Seismic Analysis of Ground Surface after Subway Station Excavation

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SUMMARY:
Adopting viscous boundary and free-field boundary to simulate the effects of infinite field, a systematic study was conducted on the change of free field seismic response caused by subway excavation considering the influence of soil-structure dynamic interaction. The seismic response of ground surface after subway excavated is compared with the corresponding response before excavation. The results show that subway excavation changes the response spectrum characters of ground surface. The effect has close relationship with seismic wave spectrum characteristics. In some fields, seismic wave produces scattering while it encounters subway station and the seismic peak acceleration of the ground are larger than those before subway excavation. The results show that the presence of subway station should be considered in the design of surface structures.

Keywords: seismic response; subway station excavation; free field; response spectrum; influence

1. INSTRUCTION

The subway systems play a vital role in alleviating the urban traffic congestion problem. Recently, lots of underground railway transportation networks have been opened to operation or are being constructed to ease the pressure on urban traffic and construction in major cities of China. Most subway stations have big size of cross-section, and are built under high buildings with dense subscribers. When large earthquake occur, the characteristics of seismic wave propagation will be changed in a specific medium. Characteristics of seismic disaster of ground buildings will be changed by metro stations excavation. So the effects of the subway stations on seismic wave propagation and free field motion distribution during earthquakes can not be neglected. The influence on the designing ground motion parameters of ground buildings by subway stations excavation should be considered in the design of surface structures.

The effect of the construction of underground structures, such as metro tunnels, on aboveground buildings has been examined thoroughly in the past, focusing mainly on the response of underground structures. Jianwen Liang (2006) analyzed the scattering of SV waves by a canyon in a horizontally layered fluid-saturated half-space using the indirect boundary element method in the frequency domain. Jianwen Liang (2006) obtains an analytical solution for the scattering of incident plane SV waves by a shallow circular-arc canyon in a saturated poroelastic half-space, using the wave function expansion method. P. Yiouta-Mitra (2007) conducted a series of dynamic plane-strain numerical analyses to investigate the effect of underground structures on surface seismic motion, quantified the effect of the soil medium characteristics, excitation frequency and tunnel diameter. Wei He (2009) compared with the seismic responses of free homogeneous half space, and got the conclusion that excavated shallow tunnel has great influence on the design parameters of ground motion, which has close relationship with earthquake wave spectrum characteristics. Ming-jue Yang (2011) discussed the influence of wave travelling effect and underground structures on adjacent building structures.

In the present work the problem is treated numerically, viscous boundary and free-field boundary were used to investigate the effect of subway excavation on the surface ground dynamic response. A simple rectangular subway station was used in the study, which was assumed to be constructed in ten layers of soil. Two horizontal earthquake records from the actual field earthquakes were used as input excitation. The behaviours of the ground monitoring points under the earthquake excitations were investigated, and the effect of the subway station depth was considered.

2. NUMERICAL MODELLING

In this paper, the numerical model was constructed. The subway station model was a cut-and-cover rectangular structure with central columns, which corresponds to the two-story access structure as illustrated in Figure 2.1. The section was 12.49 m high, 21.2 m wide and 400m long, with an average soil cover of 3 m. The central columns had a rectangular cross section of 0.8 m with an axial spacing of 10 m in the longitudinal direction. The thickness of the lateral wall was 0.8 m, the top and bottom slabs were 0.7 m, and the middle slab was 0.35 m thick respectively.

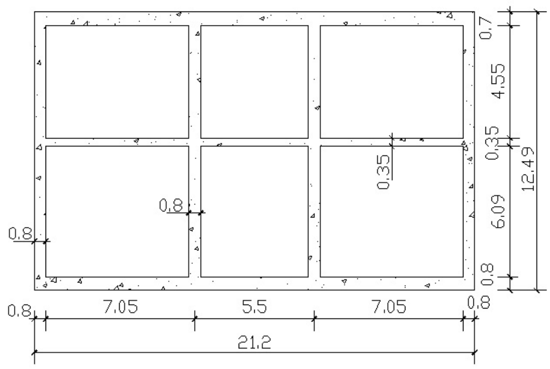


Figure 2.1. Cross section of subway station (m)

The FE analyses were conducted using Flac software. The finite element model is shown in Figure 2.2. Soil was modelled by four-node quadrilateral plane-strain elements, subway station and the central column of the station were obtained by beam element. To eliminate or avoid the detrimental effects of the artificial boundary, the numerical calculation model with is 9 times of that of subway station. The width of finite model is 190.8 m, the depth is 61.1m. Slippage and coming away between the subway and the soil were not considered under certain geological condition. To study the dynamic response of ground surface, eight points were selected as monitoring points. Point 1 is the centre of the finite element model at the ground surface. Point 2 lies the surface ground on the top of the right side wall, the distance from point 1 to point 2 is 10.6 m. And the distance from point 1 to point 4 is 38.75 m.

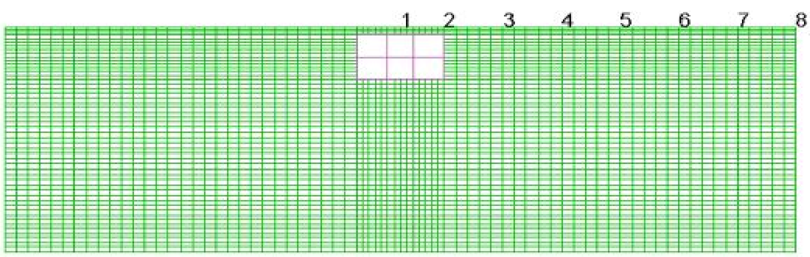


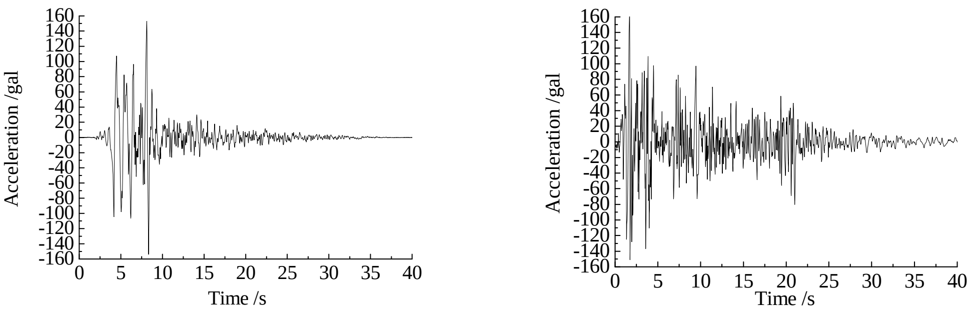
Figure 2.2. Finite element mesh and monitoring points locations

At the location of the station, the soil profile consisted of Nanjing soft soils. Elastoplastic model was selected as the constitutive model of soil, and Mohr-Coulomb strength principle was selected as the yield criterion. From up to down, the soil were divided into ten layers, each layer soil properties used for the model were showed in Table 2.1. The concrete of the subway station was modelled as an elastic material, with a unit weight of 2500kg/m^3, Poisson’s ratio of 0.2, and Young’s modulus of 30 GPa.

Table 2.1 Material Properties Examined in Finite Element Analyses

Soil Layer	Depth (m)	Bulk Modulus （MPa）	Shear Modulus (MPa)	Poisson’s ratio	Cohesion （kPa）	Internal friction angle （°）	Unit Weight (kN/m^3)	Shear Wave Velocity (m/s)
1	2.0	3.33	3.45	0.45	13	16.0	19.0	114.0
2	2.0	3.33	3.45	0.45	13	16.0	17.8	129.1
3	4.0	5.78	1.93	0.35	0	26.0	19.0	152.7
4	3.1	6.25	2.88	0.30	0	30.0	20.5	137.1
5	3.0	7.00	7.24	0.45	0	16.0	19.3	128.5
6	9.0	8.33	3.85	0.30	0	27.0	18.9	172.7
7	12.5	1.03	4.20	0.32	0	30.0	21.2	205.8
8	10.3	9.75	4.50	0.30	0	27.0	18.9	236.3
9	5.2	1.11	4.55	0.32	0	30.0	20.5	263.2
10	10.0	13.34	2.26	0.42	13	21.0	19.3	491.6

To simulate the effects of infinite field, viscoelastic boundary was adopted at the boundary of finite model. The wave reflections caused by adding the boundary condition artificially on the boundary were minimized. Two accelerations waves were scaled and input at the bottom of the discretization as the horizontal excitation in the analyses, as shown in Figure 2.3. One is Loma Priet wave, the other is El-Centro wave. No vertical excitation was used in this study. The peak value of input earthquake excitation is 154 gal.



(a) Loma Prieta Wave (b) El-Centro Wave

Figure 2.3. Input earthquake excitation

3. RESULTS AND ANALYSES

In order to study the effects of subway station excavation on the dynamic response of ground surface, some monitoring points were choose on the ground surface as shown in Figure 2. The displacement response, velocity response and acceleration response of these monitoring points were researched under different earthquake excitation.

3.1. Displacement and Velocity Response Analysis

The peak values of horizontal displacement and velocity on different surface locations are shown in Table 3.1. and Table 3.2. The results show that the displacement and velocity responses at different monitoring points on the free field surface are almost same. But these responses at different monitoring points change greatly after the subway station excavation. The displacement and velocity are significantly reduced, which indicates that the existence of subway station changes exert an important influence on seismic waves propagating. It is the shielding effect of Subway station on seismic propagation that alleviates the dynamic responses of the surface ground above subway station. But the dynamic responses at monitoring points 3 to points 6 are increased evidently. For example, the peak value of horizontal displacement at point 4 changes from 0.117 m to -0.136m after subway station excavation, increasing 16.2%; the peak value of velocity changes from 0.373 m/s to 0.433 m/s, increasing 16.1% when the earthquake excitation is Loma Prieta wave. If the earthquake excitation is El-Centro wave, the peak value of horizontal displacement at point 4 changes from 0.06 m to 0.064 m after subway station excavation, increasing 6.7%; the peak value of velocity changes from -0.168 m/s to -0.225 m/s, increasing 34%. According to scattering theory, in a certain range, seismic wave produce scattering while it encounters subway station, the dynamic responses of surface ground near subway station are amplified. The responses of surface ground far away subway station is as same as the response of free field ground, such as the responses at point 7 and point 8, which are not influenced by subway station excavation.

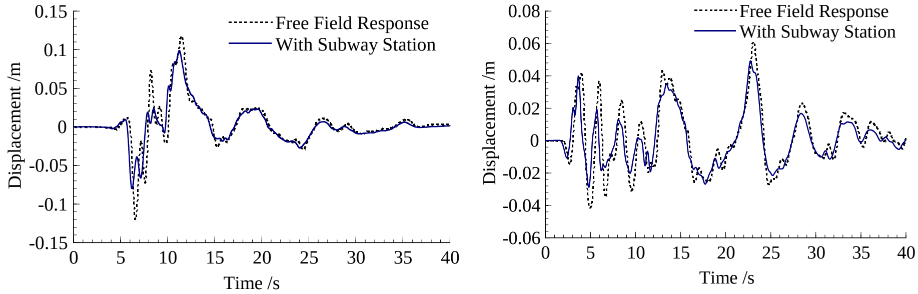
The effects of subway station excavation on the time histories of displacement at monitoring point 1 and point 2 are not very obvious according to the finite element analysis results as shown in Figure 3.1.and 3.2. Only the amplitudes are changed.

Table 3.1. Peak values of displacement and velocity at monitoring points subjected to Loma Prieta Wave

Monitoring Point	With Subway Station		Free Field	
	Displacement (m)	Velocity (m/s)	Displacement (m)	Velocity (m/s)
1	0.099	-0.227	0.117	0.374
2	0.010	-0.229	0.117	0.374
3	-0.125	0.405	0.116	0.373
4	-0.136	0.433	0.117	0.373
5	-0.127	-0.311	0.117	0.375
6	-0.123	-0.39	0.116	0.376
7	0.121	0.39	0.118	0.376
8	0.120	0.38	0.118	0.375

Table 3.2. Peak values of displacement and velocity at monitoring points subjected to El-Centro Wave

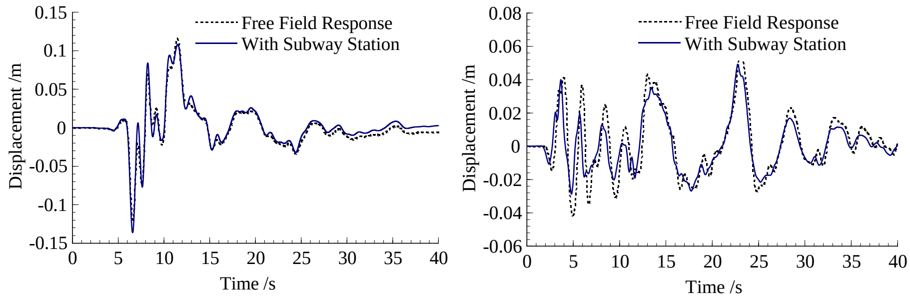
Monitoring Point	With Subway Station		Free Field	
	Displacement (m)	Velocity (m/s)	Displacement (m)	Velocity (m/s)
1	0.049	-0.126	0.063	-0.167
2	0.050	-0.117	0.062	-0.168
3	0.060	-0.21	0.060	-0.167
4	0.064	-0.225	0.060	-0.168
5	0.062	-0.201	0.059	-0.167
6	0.061	-0.185	0.059	-0.167
7	0.061	-0.16	0.058	-0.169
8	0.060	-0.16	0.059	-0.165



(a) Input Loma Prieta Wave

(b) Input El-Centro Wave

Figure 3.1. Time-histories of horizontal displacement at monitoring point 1

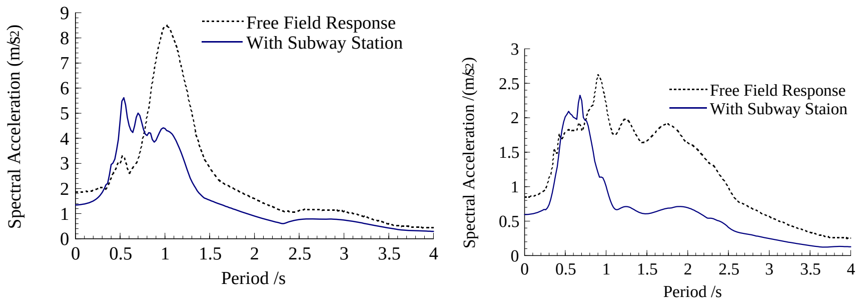


(a) Input Loma PrietaWave (b) Input El-Centro Wave

Figure 3.2. Time-histories of horizontal displacement at monitoring point 4

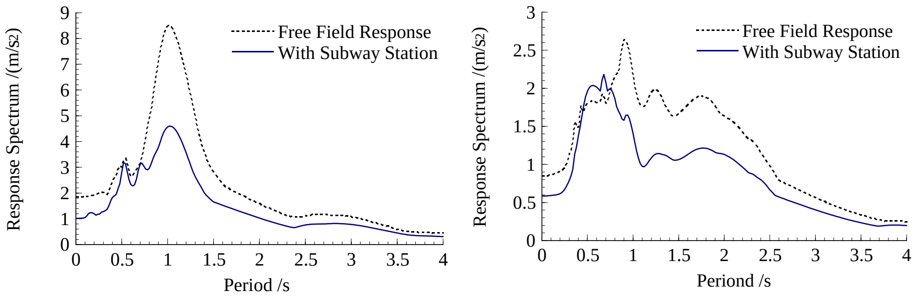
3.2. Spectral Acceleration Response Analysis

The horizontal acceleration response spectra at monitoring point 1 and point 4 before and after subway station excavation are shown in Figure 3.3., Figure 3.4. and Figure 3.5. The results show that subway station excavation has important influence on the characteristics of acceleration response spectrum. The values of earthquake acceleration response spectrum at monitoring point 1 with subway station are smaller than that before subway station excavation when inputs are Loma Prieta wave and El-Centro wave in the period range of 0.4 s to 0.8 s, in other period ranges, the values are smaller than that before subway station. The predominant period of site also changes after subway station excavation, has moving trend to short period. This kind of phenomenon occur at monitoring point 2, but the values of earthquake acceleration response spectrum at monitoring point 4 with subway station are lager than that before subway station excavation. So it indicates that the existence of subway station has vibration energy dissipation effect on the surface ground on the top of subway station, but has amplification effect on surrounding soil.



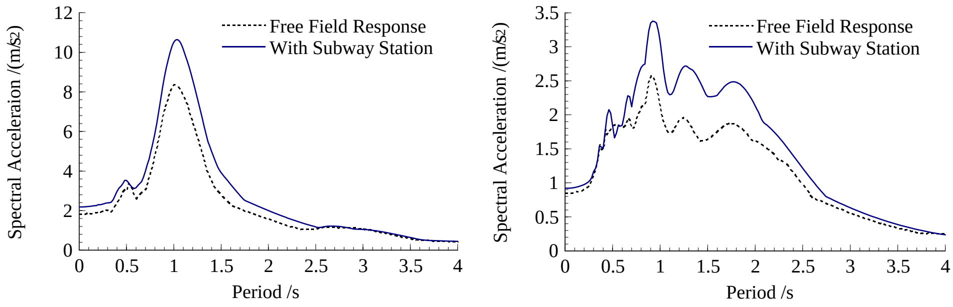
(a) Input Loma PrietaWave (b) Input El-Centro Wave

Figure 3.3. Response spectrum of horizontal acceleration at monitoring point 1



(a) Input Loma PrietaWave (b) Input El-Centro Wave

Figure 3.4. Response spectrum of horizontal acceleration at monitoring point 2

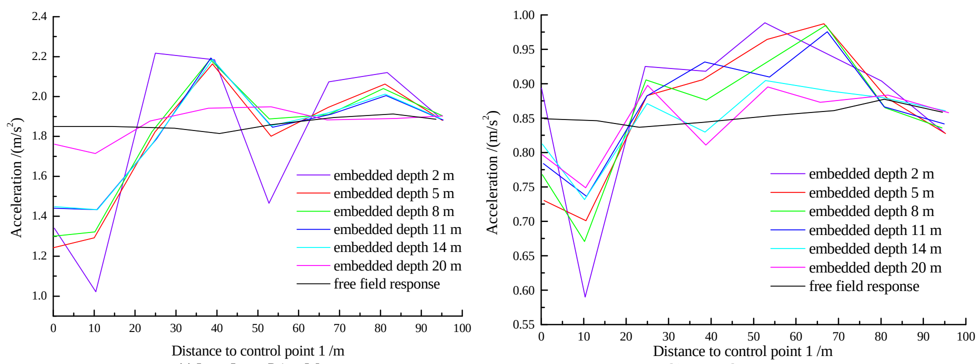


(a) Input Loma PrietaWave (b) Input El-Centro Wave

Figure 3.5. Response spectrum of horizontal acceleration at monitoring point 4

3.3. The Effect of Subway Station Locations

The effects of subway station embedded depth on the dynamic response are shown in Figure 3.6. It can be seen that the peak value of acceleration are changed significantly when the subway station embedded depth is 2 m. With increasing of embedded depth, the effect decreases gradually. The distributions of acceleration along horizontal direct are similar when the embedded depths are 5 m, 8 m and 11m. The results show that the soil around subway station has an appreciable restriction effect on the dynamic response of structure. When input is El-Centro wave, within twenty meter around monitoring point 1, the peak value of acceleration decreases because the existence of subway station as the embedded depth is 5 m. And the distance far away point 1 lies between twenty and eighty meter, the subway station excavation makes the dynamic acceleration response increasing and the seismic wave produce scattering around subway station structure. In certain extent, the subway station excavation has negative effect on the seismic behavior of ground surface buildings.



(a) Input Loma Prieta Wave (b) Input El-Centro Wave

Figure 3.6. Influence of subway station embedded depth on the peak ground acceleration

4. CONCLUSIONS

To show the effect of subway station excavation on the propagation of seismic wave and the ground motion near the station, the seismic responses and acceleration spectra of surface ground are computed and compared with those in the free field. Based on the computed results, some conclusions are made as follows:

1. The very different distribution of the ground surface motion around subway station is due to the subway station excavation. The dynamic responses of displacement, velocity and acceleration at monitoring points change greatly compared with the dynamic responses in the free field.

2. The existence of subway station has vibration energy dissipation effect on the surface ground on the

top of subway station, but has amplification effect on surrounding soil. The dynamical interaction between subway station and soil changes the dynamic characteristics of surrounding soil and further affects the dynamic response of ground buildings. So the presence of an underground structure should be considered in the design of surface structures.

3. The effect of subway station excavation on the acceleration response of surface ground changes with the embedded depth of subway station. It is increasing with the depth decreasing.

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