Numerical Simulation Analysis of Seismic Performance of Pile Foundation with Low Aspect Ratio Pier in Seasonal Frozen Soil Region

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Abstract. This study aims to analyze the influence of frozen soil layer on the seismic performance of pile foundation with low aspect ratio pier in seasonal frozen soil region by numerical simulation analysis method. A comparative analysis is conducted on the seismic performance of pile foundation with low aspect ratio pier considering pile-frozen soil interaction. The analysis focuses on failure characteristics, hysteresis characteristics, energy dissipation capacity, and stiffness degradation of the pile-soil interaction system. The results show that the seismic damage of the pile foundation with low aspect ratio pier primarily occurs in the upper section of the pile body, with the initial damage observed at the pile top. As horizontal load increases, a downward trend along the pile body is observed. Furthermore, it is discovered that the presence of seasonal frozen soil layer enhances the overall stiffness of pile-soil interaction system, thereby improving the seismic performance of the pile foundation with low aspect ratio pier.

Keywords: Seasonal frozen soil, Pile foundation with low aspect ratio pier, Hysteretic characteristics , Seismic performance.

1 Introduction

The frozen soil in China is mainly distributed in the northwest, northeast and north China, and the area is widely distributed. The seasonal frozen soil area accounts for 53.5 % of the total area of China [1]. The freeze-thaw process of seasonal frozen soil has a significant effect on the evolution of frozen soil layer [2,3]. Li Baoqi et al.[4] evaluated the maximum freezing depth and freezing rate during the freezing and thawing process in the typical seasonal frozen soil area of Northeast China by analyzing the data of frozen soil observation stations from 1960 to 2020. Large-scale linear projects in seasonal frozen soil areas have also continued to advance with the national development strategy. Pile foundation piers are widely used in highway and railway construction in permafrost regions[5]. At the same time, the construction of China 's linear engineering spans many strata active fault zones, and seismic activity is frequent. When an earthquake occurs in the seasonal frozen soil area, the seismic wave needs to pass through different soil layers in the process of transmitting the seismic wave to the

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seismic wave to the structure through the soil. For the seasonal frozen soil area, when the earthquake occurs in the two stages of freezing and thawing of the seasonal frozen soil layer, the change of soil properties is extremely prominent, and the seismic impact on the pile foundation bridge structure is also significantly different. The existence of seasonal frozen soil layer will affect the seismic response of bridge pile foundation structure. At present, a large number of researchers have studied the seasonal frozen soil area, mainly including the dynamic characteristics of the soil in the seasonal frozen soil area and the seismic response analysis of the pile foundation pier. It has been found that the special soil properties of seasonal frozen soil layer under earthquake will change the dynamic characteristics of soil [6,7]. In addition, seasonal freeze-thaw has a significant effect on the pile-soil interaction system. Xu et al. [8] studied the seismic performance of the frozen soil layer on the pile foundation railway gravity pier through experiments and finite element analysis. The research shows that the frozen soil layer is beneficial to improve the seismic performance of the structure to a certain extent, but the too thick frozen soil layer will weaken the horizontal bearing capacity of the pile foundation pier and accelerate the destruction of the system.

The above results show that the seismic hazard research of pile foundation piers mainly focuses on the structure of high-pile cap piers, while the low-pile cap piers have great pier stiffness due to their unique low aspect ratio, resulting in low-pile caps. The seismic damage characteristics and seismic performance of low-pile cap piers are different from those of high-pile cap piers. Therefore, in order to clarify the failure characteristics of low-pile cap and low-pier under earthquake action in seasonal frozen soil area and the influence of frozen soil on the seismic response of ground brick cap and pier, this paper analyzes the seismic performance of low-pile cap and low-pier in seasonal frozen soil layer under freeze-thaw condition through numerical calculation model, aiming at providing theoretical basis for seismic design of low-pile cap and low-pier in seasonal frozen soil region.

2 Finite element analysis model and loading system

2.1 Establishment of the model

Model parameter. The model parameters mainly consist of three types: concrete and reinforcement for low aspect ratio bridge pier pile foundation, as well as soil. For the constitutive model of concrete material, a damage plasticity model (CDP model) [9] is adopted. A bilinear model is used for the constitutive model of reinforcement, while a Mohr-Coulomb model [10] is chosen for the soil's constitutive model. Table 1 lists the parameters for low aspect ratio bridge pier pile foundation, while table 2 provides soil parameters.

Table 1. Mechanical parameters of pile foundation pier.

Material properties	E /MPa	γ
Concrete	23026	0.2
Steel reinforcement	203000	0.3

Table 2. Mechanical parameters of soil.

Soil type	E /MPa	γ	$\Phi/^{\circ}$	c /MPa
Unfrozen soil	30	0.3	35	0.036
Seasonally frozen soil	100	0.23	29	0.798

Unit type and pile-soil interface contact relationship. This paper focuses on the seismic performance of low pile cap and low pier structure. The finite element software is utilized to establish a numerical calculation model. The solid element C3D8R is employed to construct the soil and low pier-cap-pile foundation structure, while the truss element T3D2 is used for modeling the steel bar. The reinforcement cage and concrete are nested by the ' binding ' command. The contact relationship between the structure and the soil interface is ' frictional contact ' according to the tangential contact relationship, and the normal direction is ' hard contact ' to realize the contact, slip and separation relationship between the structure and the soil. The thickness of the seasonal frozen soil layer is consistent with the height of the cap. The normal constraint is set on the side of the soil to simulate the actual soil boundary. In the analysis step, the in-situ stress analysis step and the static analysis step are set respectively. In the in-situ stress analysis step, the in-situ stress balance is carried out to realize the equilibrium state of the soil under the action of self-weight. In addition, the vertical load of the pier top is added to simulate the upper load of the bridge in this stage, and the horizontal displacement load is added in the static analysis step to ensure that the finite element software is loaded according to the set horizontal displacement. There is a numerical calculation model as shown in Figure 1.

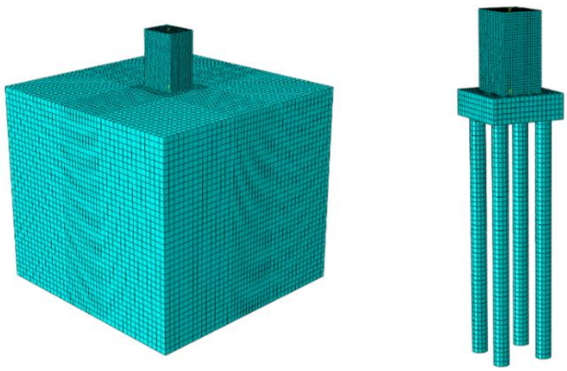


Fig. 1. Finite element calculation model.

2.2 loading mechanism

After the completion of the model, the loading system is set up, and the shear loading data is imported into the finite element software through the Excel table to realize the loading. The loading system of the numerical calculation model is designed according to the ' Code for Seismic Test of Buildings ' (JGJT 101-2015) [11]. The displacement control mechanism is adopted, and the pier top coupling reference point is selected as the loading point. The vertical load and horizontal displacement load are applied, and the displacement loading process is shown in Figure 2. The displacement load is loaded according to the step size of 2mm before 10 mm, and each stage is loaded three times. The step size of the displacement load is adjusted to 6mm after 10 mm, and the three loading system of each stage is also maintained. After the loading, the horizontal displacement is guaranteed to return to 0mm, and the residual displacement of the structure can be observed.

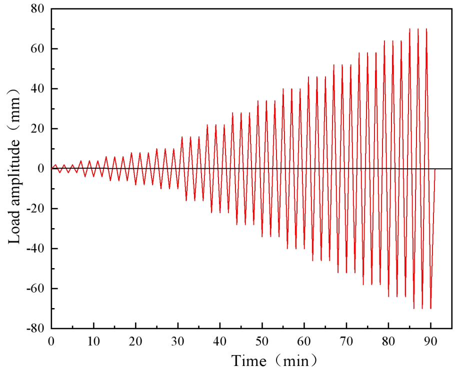
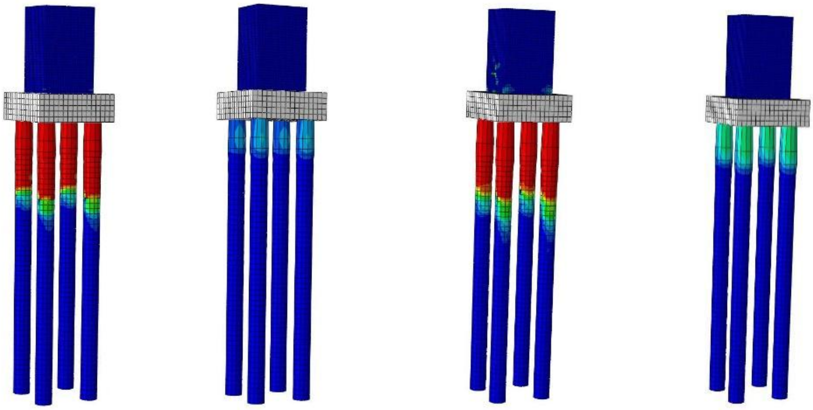


Fig.2. Horizontal displacement load system.

3 Numerical simulation analysis

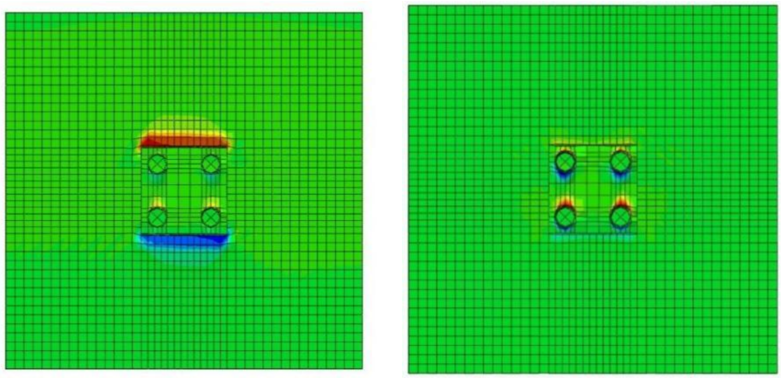
3.1 Failure characteristics

Fig.3 shows the compression damage and plastic strain cloud diagram of the structure. In the numerical simulation, the damage location of the structure is mainly concentrated in the upper part of the pile foundation, and the plastic strain is concentrated at the top of the pile. The reason is that the low aspect ratio pier makes the pier body have sufficient stiffness, which limits the occurrence of the plastic zone at the bottom of the pier, and moves the damage position of the structure down to the top of the pile, and with the increase of the load, the damage continues to move down. Under the condition of seasonal frozen soil, there is a slight compression damage at the bottom of the pier, and the plastic strain area of the pile body is also larger. This is because the existence of seasonal frozen soil layer limits the development of the horizontal displacement of the pile foundation with low aspect ratio pier, reduces the ductility of the pile foundation with low aspect ratio pier, and makes the plastic strain area of the tension foundation pier larger. The presence of a seasonal frozen soil layer in a low aspect ratio pier-soil interaction system is clearly demonstrated in Figure 4, which significantly constrains the lateral movement of pile foundation and reduces its flexibility.



(a) Unfrozen soil (b) Seasonally frozen soil

Fig. 3. Structural damage characteristics.



(a)Unfrozen soil (b)Seasonally frozen soil

Fig. 4. Soil damage characteristics.

3.2 Hysteretic characteristics

Fig.5 shows the hysteresis curve and skeleton curve obtained by numerical simulation. It is evident from Figure 5 that the initial loading stage exhibits minimal horizontal displacement at the top of the pier, resulting in a small hysteresis loop area and weak energy dissipation capacity. Consequently, the entire structure remains within the elastic range. As the horizontal load applied to the top of the pier gradually increases, there is a progressive transition from a narrow hysteresis loop area to a complete one. At this time, the structure begins to enter the elastic-plastic working state, and the energy dissipation capacity of the structure is enhanced. With the further increase of horizontal load, the area of hysteresis loop continues to increase, indicating that more energy is being dissipated within the structure, This accumulation of energy consumption can lead to potential structural damage. As the structure enters the yield stage, where it starts to deform plastically under increasing loads, the horizontal bearing capacity begins to decrease. This reduction in capacity is a result of material yielding and deformation occurring within the structure. However, seasonal freezing conditions can have a positive effect on structures with low aspect ratio piers supported by pile foundations. The freezing temperatures limit the horizontal displacement of these foundations, effectively increasing their overall stiffness. This increased stiffness enhances their ability to resist lateral loads and improves their maximum horizontal bearing capacity by up to 43.14% At the same time, in the stage of horizontal bearing capacity decline, the hysteresis curve of the pile foundation with low aspect ratio pier under unfrozen soil conditions shows a relatively gentle trend, while the hysteresis curve of the pile foundation with low aspect ratio pier under seasonal frozen soil conditions shows a sharp decline. The cause can be attributed to the high rigidity of the interaction system between piles and soil in pier foundations with low aspect ratios, resulting in a decrease in the flexibility of the pile foundation and its interaction with soil. As a result, when structural failure occurs, there is a significant reduction in the horizontal load-bearing capacity, leading to a rapid decline in overall load-carrying capability.

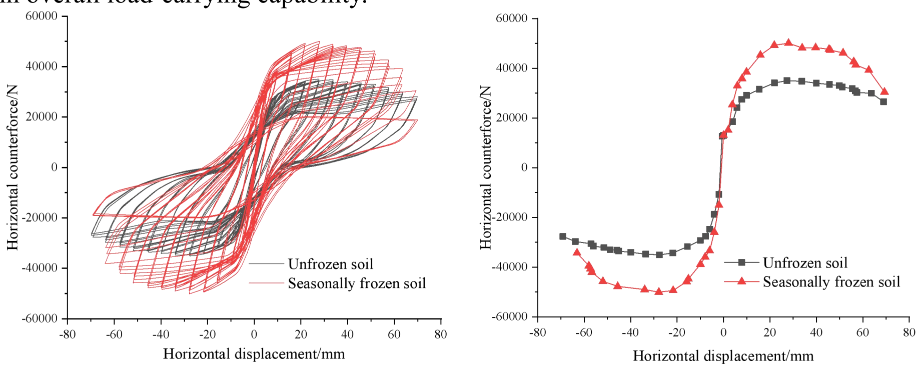
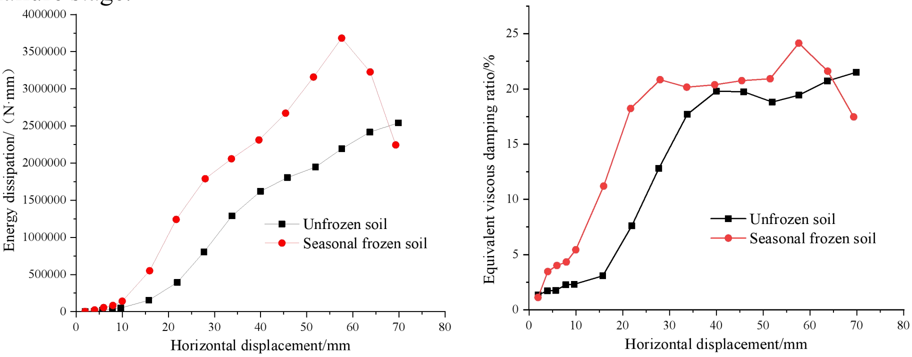


Fig. 5. Hysteresis and skeleton curve.

3.3 Energy dissipation capacity

The total energy dissipation of the pile foundation with low aspect ratio pier under cyclic loading is usually reflected by the hysteresis loop area. The energy dissipation capability of the pile foundation with low aspect ratio pier under cyclic loading is evaluated using the energy dissipation curve and the equivalent viscous damping ratio. It can be observed from Figure 6 that as the horizontal displacement load rises, both the seismic energy dissipation capacity and the equivalent viscous damping ratio of the pile foundation with a low aspect ratio pier gradually increase. Seasonal freezing increases the dissipation of seismic energy by the pile foundation with low aspect ratio pier-soil interaction system. This is because the existence of seasonal frozen soil layer increases the horizontal force required for the pile foundation with low aspect ratio pier to reach the same horizontal displacement load, resulting in more energy dissipation. According to Fig.6 (b), it can be seen that the existence of seasonal frozen soil layer increases the proportion of equivalent viscous damping. However, due to the increase of the stiffness of the pile foundation with low aspect ratio pier -soil interaction system, the equivalent viscous damping ratio decreases in the structural failure stage.



(a) Energy consuming curve (b) Equivalent viscous damping ratio curve

Fig. 6. Energy loss characterization curve.

3.4 Stiffness degeneration

The cyclic loading-induced degradation of stiffness in pile foundations with low aspect ratio piers is characterized by secant stiffness. Figure 7 illustrates the degradation curve of structural stiffness at different loading displacements. It can be observed from Fig.7 that the presence of a seasonal frozen soil layer enhances the overall stiffness of the interaction system between the pile foundation and low aspect ratio pier-soil. The initial stiffness of this system, when subjected to a seasonal frozen soil layer, is 39.73% higher compared to unfrozen soil conditions. In the early stages, there is a faster rate of stiffness degradation for pile foundations with low aspect ratio piers. However, as horizontal displacement load increases, both systems exhibit similar rates of stiffness degradation. Consequently, the existence of a seasonally frozen soil layer not only increases the overall stiffness but also accelerates its rate of degradation in pile foundations with low aspect ratio pier-soil interaction systems.

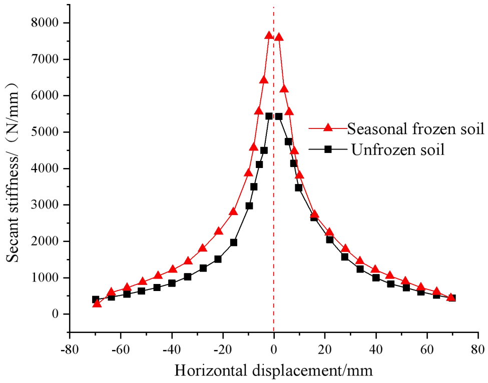


Fig. 7. Stiffness degradation curve.

4 Conclusion

In this study, numerical analysis is conducted to examine the seismic damage characteristics of pile foundation with low aspect ratio pier on seasonal frozen soil layer. Additionally, the influence of the frozen soil layer on the interaction between the pile foundation and the low aspect ratio pier-soil system under earthquake conditions is investigated The main conclusions are as follows :

1) The failure position of the pile foundation with low aspect ratio pier primarily occurs at the top of the pile and gradually progresses downward with increasing horizontal load. A plastic hinge zone is initially formed at the pile top .

2) The hysteresis loop of pile foundation in seasonal frozen soil exhibits greater completeness, resulting in enhanced horizontal bearing capacity. Specifically, there is a 43.14 % increase in the horizontal bearing capacity of pile foundation. Moreover, the stiffness of pile-soil interaction system is augmented, and the presence of a seasonal frozen soil layer contributes to improved seismic performance of the pile foundation with low aspect ratio pier.

3) The existence of a seasonal frozen soil layer restricts the degradation capabilities within the pile foundation with low aspect ratio pier -soil interaction system while enhancing its bearing capacity. However, it diminishes ductility of the pile foundation with low aspect ratio pier-soil interaction system and elevates failure rates of the pile foundation-soil-pier system.

4) Under the action of seismic load, the damage of the low aspect ratio pier pile foundation is concentrated at the top of the pile, which is invisible, resulting in the neglect of the post-earthquake maintenance stage. Through comparative study, this paper can provide reference for the post-earthquake repair of such projects.

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