Dynamic response analysis of the integrated station-bridge elevated station under the pile-soil interaction

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Abstract. In order to study the dynamic response of the integrated station-bridge structure under the pile-soil interaction, a model was established by finite element software for dynamic analysis. According to a practical project, two mechanical models are established: one is the pile-soil interaction model, the other is the rigid foundation model. The dynamic responses of the two models were analyzed respectively, and then the results were compared. The results show that: the structure with pile-soil interaction has a longer period and higher flexibility; Under the action of frequently occurred earthquakes, the maximum displacement of the structure with pile-soil interaction increases and the base shear decreases; Under the action of seldomly occurred earthquakes, the structural displacement and base shear under the pile-soil interaction become larger, and the transverse displacement is more affected than the longitudinal displacement. It is concluded that: the assumption of rigid foundation makes the result more conservative, and the influence of pile-soil interaction cannot be ignored in seismic response analysis.

1 Introduction

Elevated station buildings can generally be divided into two categories: "integrated station-bridge structure" and "detached station-bridge structure" [1,2]. The separation of other major structures bearing non-vehicle loads and the crane girder structures bearing vehicle loads is "detached station-bridge structure"; otherwise, it is "integrated station-bridge structure". The integrated station-bridge structure is composed of building units and bridge units. It not only has the characteristics of building and bridge structures, but also makes the building and bridge structures form a whole to play a role [3,4].

The research on the structure at home and abroad is still in the preliminary stage, so no effective theory has been formed, and the earthquake resistant design code has not been formulated. Therefore, the earthquake resistant design code for buildings and bridges is usually used to design detached station-bridge structures. The code refers to *Code for seismic design of buildings* [5] and *Code for seismic design of railway engineering* [6].

The integrated station-bridge structure is a new structure system which has emerged in recent years. Its stress characteristic is complex, the earthquake action is difficult to analyze. In order to study its dynamic response, we usually combine the building and the bridge into a structure [7] and then analyze the structure. In order to verify the earthquake resistance of the structure, the structural elastic-plastic [8] time history analysis of the structure under the action of megaseism should also be carried out. In addition, the foundation type has a non-negligible influence on the dynamic response and

stress characteristics of the structure, and the appropriate foundation type should be fully considered in the design [9,10]. When building a model, we usually use only fixed constraints to simplify the calculation. However, in the actual situation, dynamic load deforms the foundation, which affects the dynamic response and stress characteristics of the superstructure [11]. Therefore, in order to accord with the actual situation, we should establish the foundation of pile-soil interaction.

In order to study the dynamic response of the integrated station-bridge structure based on pile-soil interaction, this paper takes the actual engineering of xi 'an metro line 5 as an example and establishes models through finite element software. The "m" method [12] was used to simulate the pile-soil interaction. The dynamic response and stress characteristics of structures under earthquake action are analyzed, and the results are compared to obtain the effect of pile-soil interaction on the structure.

2 Structural modal analysis

2.1. Finite element model

Finite element software MIDAS/GEN was used to establish the three-dimensional space finite element model. The beam element was used for girders, columns, foundations and piles, and the shell element was used for floor slabs. Fixed connection of column bottom and ground to simulate rigid foundation (**Figure1**). The pile element is divided appropriately, and elastomeric bearing is added according to the stiffness coefficient of soil

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spring to simulate the pile-soil interaction (**Figure2**). Floor elements, beam elements and column elements are Concurrent units. When calculating the dynamic response, this structure only considers the

Figure1.Rigid foundation model

longitudinal-horizontal earthquake action and the transverse-horizontal earthquake action, so only considers the horizontal pile-soil interaction.

Figure2.Pile-soil interaction model

2.2. Structural modal analysis

Modal analysis is the main method to study the dynamic characteristics of structures [13]. Therefore, the calculation of the self-vibration characteristics is a prerequisite for the analysis of the dynamic response. Since the rigidity and mass of the structure vary greatly in the longitudinal and the transverse direction, there are obvious space effect, and the dynamic response of the structure is relatively concentrated, the subspace iteration method is suitable for solving the model.

The pile-soil interaction model and the rigid foundation model are analyzed. The periodic changes of the first 15 modal order is shown in **Figure3**. According to the results, the natural vibration period of the pile-soil interaction model is longer, and the increase of the first period and the fifth period is the largest. The first period increased from 0.637s to 0.961s, an increase of about 51%. As the order increases, the two curves converge. It can be seen that the rigidity becomes smaller and the period becomes longer due to the pile-soil interaction.

Table1.The first four modes

The modal	Rigid foundation	piles -soil interaction
1	transversely translational	transversely translational
2	longitudinally translational	longitudinally translational
3	torsional deformation	torsional deformation
4	torsional deformation	torsional deformation

Figure3. Periodic changes of the first 15 modal order numbers

In addition, the first four modal order of the two models change the same: the the first-order mode is mainly transversely translational; the second-order mode is mainly longitudinally translational; the third-order mode and fourth-order mode are mainly torsional deformation. Thus, the longitudinal rigidity of the structure is greater than the transverse ,and the low order

modes are basically the same, regardless of the pile-soil interaction. The results are shown in **Table1**.

3 Dynamic response analysis of structures under the frequently occurred earthquake action

3.1. Response spectrum analysis of structures under the frequently occurred earthquake action

In the case of frequently occurred earthquake, the maximum seismic influence coefficient is 0.16, the eigenperiod is 0.40, and the damping ratio is 0.05. The structure model adopts CQC method to modal combination and obtain the dynamic response of the structure under the bidirectional seismic action. The results of two kinds of foundation assumptions are compared to obtain the effect of pile-soil interaction on the structure. The calculated results are shown in the following table

Table2. Longitudinal story drift and interlaminar displacement angle

Floor	Rigid foundation model		Pile-soil interaction model	
	Story drift/m	Interlaminar displacement angle	Story drift/m	Interlaminar displacement angle
1	0.0004	1/16625	0.0014	1/4714

2	0.0061	1/848	0.0060	1/926
3	0.0058	1/911	0.0058	1/908
4	0.0007	1/2883	0.0007	1/2839

Table3. Transverse story drift and interlaminar displacement angle

Floor	Rigid foundation model		Pile-soil interaction model	
	Story drift/m	Interlaminar displacement angle	Story drift/m	Interlaminar displacement angle
1	0.0024	1/2698	0.0039	1/1673
2	0.0050	1/1037	0.0044	1/1175
3	0.0043	1/1235	0.0035	1/1512
4	0.007	1/2876	0.0006	1/3446

It can be seen from **Table2** and **Table3** that: the maximum story drift of the two models under the bidirectional seismic action occurs in the second layer; in the model of pile-soil interaction, only the story drift of the second layer is smaller than that of the rigid foundation model, while the rest layer is larger than that of the rigid foundation model; the maximum interlaminar displacement angle of the rigid foundation model is

1/848 and 1/1037 in both the longitudinal and transverse directions, which is less than 1/550 in the earthquake resistant design code; the maximum interlaminar displacement angle of the pile-soil interaction model is 1/848 and 1/1037 in both the longitudinal and transverse directions, which was also less than 1/550 in the earthquake resistant design code. Both models conform to the specification.

Table4. base shear under the bidirectional seismic action

Earthquake action	Direction of structure	Rigid foundation model/kN	Pile-soil interaction model/kN
Longitudinal earthquake action	Longitudinal	4.28e+04	3.95e+04
	Transverse	4.27e+03	3.64e+03
Transverse earthquake action	Longitudinal	4.59e+03	3.66e+03
	Transverse	4.12e+04	3.47e+04

Table4 shows that: in the model of pile-soil interaction, the base shear decreases under the response spectrum, and the decrease range is less than 10%; the results of the rigid foundation model are conservative under the frequently occurred earthquake.

3.2. Time history analysis of structures under the frequently occurred earthquake action

3.2.1. Selecting seismic waves

According to the Code for seismic design of buildings, under the frequently occurred earthquake, especially irregular buildings should undergo not only response spectrum analysis but also time history analysis. In time history analysis, natural seismic waves and artificial seismic waves should be selected as input waves, and the number of natural seismic waves should not be less than 2/3 of the total number. The characteristics of seismic waves should be consistent with the construction site conditions and meet the requirements of the site environment, seismic precautionary intensity and duration. ASCE [14] stipulated that the selection of seismic waves should take into account such factors as earthquake magnitude, epicentral distance and

hypocentral distance. According to the site conditions of the building and the wave selection elements provided by the Pacific seismic research center (**Table5**), a total of three seismic waves were selected as input waves: two natural seismic waves (GM1, GM2) and one artificial wave (GM3), and artificial wave is obtained by software SIMQKE_GR and Spectrum_Chinese. The information of seismic wave GM1 and GM2 is shown in **Table6**.

Table5. Selected seismic wave elements

Elements	Scope
Earthquake magnitude	
Epicentral distance/km	5~9
Hypocentral distance/km	0~500
	0~500
	250~500
Vs30/m/s	

Instructions: Xi 'an is located at the site of the near moderate earthquake; The equivalent velocity of waves at 30m above the surface.

Table6.Natural wave information

Number	Name	Time	Record the platform	Earthquake magnitude	Epicentral distance /km	Vs30/m/s
GM1	Parkfield	1966	Cholame - Shandon Array #12	6.19	17.64	408.93
GM2	San Fernando	1971	2516 Via Tejon PV	6.61	55.2	316.46

3.2.2. The result of elastic time history analysis

In orderto obtain the base shear of the structure, the model was calculated by the mode superposition response spectrum method and time history analysis. The

response spectrum result for the rigid foundation model is codenamed CQC. The base shear results are shown in **Table7**.The ratio of time history analysis results to response spectrum analysis results is shown in **Table8**.

Table7.Base shear under different seismic waves

Earthquake action	Direction of structure	CQC/kN	GM1/kN	GM2/kN	GM3/kN
Longitudinal earthquake	Longitudinal	4.28e+04	4.07e+04	4.87e+04	3.81e +04
	Transverse	4.27e+03	3.36e+03	4.43+03	3.54+03
Transverse earthquake	Longitudinal	4.59e+03	3.33e+03	4.72e+03	3.75e+03
	Transverse	4.12e+04	4.26e+04	4.49e+04	4.01e+04

Table8.Result ratio of base shear

Earthquake action	Direction of structure	GM1/CQC	GM1/CQC	GM1/CQC
Longitudinal action	Longitudinal	0.95	1.13	0.89
	Transverse	0.78	1.03	0.82
Transverse earthquake	Longitudinal	0.72	1.02	0.81
	Transverse	1.03	1.13	0.94

The results show that:80%the base shear of the structure calculated by each seismic wave is not less than 65% of the result calculated by the mode-superposition response spectrum method, and the average base shear of the structure calculated by the three seismic waves is not less than 80% of the result calculated by the mode-superposition response spectrum method.It can be proved that the selected seismic waves conform to the specification.

4 Elastic-plastic time history analysis of structures under the seldomly occurred earthquake action

Under the seldomly occurred earthquake action, some structures have entered the plastic stage, and the internal forces have been redistributed due to the yielding of some units. Therefore, according to the elastic time history analysis, the obtained results can no longer truly

reflect the dynamic response under the seldomly occurred earthquake action. Elastic-plastic time history analysis adopts the direct integration method [15] and can accurately simulate the whole process of the dynamic response and detect the weak parts of the structure under the earthquake action, which is an effective supplement to the seismic calculation method.

4.1. Selecting seismic waves

The rules for selecting seldomly occurred earthquake waves are the same as those for selecting frequently occurred earthquake waves. In the case of seldomly occurred earthquakes, the maximum seismic influence coefficient is 0.12. In this paper, two natural waves(RSN9, RSN68)and one artificial wave are selected as input seismic waves for time history analysis. The information of seismic wave RSN9 and RSN68 is shown in **Table9**.

Table9.Natural wave information

Number	Name	Time	Record the platform	Earthquake magnitude	Epicentral distance /km	Vs30/m/s
RSN9	Borrego	1942	El Centro Array #9	6.5	56.88	213.44
RSN68	San Fernando	1971	LA - Hollywood Stor FF	6.61	22.77	316.46

4.2. Elastic-plastic time history analysis under the seldomly occurred earthquake action

Three selected seldomly occurred earthquake waves are input to analyze the elastic-plastic time history of the structure. By selecting a point on the top of the structure as the displacement detection point, the displacement

time history curve of this point can be obtained. we can analyze the time history curves of rigid foundation model and pile-soil interaction model, and summarize the rule of influence of pile-soil interaction on structure.

1. stress and displacement analysis under the seismic wave RSN9 action

Figure4.The time history curves of the base shear and the displacement

As shown in **Figure4**, (a) and (b) can see that the pile - soil interaction under the action of natural wave RSN9 has a magnifying effect on the base shear, with the maximum increase in the transverse by 1.5 times and the maximum increase in the longitudinal by 1.1 times. From (c) and (d), it can be seen that the pile -soil interaction

under the action of seismic wave RSN9 has a magnifying effect on the structural displacement, with the maximum increase in the transverse by 1.5 times and the maximum increase in the longitudinal by 1.1 times.

2. stress and displacement analysis under the seismic wave RSN68 action

Figure5.The time history curves of the base shear and the displacement

As shown in **Figure5**, (a) and (b) can see that the pile -soil interaction under the action of natural wave RSN68 has a magnifying effect on the base shear, in which the transverse increases significantly, reaching 2 times. From (c) and (d), it can be seen that pile-soil interaction under the action of natural wave RSN68 has a magnifying effect on displacement, in which the transverse increases significantly, reaching 1.2 times.

3. stress and displacement analysis under the artificial seismic wave action

As shown in **Figure6**, (a) and (b) can see that the pile -soil interaction under the action of Artificial seismic wave has a magnifying effect on the base shear, in which the transverse increases significantly, reaching 1.8 times. From (c) and (d), it can be seen that pile-soil interaction under the action of Artificial seismic wave has a magnifying effect on displacement, in which the transverse increases significantly, reaching 1.2 times.

Figure 6. The time history curves of the base shear and the displacement

5 Conclusions

Based on the actual project, we use the finite element software MIDAS/GEN to establish the integrated station-bridge structure model and analyze its dynamic response under the rigid foundation action and pile-soil interaction. Through the comparison of the two results, we analyzed the influence of pile-soil interaction on the dynamic response of the structure. Thus the following conclusions can be drawn:

(1) Compared with the rigid foundation, the pile-soil interaction makes the structure period longer and the rigidity smaller. Whether or not there is pile-soil interaction, the low order mode of the two structures is basically the same, and the first-order mode is mainly transverse translation.

(2) Compared with the rigid foundation, under frequently occurred earthquake action, the pile-soil interaction reduces the base shear and increases the maximum story drift. The rigid foundation under frequently occurred earthquake action makes the result more conservative.

(3) Compared with the rigid foundation, under seldomly occurred earthquake action, the pile-soil interaction increases the base shear and top floor displacement, and the transverse increase is significantly greater than the longitudinal increase. Based on the rigid foundation, the time history analysis results are smaller under the seldomly occurred earthquake action. Therefore, when analyzing the dynamic response, the influence of pile-soil interaction on the structure cannot be ignored.

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