Dynamic Response Analysis of Pile Foundation in Liquefied Site Covered by Frozen Soil

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Abstract. Both frozen soil and liquefaction have a great influence on the dynamic response of pile foundation. Based on the OpenSees platform, a calculation model of pile-soil interaction was established. The peak ground motion of 0.6g was input and the acceleration, displacement, pore water pressure and effective stress of pile foundation and soil were analyzed. The results show that liquefaction occurs at the bottom of the sandy soil and the excess pore pressure ratio exceeds 0.8. The coverage of the frozen soil layer causes the pile foundation not to produce greater lateral displacement when the bottom soil layer is liquefied, which improves the bearing capacity of the pile foundation.

Keywords: frozen soil, liquefied site, pile foundation, dynamic response.

1 Introduction

Frozen soil is an important part of the cryosphere, and its existence directly affects the performance of engineering structures. Globally, frozen soil is mainly distributed in Russia, Canada, China and Alaska in the United States [1]. China is the world 's third largest country of frozen soil, frozen soil area accounts for about 75% of the land area, of which permafrost accounts for 21.5% of the land area, seasonal frozen soil accounts for 53.5% [2]. At the same time, most of the frozen soil in China locates in seismically active areas, where crustal tectonic activities are intense and strong earthquakes are frequent. In recent years, with the rapid development of engineering construction in frozen soil regions, the safety of engineering under earthquake has attracted the attention of scholars.

Studies have shown that the temperature and moisture content of frozen soil are inextricably linked. The two affect each other and work together on the pile foundation. Zhang [3] found that the change of initial water content of soil had little effect on the horizontal bearing capacity and pile displacement of pile-frozen soil system, but with the optimal water content of soil as the boundary, there was a big difference in the stiffness change of pile-frozen soil system on both sides of the boundary water content. Wu [4] found that the accumulation and transformation of ground gene vibration energy is reflected in the temperature rise effect of negative temperature frozen soil. Combined with the shaking table test and the numerical simulation analysis, Hans Vaziri [5] found

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that the horizontal stiffness of pile under frozen soil layer is one order of magnitude higher than that without frozen soil layer, and its resonant frequency is four times higher than that without frozen soil layer. Feng Xiong [6] studied the seismic performance of the soil-pile-pier system, and found that seasonal frozen soil can cause significant changes in the stiffness and damping ratio of the pile-soil system, which have a greater impact on the dynamic response of the pier. This effect increases with the decrease of the pier height-span ratio or the increase of the overall stiffness of the pier.

In addition, seismic records show that the 2003 Bachu County earthquake in Xinjiang, the 2010 Yushu Ms7.1 earthquake in Qinghai, the 2016 Ms6.6 Akto earthquake in the northwest Pamir Plateau, and the 2022 Menyuan 6.9 earthquake in Qinghai all showed seismic liquefaction [7-8]. The research on the influence of the combined action of liquefaction and frozen soil on the bridge pile foundation needs to be developed urgently. Zhaohui Yang used cement-bonded panels to simulate frozen soil and carry out shaking table test of pile foundation under sand liquefaction with the cover of frozen soil layer [9]. It was found that three plastic hinges were formed during the liquefaction process, located at the crust-loose sand interface, partially liquefied dense sand layer and ground [10]. The pore water pressure generated by the dynamic stress gradient is redistributed upwards to areas where the effective stress is lower, resulting in an increase in liquefaction potential [11].

In summary, the coverage of the frozen soil complicates the dynamic response of pile in liquefiable site. In order to further analyze the acceleration response law of pile foundation when frozen soil and sandy soil both exist and study the liquefiable depth of sandy soil under the condition of overlying frozen soil, this paper establishes a numerical calculation model of pile-soil interaction by OpenSees. The El-Centro seismic wave with a peak ground motion of 0.6g is input, and the pore water pressure of sandy layer and the peak acceleration of pile foundation are analyzed.

2 Numerical Calculation Model

2.1 Properties of soil and pile foundation

The model soil is divided into three layers, the bottom is 1.25m thick clay layer, the middle is 8.75m thick saturated sandy soil layer, and the top is 1.5m thick frozen soil layer. The PDMY elastic-plastic material in the OpenSees library is selected as the sandy soil material, which can simulate liquefaction and the volume shrinkage or expansion caused by shear. The PIMY elastic-plastic material is selected for frozen soil and clay material. At the same time, the brickUP unit is given to adjust the permeability coefficient of the soil to realize the solid-fluid coupling analysis. The diameter of the steel pipe pile is 1.5m, the length of the pile is 12m, and the wall thickness is 5cm. The section of pile foundation is selected as Elastic Section for nonlinear beam-column element analysis, and the element is selected as Beam-Column Element. The Young 's modulus of the section is $3.5e^7$kPa, and the shear modulus is $2.3e^7$kPa. The establishment of the model is completed as shown in Fig. 1. The physical properties of soil are shown in Table 1.

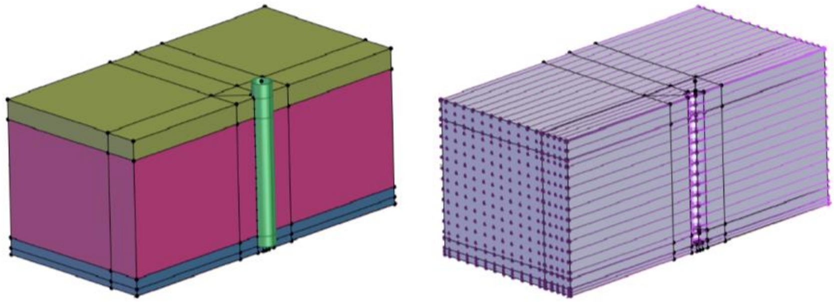

Fig. 1. Calculation model and boundary conditions

Table 1. The physical properties of soil

Soil layers	Density(kg/m^3)	Shear(kPa)	Bulk(kPa)	FrictionAng(°)	e
Frozen soil	2000	2.1e^5	1.05e^6	36	/
Sandy soil	1850	7e^4	1.875e^5	32	0.73
Clay	1800	1.5e^5	7.5e^5	30.1	/

2.2 Boundary conditions and input ground motion

In the static analysis, the x-axis displacement of the soil is constrained. After the static analysis, the x-axis constraint is released, and the Equal DOF is used to ensure the consistent displacement in the x-axis direction according to different height of soil layers to realize the boundary conditions during the seismic force loading process. The pile-soil contact surface is established separately and the beamSolidCoupling connection is applied. The pile cap and second-stage load are simplified as mass node loads applied to the top of the pile, and the load is 1421.88kN. The input ground motion direction is one-way x-axis, and the peak value is 0.6g, as shown in Fig. 2.

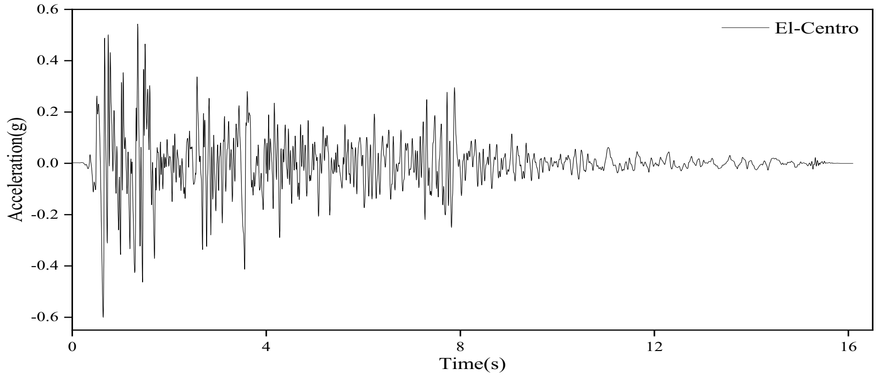

Fig. 2. Input ground motion curve with time

3 Calculated Results

3.1 Analysis of sand liquefaction

After the loading, the pore water pressure and effective stress time history curves at the bottom, middle and top of the sandy soil layer were extracted. The data shows that the excess pore water pressure of the sandy soil layer gradually increases with the loading time, and the effective stress gradually decreases. Among them, the growth amplitude of pore water pressure at the bottom is the largest. In order to further analyze the liquefaction degree of sandy soil layer, the time history curve of excess pore pressure ratio is drawn as shown in fig. 3. The total stress of the soil is equal to the sum of the effective stress and the pore water pressure. When the effective stress is reduced to 0, the soil is completely liquefied and the bearing capacity is lost. At this time, the excess pore pressure ratio is 1. When the excess pore pressure ratio exceeds 0.8, it is determined that the soil begins to liquefy, which is the imaginary line in Fig. 3. Under the condition of inputting 0.6g ground motion peak, the excess pore pressure ratio at the bottom of the sandy soil layer exceeds 0.8, the middle is stable at about 0.5, and the top is stable at about 0.3. Therefore, the sandy soil layer of the overlying frozen soil can be liquefied, and the liquefaction starts from the bottom. The height of the liquefied layer does not reach half of the sandy soil layer.

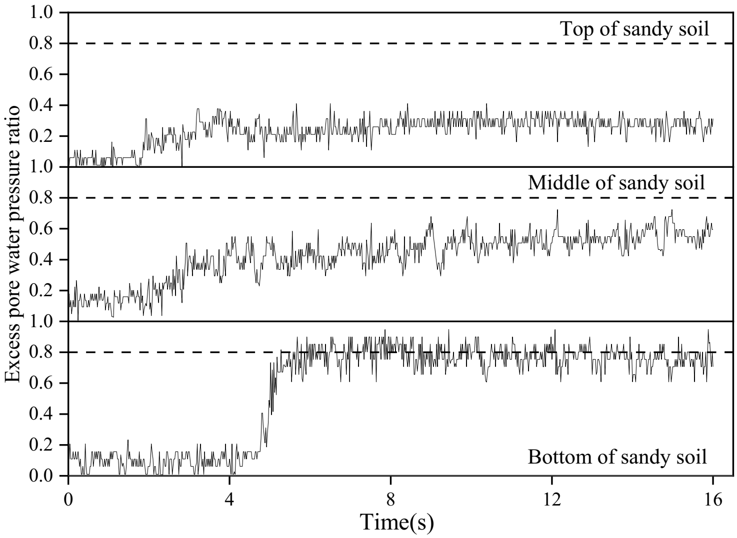

Fig. 3. Time history curve of excess pore pressure ratio

3.2 Model dynamic analysis

During the dynamic calculation, the acceleration P-A1 at the top of the pile, the acceleration P-A2 at the frozen soil layer of the pile, the acceleration P-A3 in the middle of the sandy soil layer of the pile, the acceleration P-A4 at the bottom of the pile, the acceleration A1 of the frozen soil, the acceleration A2 at the top of the sandy soil layer, the acceleration A3 in the middle, the acceleration A4 at the bottom are recorded in real time. The peak acceleration of all observation points is shown in Table 2.

By analyzing the data in Table 2, it is found that the peak acceleration of soil increases with the increase of height, which indicates that soil has amplification effect on seismic wave. The peak acceleration A1 of the frozen soil is smaller than the peak acceleration A2 at the top of the sandy soil layer, indicating that the frozen soil has an inhibitory effect on the amplification effect of seismic waves. Therefore, when the earthquake occurs, the overlying frozen soil is beneficial to the structure. However, due to the existence of the frozen soil, the soil will produce a sudden displacement at the junction of the two soil layers. So it is necessary to consider the pile foundation damage caused by the sudden displacement. The peak acceleration of pile foundation increases with the increase of soil height. The peak acceleration P-A1 at the top of the pile is greater than P-A2 at the frozen soil, indicating that the frozen soil can suppress the dynamic disturbance of the pile. Therefore, the pile does not produce greater lateral displacement when the bottom sandy soil is liquefied, which improves the bearing capacity of the pile.

Table 2. Peak acceleration of observation points

Position of observation point	P-A1	P-A2	P-A3	P-A4
Peak acceleration(g)	0.507	0.403	0.451	0.346
Position of observation point	A1	A2	A3	A4
Peak acceleration(g)	0.691	0.763	0.674	0.459

4 Conclusion

In this paper, a pile-soil interaction calculation model is established based on the OpenSees platform. The peak acceleration of 0.6g is input and the calculation is completed. The following conclusions are obtained by analyzing the variation of pore water pressure and acceleration:

1. When 0.6g seismic wave is loaded, the sandy soil with overlying frozen soil can liquefy, and the liquefaction height does not reach half of the sandy soil.
2. The high-strength overlying frozen soil can improve the bearing capacity of the pile foundation in the liquefiable site.
3. The frozen soil can suppress the amplification effect of seismic waves and the dynamic disturbance of pile foundations, but it is necessary to consider the abrupt displacement at the junction of frozen soil and sandy soil.

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