Numerical Analysis of Seismic Response of Bridge Pile Foundation in Seasonally Frozen Soil Regions

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Abstract. In seasonal permafrost regions, the freezing and thawing of seasonally active layers can significantly change the site ground vibration characteristics and thus have a great impact on the seismic response of buildings. In this study, a three-dimensional finite element model of pile foundation is established considering the seasonal frozen soil field effect, and the influence of seasonal frozen soil layer on the seismic response of pile foundation is analyzed. The results show that the seasonal frozen soil layer greatly inhibits the elevation amplification effect of the surface acceleration amplification factor. At the same time, the strong constraint of the frozen soil layer makes the relative motion of pile foundation and shallow-buried foundation smaller, and the peak acceleration amplification factor of the two is less different. In this case, the existence of seasonal frozen soil layer is beneficial to pile foundation.

Keywords: Seasonal frozen soil; Pile foundation; Acceleration peak amplification factor; Finite element model.

1 Introduction

Compared with areas without frozen soil, frozen soil will change the dynamic characteristics of the site, thus significantly changing the earthquake damage of buildings in the frozen soil area [1,2]. The existence of seasonal frozen soil layer thickness will cause changes in physical parameters and mechanical properties of frozen soil, and the seismic response of frozen soil site will also change, and the seismic safety of pile foundation will also be affected [3,4]. The study of Sritharan et al. shows that even a small thickness of frozen soil layer will have a significant impact on the seismic response of Bridges [5]. Scholars represented by Yang et al. conducted long-term monitoring of Bridges in seasonal frozen soil areas in Alaska, and believed that the seasonal freeze-thaw process of soil mass had the greatest impact on the dynamic response of pile-based Bridges [6]. Gao Feng et al. analyzed the influence of frozen soil layer on the seismic response of bridge structures by using the wave method, and found that the frozen soil site conditions and foundation forms are closely related to the seismic response of bridge structures [7]. Zhang et al. compared the seismic performance of pile-soil system under the condition of unfrozen ground and frozen ground by using a pseudo-static test model. The results show that the existence of frozen soil layer can

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suppress seismic effect to a certain extent, which is conducive to the seismic safety of bridge structures in cold areas [8]. Based on the dynamic triaxial test, Qi Jilin et al. used a one-dimensional shear beam model to study the effect of frozen soil layer on ground motion, and found that the seasonal frozen soil layer on the surface has a certain inhibition effect on strong earthquakes, that is, it has a positive impact on the seismic safety of structures in the frozen soil area. The presence of frozen soil also changes the site's pre-eminent period, which is fatal to structures with similar self-oscillating periods [9]. Based on the finite element model, Li Tao et al. analyzed the seismic response of foundation to the embedment of bridge pile foundation, and the results showed that the degradation of frozen soil would lead to the reduction of foundation embedment [10]. Although pile foundation has been widely used in the field of bridge, the work performance of pile foundation under the effects of earthquake, freeze-thaw effect and earth pressure is not perfect. Therefore, considering the change of mechanical properties of frozen soil and the occurrence of earthquakes, it is of practical significance to conduct seismic dynamic analysis of frozen soil pile foundation in seasonal frozen soil region.

2 Finite element modeling of pile foundation

2.1 Brief description of the finite element model

Since the movement direction of soil-pile foundation relative to the ground is geometrically symmetric, only the corresponding semi-symmetric model needs to be established. Solid elements were used in the soil model, pile foundation and bearing table model, and C3D8R elements were used for discretions. In order to accurately simulate the ground motion response to the geodynamic response of bridge pile foundation, the maximum size of model elements was no more than 1m, and the seasonal frozen soil thickness was 4m. The finite element model of pile foundation was shown in Figure 1.

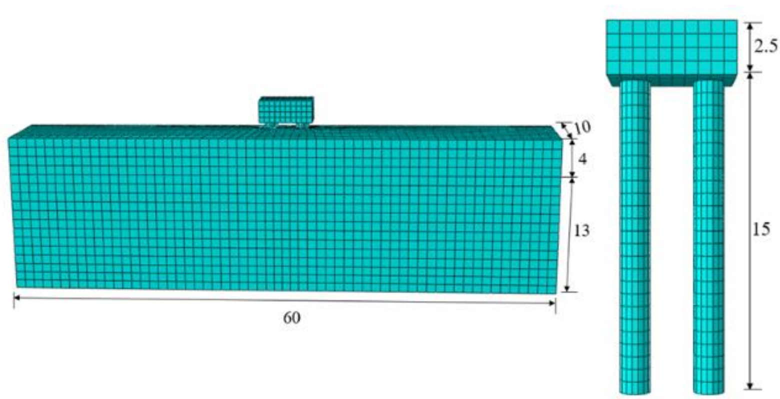

Fig. 1. Finite element model of pile foundation (Unit: m)

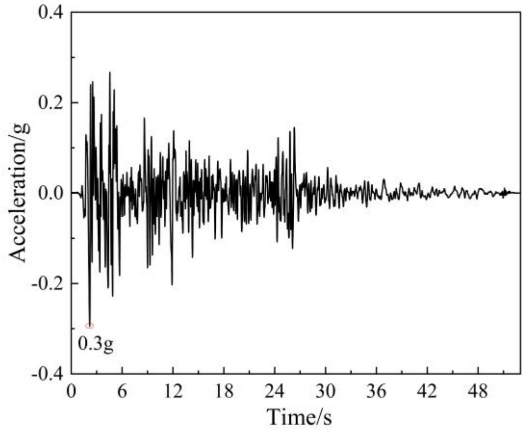

Fig. 2. 0.3g El-Centro wave

The model boundary is set as follows: (1) there is no constraint along the horizontal excitation direction (X direction) at each boundary, and the limiting displacement constraint is set in the Y direction orthogonal to the excitation direction; (2) Binding constraint boundary conditions are adopted for each boundary along the horizontal excitation direction (X direction), that is, boundary nodes at the same elevation are bound together by Equation constraint command in ABAQUS, and the relative displacement of degrees of freedom of bound boundary nodes is zero through the given motion equation, so that the motion is consistent; (3) Input the horizontal seismic acceleration time history along the X direction of excitation directly at the bottom boundary; (4) The top surface of the soil layer and the cap are set free. Input 0.3g EL-Centro seismic wave, and its acceleration time history curve is shown in Figure 2.

2.2 Reinforced concrete model

The diameter of pile foundation is 1.5m, the length is 15m, and the ratio of longitudinal reinforcement is 0.43%. Elastoplastic model and concrete plastic failure (CDP) model are used to simulate the mechanical behavior of reinforced concrete respectively, and the relevant parameters are shown in Table 1 and Table 2.

Table 1. Basic properties of the steel and concrete

Parameters	Steel	Concrete	Reinforced concrete
Density (kg/m^3)	7.85×10^3	2.58×10^3	2.58×10^3
Young's modulus (MPa)	2.1×10^5	3.0×10^4	3.0×10^4
Strain-hardening ratio	0.01	—	—
Poisson ratio	0.3	0.2	0.2
Yield strength (MPa)	335	Tab.2	5.1

Table 2. Concrete damaged plasticity (CDP) model parameters

Young 's modulus (GPa)	Tensile stress(MPa)	Tensil strain(×10^{-3})	Tensile damage	Compressive stress (MPa)	Compressive strain	Compressive damage
	2.000	0.00	0.000	25.286	0.00000	0.000
	1.873	0.05	0.260	28.829	0.00035	0.074
	1.683	0.08	0.350	30.000	0.00064	0.144
	1.506	0.10	0.425	28.699	0.00101	0.219
	1.356	0.13	0.486	25.964	0.00143	0.303
	1.231	0.15	0.535	22.971	0.00186	0.386
25.8	1.127	0.17	0.576	20.222	0.00228	0.460
	1.040	0.19	0.610	17.857	0.00268	0.522
	0.967	0.21	0.639	15.871	0.00308	0.574
	0.904	0.24	0.663	14.214	0.00346	0.617
	0.850	0.26	0.685	12.826	0.00384	0.683
	0.813	0.29	0.701	11.656	0.00420	0.731
	0.779	0.31	0.723	10.664	0.00456	0.892

2.3 Soil model parameter

The Mohr-Coulomb model was selected for the soil mass in this model, and the basic parameters of the soil mass used in the modeling were obtained through experiments, as shown in Table 3. The contact property of pile and soil is defined as surface-surface contact behavior, tangential mechanical behavior between pile and soil is set as "penalty", and normal behavior is set as "hard contact".

Table 3. Essential parameters of the soil

Soil types	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Friction angle (°)	Cohesion (kPa)
Unfrozen	1960	25.1	0.3	30.1	49.3
Frozen	1960	372	0.2	36	251

3 Seismic response of bridge pile foundation in seasonal frozen soil

3.1 Ground acceleration responses

By comparing the acceleration time-history curves of surface acceleration under the conditions of unfrozen soil and seasonal frozen soil, as shown in Figure. 3, it can be found that the shaking duration of the two is basically the same, and the shape of the acceleration time-history curves is roughly the same, but the acceleration amplification factors of the two are different. The peak value of surface acceleration under the condition of frozen active layer is significantly higher than that under the condition of unfrozen soil. This indicates that the existence of seasonal active layer inhibits the seismic response of the foundation soil.

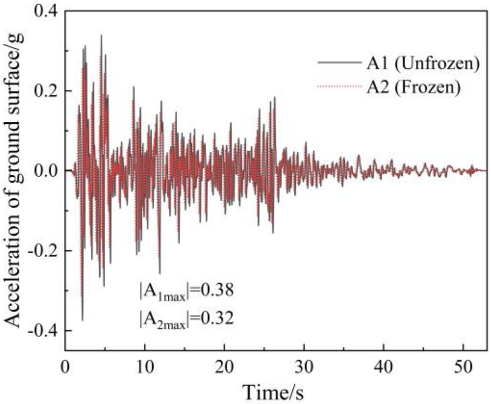

Fig. 3. Ground surface acceleration responses

3.2 Acceleration amplification factor of foundation soil

It can be seen from Table 4 that when seismic waves are input at the bottom of the soil, the peak acceleration amplification coefficients of the soil at different depths are also different. In addition, under different site types, the peak acceleration amplification coefficient of foundation soil is different at the same depth. In the frozen soil, the peak acceleration amplification coefficient of foundation soil is significantly lower than that at the same depth under the condition of unfrozen soil. However, under these two site conditions, the peak acceleration amplification coefficient decreases first and then increases with the increase of soil elevation.

Table 4. Peak acceleration amplification factor of soil along depth in different conditions

Site type	-17m	-8.5m	0m(Ground surface)
Unfrozen soil	1.0	0.83	1.42
Frozen soil	1.0	0.88	1.31

3.3 Acceleration amplification factor of pile foundation

It can be seen from Table 5 that under ground motion, after the seismic energy propagates from the pile end to the ground through the pile body, the acceleration peak amplification factor of the pile top is greater than 1, while the acceleration peak amplification factor of the cap is larger than that of the pile top. When the active layer is frozen, the peak acceleration amplification coefficient of the cap increases slowly, which is because the pile is more constrained by the foundation soil after the upper soil is frozen.

Table 5. Peak acceleration amplification factor of pile foundation along depth in different conditions

Site types	Pile toe(-14.2m)	the Middle of pile(-7.5m)	Pile head(0m)	Cap(2m)
Unfrozen soil	1.15	0.86	1.05	1.13
Frozen soil	1.10	0.91	1.3	1.32

4 Conclusions

In this study, the effect of seasonal frozen soil is fully considered, and the influence of seasonal frozen soil on the dynamic response of bridge pile foundation is studied based on the finite element model. The main conclusions are as follows:

(1) Compared with the unfrozen ground, the peak value of surface acceleration under the seasonally frozen ground is generally smaller, and the existence of seasonal active layer may weaken the amplification effect of the ground on seismic waves.

(2) The presence of frozen soil inhibits the amplification effect of foundation soil, and the amplification effect of foundation soil on ground motion is smaller than that of unfrozen soil, so the acceleration peak amplification factor of frozen soil is smaller than that of unfrozen soil.

(3) In the frozen state of the foundation soil surface, there is a small difference between the peak acceleration amplification coefficients of pile foundation and foundation soil. The strong constraint of frozen soil makes the relative movement of pile foundation and shallow foundation smaller. Compared with unfrozen ground, the seasonal frozen soil is favorable to pile foundation.

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