Dynamic Response Analysis of High-cap Pile Foundation in Seasonally Frozen Soil Region based on OpenSees

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Abstract. The frozen soil layer exhibits distinct mechanical properties compared with the unfrozen soil, leading to diverse dynamic responses of pile foundation within it under dynamic loads. Consequently, disregarding frozen soil in the seismic problem of cold region engineering is deemed unsafe. This study establishes a numerical analysis model using the OpenSees finite element analysis platform to investigate the dynamic response of the high-cap pile foundation within the frozen soil layer, this paper. The dynamic analysis is carried out by subjecting the pile foundation to varying peak ground accelerations (PGA) and different types of ground motion inputs. The PGA and response spectrum analysis of the calculated acceleration time history show that the frozen soil-unfrozen soil transition layer amplifies the dynamic response of the pile foundation. In addition, given that the Kobe waves closely match with natural frequencies of the pile-soil system, resonance occurs within the pile foundation. leading to an increase in the acceleration response spectrum value and intensification of the dynamic response of the system. Conversely, the presence of a frozen soil layer inhibits the dynamic response of the pile foundation, thereby providing protective benefits.

Keywords: High-cap pile foundation, seasonally frozen soil, Dynamic response analysis, OpenSees platform.

1 Introduction

Frozen soil is widely distributed globally, with significant concentrations in China, Russia, and Alaska in the United States [1]. As the world's third largest permafrost country, China has approximately 75% of its land covered by permafrost, with seasonal frozen soil accounting for 53.5%. The presence of frozen soil alters the stress state of engineering structures and impacts their safety. Frozen soil areas are often situated in seismically active regions within the Earth's crust. Therefore, conducting seismic analysis on engineering structures within frozen soil areas holds immense significance.

Initially, the focus of researchers was on investigating the mechanical characteristics of soil in a frozen soil, taking into account influential factors like water content and temperature. Baker et al.[2] found that the mechanical properties of

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frozen soil were mainly affected by temperature, water content, and loading confining pressure. Secondly, the mechanical properties of frozen soil are of significant importance in geotechnical engineering, and it is crucial to investigate the impact of cycle number and loading rate on these properties. Gaining insights into how frozen soil behaves under different cycle numbers and loading rates can offer valuable knowledge for the design of structures and infrastructure in cold regions [3,4]. Although the above studies are based on the conclusions drawn from static triaxial tests, the mechanical properties of frozen soil are greatly influenced by temperature fluctuations, leading to significant variations in its strain rate. With decreasing temperature, the stiffness of frozen soil increases while its deformability decreases. These changes directly affect the shear wave velocity of frozen soil [5].

Building upon the initial assertion, carrying out extensive experiments focusing on the mechanical characteristics of frozen soil could yield significant knowledge applicable to real-world engineering scenarios. Through comprehensive examination and comprehension of the behavior exhibited by frozen soil under various circumstances, engineers can enhance their ability to devise more efficient structures and infrastructure in frigid regions. In recent years, in addition to conventional static tests and shaking table experiments, researchers have also investigated the seismic characteristics of frozen soil-structure systems using various alternative experimental approaches. These include laboratory-scale centrifuge testing, which enables the replication of real earthquake conditions on a smaller scale. By subjecting models of frozen soil-structure systems to centrifugal forces that simulate seismic waves, valuable insights can be obtained regarding their behavior and response under different loading scenarios. Zhang and Guan et al. [6,7] conducted an extensive investigation to explore the various factors that impact the seismic performance of pile foundations. Their specific focus was on high-cap pile foundations located in regions with seasonal frozen soil conditions. In order to gain a more profound comprehension, they performed quasi-static tests on these pile foundations and combined their experimental findings with numerical simulations. Zhang and Guan et al. [8,9] found that the frozen soil layer has strong filtering characteristics by conducting free-field shaking table experiments in permafrost and seasonal frozen soil areas. The dynamic analysis test of free field lays a foundation for the analysis of the dynamic response of frozen soil-structure systems. Xing et al. [10,11] performed a shaking table experiment to further examine the dynamic behavior of pile foundations in sandy soil sites containing frozen soil layers. The objective of their investigation was to assess the potential safety hazards related to neglecting frozen soil when designing shallow foundations.

In summary, the existence of permafrost will significantly change the dynamic response of the structure. To explore the dynamic characteristics of high-cap pile foundations in seasonal frozen soil areas, a 3D solid model is established based on the OpenSees platform. By analyzing the dynamic response of pile foundation in 0.6g PGA El wave and Kobe wave and 0.8g PGA El wave and Kobe wave, the influence of permafrost on the dynamic characteristics of high-cap bridge pile foundation is clarified.

2 Numerical Calculation Model

2.1 Soil element and constitutive

In the calculation, 3D solid modeling is employed, utilizing stdBrick as the soil element. In addition, the soil constitutive in OpenSees includes pressure-independent soil yield constitutive PIMY and pressure-sensitive constitutive PDMY. The volume stress and strain of PIMY remain elastic, but its deviatoric stress and strain will enter the plastic stage. Because its stress-strain state is not affected by the change of pressure, the soil constitutive model is usually used for clay simulation. PDMY elastoplasticity is sensitive to pressure changes, especially sand under cyclic loading, so PDMY constitutive is generally used for sand simulation.

Because the model is modeled by Lanzhou Loess, PIMY is selected as the soil constitutive in the numerical model. In this constitutive model, the shear strength is defined as Eq.1.

$$\tau_f = \frac{2\sqrt{2}\sin\varphi}{3-\sin\varphi}p' + \frac{2\sqrt{2}}{3}c \tag{1}$$

Where φ is soil internal friction Angle, p' is effective instantaneous confining pressure, and c is effective cohesion.

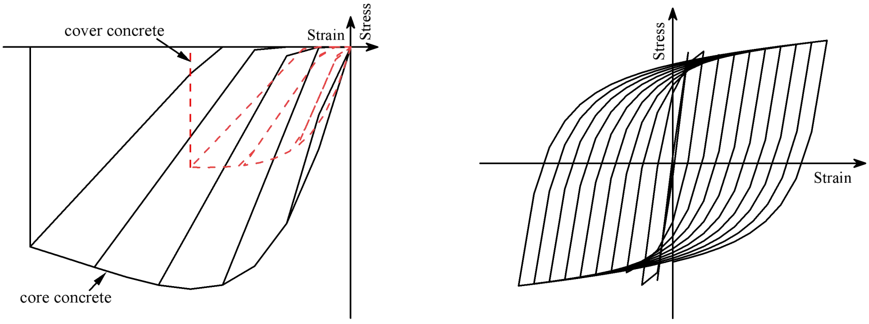
In the model, the soil layer is divided into two layers: the frozen soil layer and the unfrozen soil layer, the thickness of the frozen soil layer is 40cm, and the thickness of the unfrozen soil is 110cm.. The selection of soil constitutive parameters involves using medium clay parameters recommended by OpenSees for the unfrozen soil while employing hard clay parameters for the frozen soil. Table 1 presents the chosen parameters for both frozen and unfrozen soils.

Table 1. The value of soil mechanical parameters.

Parameter Type	Frozen	Unfrozen
$nd	3	3
$rho	1.8e-06	1.5e-06
$refShearModul (Gr)	150	60
$refBulkModul (Br)	750	300
$refBulkModul (Br)	0.075	0.037
$peakShearStra (γmax)	0.1	0.1

2.2 Pile foundation and cap simulation

In OpenSees, Concrete04 Material is selected for concrete constitutive, and Steel02 Material is selected for steel constitutive. Fig.1 is constitutive of concrete and steel material. To model the reinforced concrete section more reasonably, the fiber section is selected in OpenSees to divide the section area of the reinforced concrete section. Among them, the diameter of the pile foundation is 150mm, the length is 150cm, the material is C30 concrete, and the reinforcement ratio is 0.2 %. Four steel bars with a diameter of 6mm are selected for the section of the pile foundation, and the thickness of the concrete protective layer is 15mm. According to this section, the core concrete is divided into 6 × 4 fiber areas, and the concrete protective layer is 4 fiber areas. The division of the fiber area of the reinforced concrete section of the pile foundation is shown in Fig.2.



a. concrete constitutive b. constitutive modeling of steel

Fig. 1 Constitutive of concrete and steel material.

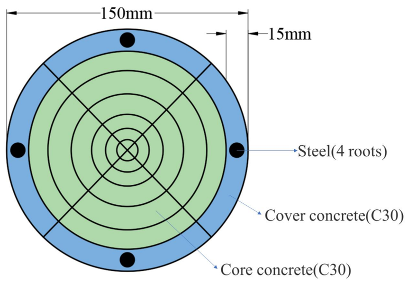


Fig. 2 Division of fiber area of reinforced concrete section of pile foundation.

The pile foundation will enter a nonlinear state when the ground motion PGA is large. The displacement shape function in ' Displacement-Based Beam-Column Element ' is calculated by Hermite cubic interpolation function, so it is necessary to divide enough elements to ensure the accuracy of nonlinear calculation, so the calculation efficiency will be slowed down, but the internal force value at the element integration point can be extracted to obtain the stress state at different sections. The ' Force-Based Beam-Column Element ' is calculated based on the flexibility method, so the calculation accuracy can be guaranteed without dividing too many integration points, but the internal force of the control section cannot be extracted. In summary, in this study, the focus is on the nonlinear research of pile foundation, so the pile foundation unit is selected as displacement beam-column Element. The elastic beam-column element with large stiffness can be selected for the pile cap element.

2.3 Pile-soil interaction

Because this study uses the method of 3D solid modeling to simulate, the method of using a p-y dynamic curve will lead to poor calculation accuracy and convergence.

Therefore, ZeroLengthContact Element in OpenSees is used to simulate the pile-soil contact friction relationship. ZeroLength Element is used to establish the connection relationship between soil nodes and pile foundation nodes, and the axial, tangential, and normal stiffness coefficients are given to realize the simulation of friction contact relationship. Due to the difference in friction contact between frozen soil and unfrozen soil and pile foundation, Table 2 is the value of ZeroLengthContact Element parameters of frozen soil and unfrozen soil and pile foundation.

Table 2. The value of soil mechanical parameters.

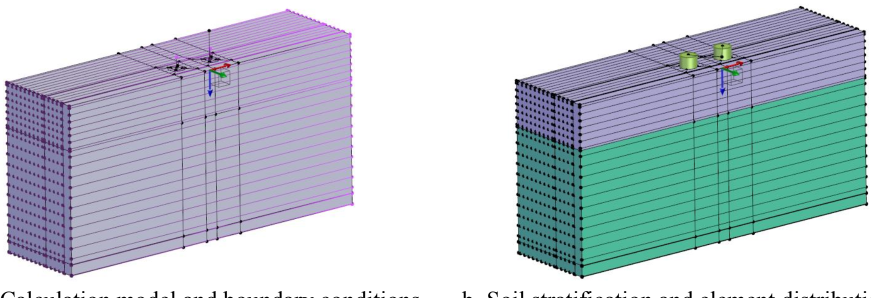
Parameter Type	Frozen	Unfrozen	Bottom
$Kn	150	85	85
$Kt	1.45	0.8	0.8
$mu	0.4875	0.3545	0.3545
Orientation Type	link direction	link direction	local axes

2.4 Boundary conditions and loading

In the analysis, the soil is first constrained in the x and y directions for gravity analysis. After the gravity analysis is completed, the x-direction constraint is contacted and the x and y-direction degrees of freedom of the left and right sides of the soil are constrained by EqualDOF, and the pile foundation, cap, and concentrated mass are activated for dynamic analysis. The loading form is consistent with excitation loading.

2.5 Boundary conditions and loading

To improve the computational efficiency, the 2 × 2 pile foundation is symmetrically modeled. At the same time, the load of the pier and the superstructure is added to the top of the pile cap in the form of additional mass. The total weight of the upper mass and the pier is 3.2 t. Before the calculation, the initial stress field is obtained by soil gravity analysis, and then the dynamic analysis is carried out. Fig. 3 is the finite element calculation model and element division.



a. Calculation model and boundary conditions b. Soil stratification and element distribution

Fig. 3 Division of fiber area of reinforced concrete section of pile foundation.

2.6 Selection and input of seismic wave

Due to the lack of ground motion record data in permafrost regions, the representative El wave and Kobe wave are selected as input waves for calculation. The input direction is x direction, the type is consistent excitation input. Fig.4 shows two types of ground motion records.

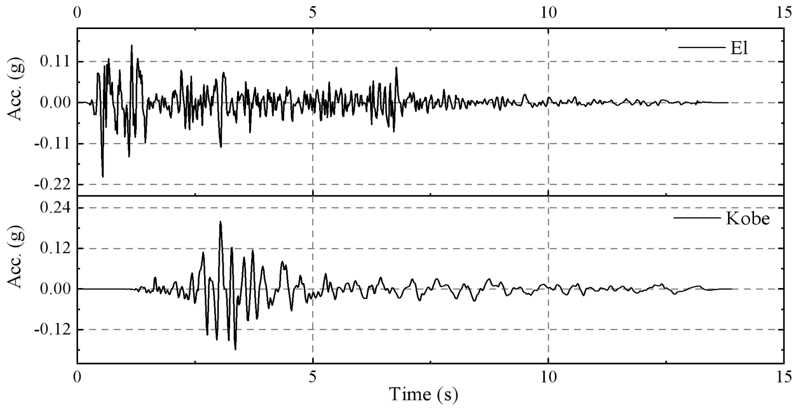


Fig. 4 Numerical simulation of loading conditions.

To analyze the dynamic response characteristics of pile foundations under different types of ground motion and different PGA, the following table is the loading condition of this numerical simulation calculation.

Table 3. The value of soil mechanical parameters.

Test conditions	Type	PGA	Direction
El-1	El	0.6g	X Direction
El-2	El	0.8g	X Direction
KB-1	KB	0.6g	X Direction
KB-2	KB	0.8g	X Direction

3 Dynamic response analysis of pile foundation

3.1 Pile foundation acceleration response analysis

According to the data obtained from the OpenSees finite element model analysis, the PGA analysis of the pile at different heights is shown in Fig. 5. It is obvious that the PGA of the pile foundation gradually decreases with depth, which is because the pile-soil interaction (PSI) absorbs part of the ground motion energy, and the response of the pile foundation gradually increases with the increase of the input ground motion

PGA. Secondly, it can be found that the PGA of the pile foundation in the transition layer of frozen soil and unfrozen soil increases, which indicates that the transition layer has a significant difference in PSI due to the large difference in stiffness between frozen soil and unfrozen soil, resulting in a larger ground motion response of the pile foundation in the transition layer. However, the PGA of the pile foundation decreases continuously from the frozen soil-unfrozen soil transition layer to the frozen soil layer, indicating that the presence of a frozen soil layer reduces the seismic response of the pile foundation and serves as a filter for ground motion, thereby protecting the pile foundation. Finally, it can be found that the PGA of the high pile cap pile foundation exposed outside the soil layer will be enlarged, which is unfavorable for the dynamic response of the pile foundation outside the soil surface.

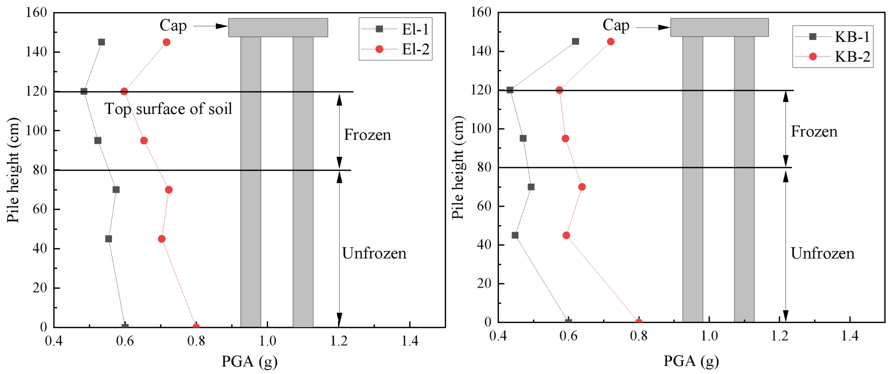


Fig. 5. PGA of pile foundation at different depths.

3.2 Pile foundation acceleration response spectrum analysis

To thoroughly investigate the dynamic response spectrum characteristics of pile foundations, it is essential to compute the acceleration response spectrum. This can be achieved by analyzing the acceleration time history obtained through finite element analysis with a damping ratio of 5%. By considering this specific damping ratio, we can accurately assess how the pile foundation responds to seismic or dynamic loads, as shown in Fig. 6, the acceleration response spectrum at different positions under different working conditions. From the diagram, it is clear that with the increase in PGA of the input ground motion, there is a progressive rise in the response spectrum value exhibited by pile foundations. This finding emphasizes a significant correlation between the intensity of ground shaking and its influence on the performance of pile foundations. After conducting further analysis on the response spectrum values in both the frozen soil layer and the unfrozen soil layer, it becomes apparent that there is a significant disparity between the acceleration response spectrum value in the frozen soil layer and that of the pile foundation in the unfrozen soil layer. This observation strongly indicates that the presence of a frozen soil layer has a considerable influence on mitigating or impeding the dynamic response of the pile foundation. Secondly, it can be seen that the predominant period of the same soil layer under different PGA ground motions is different when the El wave is input. With the increase of seismic wave PGA, the predominant period becomes longer. This is because the pile foundation enters the nonlinear damping ratio under strong earthquakes. So that the period of excellence becomes longer. However, under the input of the Kobe wave, the predominant period of pile foundation in frozen soil does not change, and the predominant period in unfrozen soil becomes shorter. This is related to the characteristic frequency of the Kobe wave. Because the Kobe wave is close to the natural frequency of the structural system, the pile foundation resonates, the predominant period of the pile foundation becomes shorter, and the acceleration response spectrum value increases.

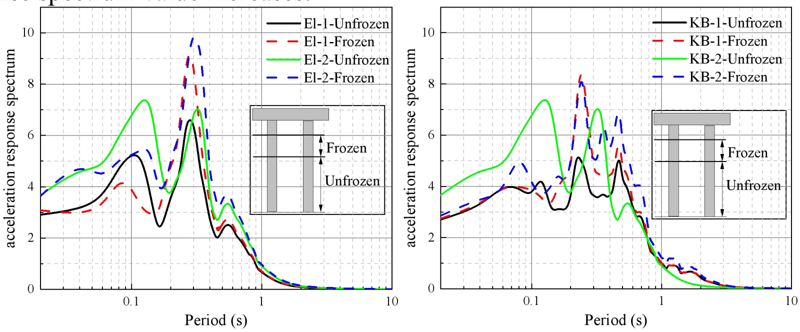


Fig. 6. Pile foundation acceleration response spectrum.

4 Conclusion

In this paper, , a numerical model for dynamic analysis of high-cap pile foundation within seasonal frozen soil is established based on the OpenSees finite element analysis platform. Subsequently, PGA and response spectrum analysis are carried out by inputting 0.6g and 0.8g El wave as well as Kobe wave. Based on these analyses, the following conclusions can be drawn:

(1) The transition layer between frozen and unfrozen soil, as well as the exposed soil surface of the high pile cap, significantly amplifies the acceleration of the pile foundation, thereby facilitating the generation of substantial internal forces.
(2) By incorporating both PGA and response spectrum analysis for the frozen soil layer, it is evident that the frozen soil layer absorbs a portion of ground motion energy, effectively suppressing the dynamic response of the pile foundation.
(3) Given that the Kobe waves closely match with natural frequencies of the pile-soil system, resonance occurs within the pile foundation. The predominant period of the pile foundation is reduced, leading to an increase in the acceleration response spectrum value and intensification of the dynamic response of the system.

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