Liquefaction and Settlement Analysis of Silt Soil Foundation in High Earthquake Intensity Region

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Abstract. The under-crossing tunnel of east external ring of Kunming is one of the most important projects of the Kunming south railway station hub construction. Two layers of silt soil are found in tunnel mileage K2+100-K2+200 and one of them is just under the tunnel floor. Since the project is on high seismic intensity region and the silt soil foundation is easy to be liquefied, it is important to analysis the liquefaction and settlement of the silt soil foundation. In the paper, the whole process of silt soil foundation liquefaction and settlement analysis is presented based on finite difference method. The results indicate that the silt soil foundation will not be liquefied under the design seismic load and the settlement of the silt soil foundation is satisfied.

Introduction

With the high speed of infrastructure constructions in China, more and more highways and tunnels are constructed on soft foundations and in high seismic intensity regions. On the one hand, the soft foundation has low bearing capacity and large consolidation settlement; on the other hand, under the seismic action, the large foundation settlement caused by seismic liquefaction will induce the failure of engineering structures. Therefore, it is required to perform seismic analysis of soft foundation in high earthquake intensity regions[1-3].

This paper takes the east outer ring road tunnel project of Kunming as an example. In the process of investigation, two layers of silt soil, 11m thick and 14m thick respectively, were found in the tunnel mileage from K1+900 to K2+380, where the 14m thick layer of silt soil was just under the tunnel floor. Since the project is in 8-degree earthquake intensity region, and the silt soil foundation has low bearing capacity and under the action of earthquake it is easy to be liquefied, the seismic performance of the tunnel foundation should be analyzed.

Engineering Background

The total tunnel length of Kunming east outer ring road is 2040m, with starting mileage K0+600 and ending mileage K2+640. The earthquake fortification is designed with peak ground acceleration (PGA) of 0.20g.
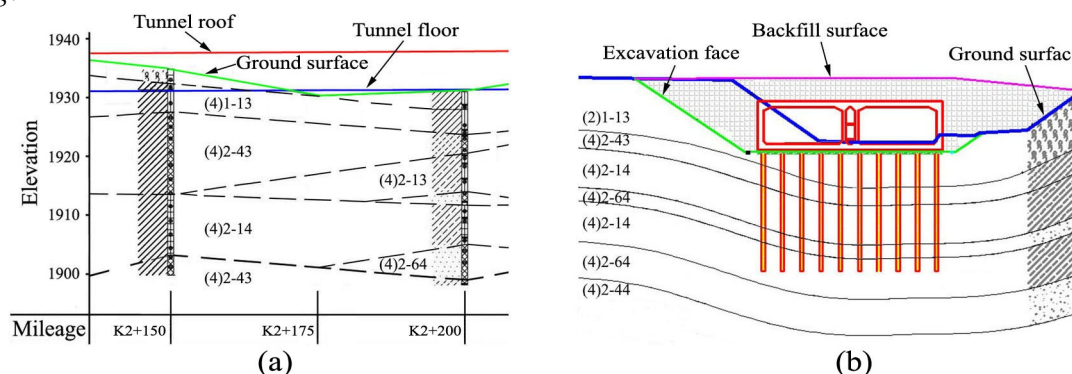

Fig. 1 K1+900-K2+380 mileage profiles: (a) longitudinal profile; (b) cross-sectional profile

As shown in Fig. 1, within the mileage from K1+900 to K2+380, there are two layers of silt soil (stratum number: (4)2-43) with thickness of 11m and 14m respectively, where the 14m thick layer of silt soil is just under the tunnel floor. The PHC pipe piles with diameter of 500mm and wall thickness of 125mm are adopted as foundation reinforcement. The spacing distance of the PHC pipe piles are 3.2m in both cross-sectional and longitudinal directions. The tunnel linings are cast-in-place with C35 concrete. The thickness of tunnel roof, floor, side walls and middle wall is 1.0m, 1.2m, 1.0m and 0.6m respectively.

Model Description

The geometry model is set up using the typical profiles as shown in Fig. 1. In dynamic analysis, the mesh size has direct influence on the computation precision, and the numerical model cannot be entirely in agreement with the actual project, it is necessary to do some simplifications in modelling. Some thin stratums are merged and some irregular stratums are regularized. However, the silt soil stratum are kept the original feature. The size of each stratum is shown in Fig. 2(unit: meter).
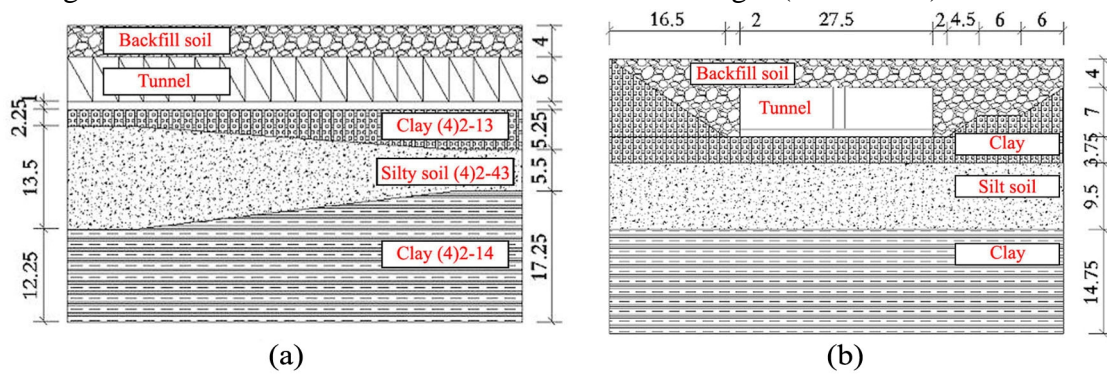

Fig. 2 Geometry model profiles: (a) longitudinal profile; (b) cross-sectional profile

Fig. 3 demonstrates the arrangement of PHC pipe piles and the tunnel structure. The three dimensions (length, width and height) of the geometry model are 60m, 64.5m and 39m.
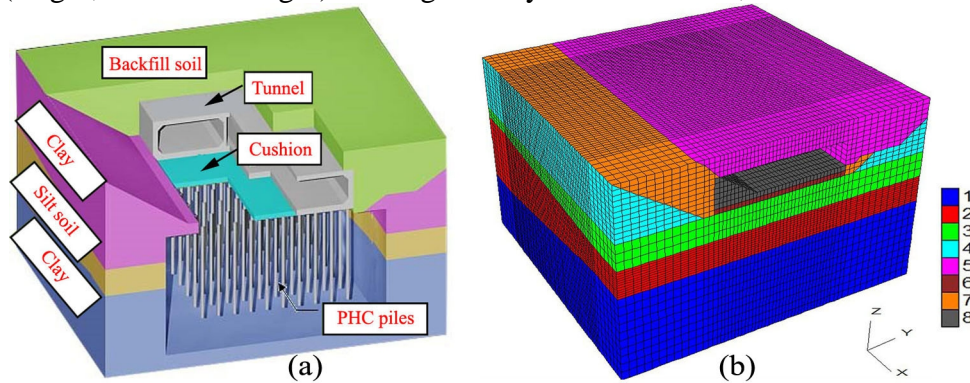

Fig. 3 Three-dimensional models: (a) geometry model; (b) numerical model

FLAC3D software is adopted in the numerical modelling. It can simulate different geotechnical engineering conditions, such as excavation, large deformation, seepage and dynamic analysis and the simulation results are reliable and applicable which have been widely proved[4-6]. In this paper, the soil liquefaction which involves both seepage and dynamic analysis, can be easily simulated in FLAC3D. It provides the Finn model for soil liquefaction analysis, which has been widely used in the study of liquefaction.

In dynamic analysis, the wave propagation is directly related to the input wave frequencies and the soil properties. Research works by Lysmer and Kuhlemeyer[7] show that in order to accurately describe the wave propagation, the mesh size must be less than 1/8-1/10 of the minimum wave length, because if the mesh size is too large, high frequency waves can hardly pass through.

Since the simulated model is mainly composed of soft soils which has small modulus, the wave length of the high frequency part of the earthquake wave can be very small. Besides, the simulated

model size is relatively big which will result in huge element number. In order to keep better computational feasibility and accuracy, as shown in Table 1, the mesh size of the silt soil stratum is set to 1/8 of the wave length, and the other stratums are set to 1/4 of the wave length.

Table 1 Mesh size control

Stratum	Wave velocity v_s [m/s]	Wave frequency F [Hz]	Wave length ΔL [m]	Element size [m]	
				$1/8\Delta L$	$1/4\Delta L$
Backfill soil	75.3		7.53	0.94	1.88
Clay (2)1-13	60.9	10	6.09	0.76	1.52
Silt soil (4)2-43	60.8		6.08	0.76	1.52
Clay (4)2-14	67.7		6.77	0.85	1.61

According to the control size in Table 1, the element size of the silt soil stratum is 0.75m, the others are 1.5m. In FLAC3D, the PHC pipe pile and tunnel lining are simulated using pile and shell structural elements respectively.

The ideal Mohr-Coulomb elastic-plastic model is adopt in the numerical simulation. The physical and mechanical parameters are shown in Table 2, Table 3 and Table 4. All stratums have no tensile strength. The Biot coefficient is 1.0 and the fluid modulus is 200MPa.

Table 2 Mohr-Coulomb model parameters

Stratum	Shear modulus [MPa]	Bulk modulus [MPa]	Cohesion [kPa]	Fraction angle [°]
Backfill soil	7.60	12.67	39.91	13.21
Clay (2)1-13	4.81	14.44	24.78	10.01
Silt soil (4)2-43	5.77	12.50	5.80	23.21
Clay (4)2-14	6.80	11.33	38.71	11.06

Table 3 Stratum permeability parameters

Stratum	Dry density [g/cm^3]	Void ratio	Permeability coefficient
Backfill soil	1.34	1.10	1.25E-6
Clay (2)1-13	1.30	1.21	6.77E-7
Silt soil (4)2-43	1.56	0.79	1.20E-3
Clay (4)2-14	1.48	0.93	7.52E-7

Table 4 Dynamic analysis parameters

Stratum	Damping	Damping coefficient	Finn parameter
Backfill soil	0.051	0.161	
Clay (2)1-13	0.042	0.132	
Silt soil (4)2-43	0.029	0.090	C_1=0.295, C_2=1.357
Clay (4)2-14	0.037	0.116	

The PHC pipe pile parameters are: Young's modulus 28.5GPa, Poisson's ratio 0.21, density 1.875g/cm^3, shear spring cohesion 79kN/m, shear spring fraction angle 5°, shear spring stiffness 63MPa, normal spring cohesion 90kN/m, normal spring fraction angle 5° and normal spring stiffness 19MPa. The phreatic surface is just below the tunnel floor.

The three principle stresses should be equal to the pore water pressure when the soil is liquefied. In numerical simulation, the excess pore water pressure ratio is often used as liquefaction indicator. As shown in Eq. 1, where r_u is the excess pore water pressure ratio, σ_m is the mean effective stress in calculating process and σ_{m0} is the initial mean effective stress. Eq. 1 indicates that if r_u equals to 1, the soil is liquefied, otherwise, the soil is not liquefied.

$$r_u = 1 - \sigma_m/\sigma_{m0}. \tag{1}$$

Simulation Results

Without ground motion records, artificial earthquake wave is adopted in the dynamic analysis. As shown in Fig. 4, the PGA of the artificial earthquake wave is 0.2g, the duration time is 22s and the main

frequency range is 0Hz-10Hz. The baseline drift of velocity and displacement time histories has been revised in the simulation.
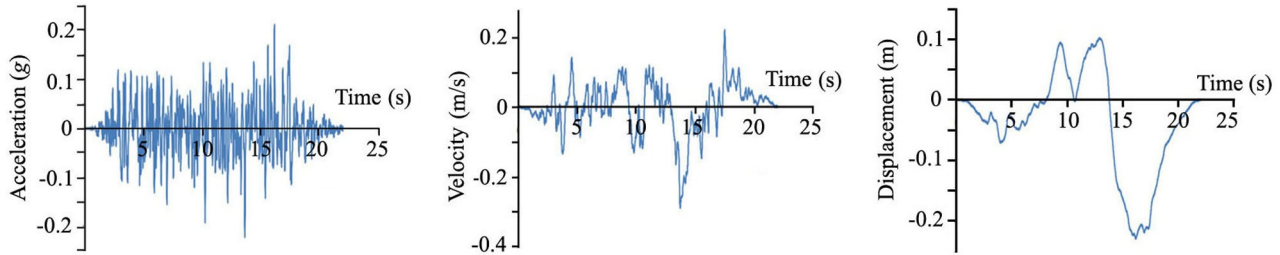

Fig. 4 The artificial earthquake wave

The dynamic analysis is performed by using the numerical model in Fig. 3(b). As shown in Fig. 5(a), three measuring points, i.e., Y1, Y2 and Y3, are located in the silt soil stratum to record the variation of the excess pore water pressure ratio r_u. Fig. 5(b) shows that during the time of 2.5s-5.0s and 12.0s-16.0s, r_u increases notably, and during the last four seconds, r_u changes slightly. At the end of the artificial earthquake, r_u of Y2 measuring point reaches the maximum value 0.207.
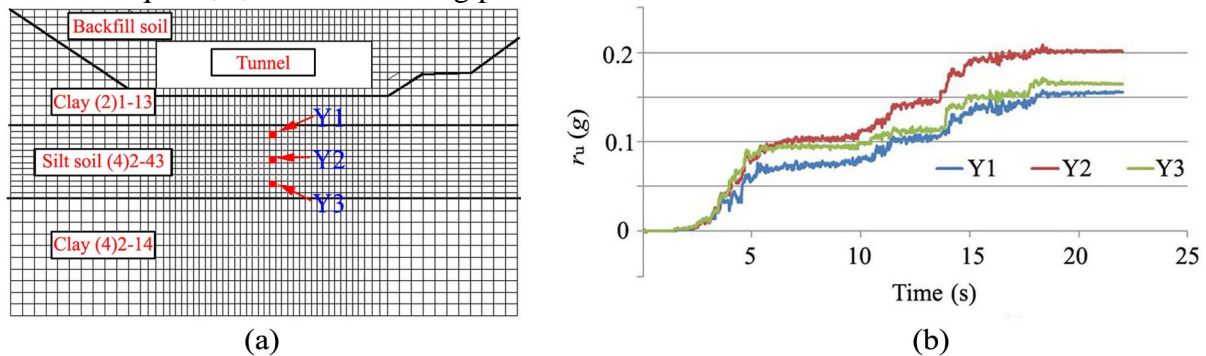

(a)   (b)

Fig. 5 r_u measurement: (a) r_u measuring point arrangement; (b) r_u vs time curve

Fig. 6 shows the distribution of r_u at the end time of the artificial earthquake when the maximum value of r_u occurs. It can be seen that the value of r_u in the silt soil is obviously higher than that in other stratums which indicates the Finn model setting of the silt soil stratum is valid. The maximum values of r_u mainly appear in the silt soil layer underneath the tunnel. The r_u values change between 0 to 0.2 which indicates that under the action of artificial earthquake the silt soil will not be liquefied.

Fig. 7 shows the settlement contour map. The settlement value varies gradually in diagonal direction and the maximum value is about 25mm. The differential settlement value is 21.5mm for point A and B and 15.9mm for point C and D. The differential settlement is relatively low which indicates that under the artificial earthquake, the differential settlement will not cause the failure of tunnel structure.
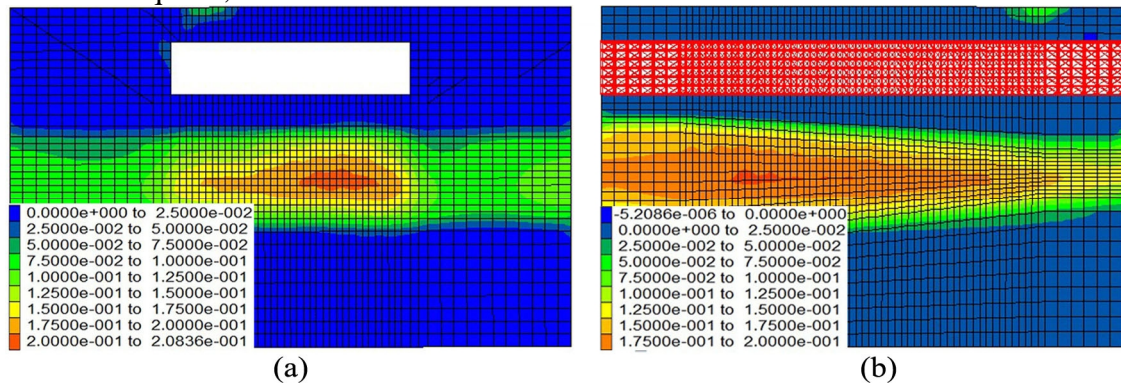

(a)   (b)

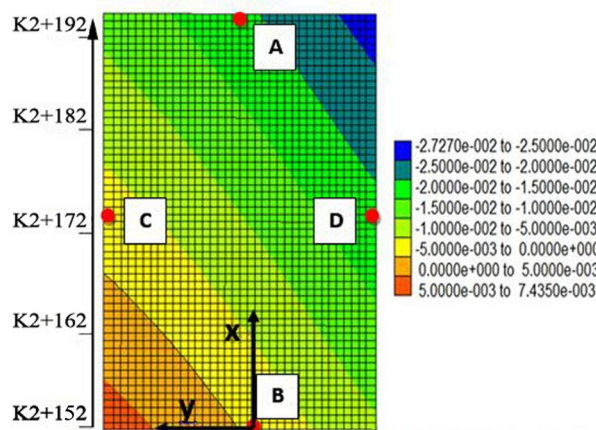Fig. 6 Contour map of r_u: (a) longitudinal distribution; (b) cross-sectional distribution

Fig. 7 Longitudinal settlement contour map

Conclusions

Through the simulation and analysis of the soft soil foundation under artificial seismic loading, we come to the following conclusions:

1. At the end of the artificial earthquake wave, excess pore water pressure ratio reaches its maximum value which is about 0.2 in the simulation. The foundation liquefaction will not occur under the designed seismic load.

2. At the end of the artificial earthquake wave, the settlement value is diagonal distributed and varies uniformly along the diagonal direction. The differential settlement is relatively low which indicates that under the designed seismic load, the differential settlement will not cause the failure of tunnel structure.

Acknowledgments

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