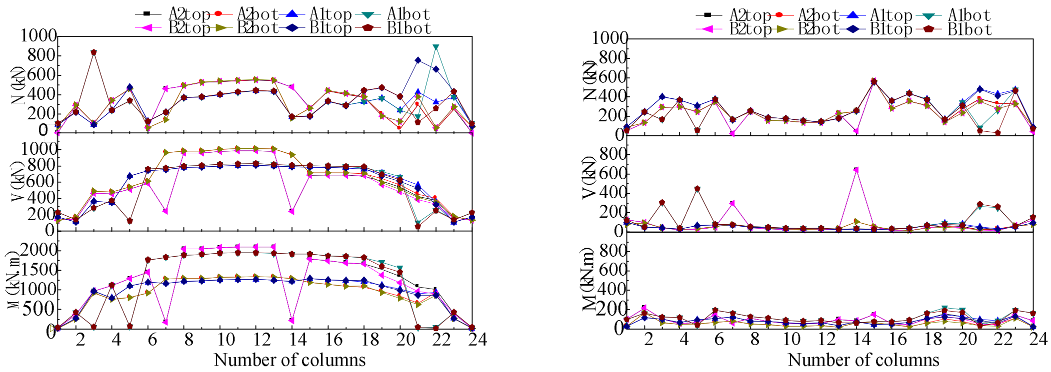


（a） Acceleration

（b） Displacement

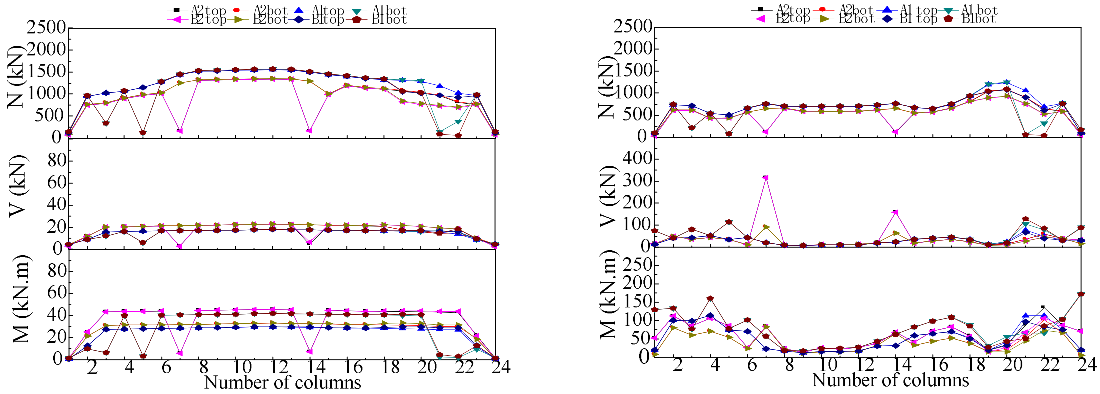
Fig. 5. Loma Prieta wave

The direction of a train moving was set as the longitudinal direction. There aere four cases including transverse propagating of SV and P waves and longitudinal propagating of SV and P waves. The time step and length of waves met the relation defined in Eq. (9). The seismic responses of the middle columns were shown in Fig.6 and Fig.7. The results of inputting the SV waves showed that the story drifts and the internal forces of middle columns under transverse waves were larger than those under longitudinal waves. It was obviously in a bending moment. The responses of P waves showed that the axial forces under waves in the transverse direction were slightly larger than the forces in the longitudinal direction. The shear forces and bending moments under waves in the transverse direction were larger than the forces under waves in the longitudinal direction. The displacement of the structure was not considered because its deformation was the same as the soil around the structure. The displacement for the medium columns under SV waves in transverse and longitudinal directions were shown in Fig. 8.



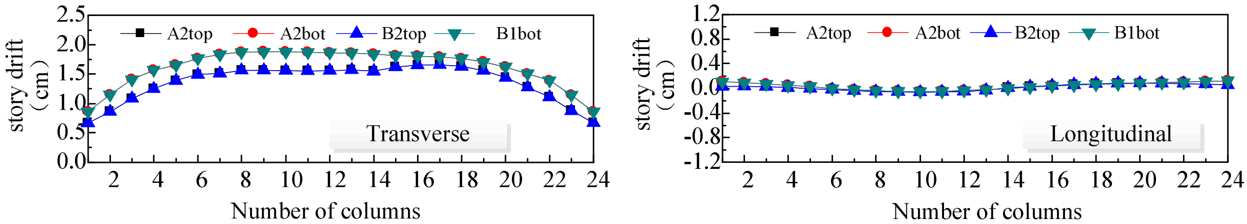
(a) Transverse waves of SV (b) Longitudinal waves of SV

Fig. 6. Internal forces for medium columns under SV waves in the transverse and longitudinal directions



(b) Transverse waves of SV (b) Longitudinal waves of SV

Fig. 7.Internal forces for medium columns under P waves in the transverse and longitudinal directions



(a) Transverse waves of SV (b) Longitudinal waves of SV

Fig. 8.The displacement for medium columns under SV waves in the transverse and longitudinal directions

Conclusions

Based on equivalent viscous elastic boundary element and lump mass finite element models, a three dimension model of the large subway station was established using ABAQUS software. Mode analysis showed that the structure vibration was the same as the soil foundation around. The time analysis of SV and P waves were made and the results of seismic responses of middle columns showed that the large station had a different response under SV and P waves. The most vulnerable case of the subway station was when the SV waves propagated in the transverse direction. It is important to establish the 3D soil-structure model to consider the long and large station with variation in stiffness under motions in the horizontal and vertical directions.

Acknowledgments

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