Seismic Response and Nonlinear Mechanical Characteristics of Bridge Pile Foundation in Yushu Permafrost Area

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In order to analyze the application effect of bridge pile foundation in Yushu permafrost area, this paper uses the research methods of theoretical analysis, model testing, and numerical simulation to collect soil samples in the Yushu area, study various indicators of frozen soil, simulate different frozen soil foundations in the Yushu area, and study different seismic waves under the influence of different temperatures. The seismic response mechanism of bridge pile foundations in the Yushu permafrost region under the influence of loading mode, soil material, and single pile in different permafrost regions is analyzed, and the dynamic response and mechanical nonlinear characteristics of displacement and deformation under different seismic forces are obtained. The simulation results show that under the influence of different temperatures, different seismic wave loading methods, and different soil quality single piles, the bridge pile foundation in the Yushu permafrost area has obvious seismic response laws and obvious mechanical nonlinear characteristics. Under the influence of permafrost material, most single piles have response coefficients of between 0 and 1.

1. Introduction

China is a country with a wide distribution of permafrost areas in the world, accounting for 10% of the world’s permafrost areas. Affected by global warming, a large number of permafrost regions are gradually degenerating. In the process of degradation, the upper limit of permafrost moves down, which reduces the strength of permafrost and has a great impact on the structures in permafrost regions.

With the continuous development of engineering construction in permafrost regions, people pay more and more attention to the study of frozen soil mechanics, in order to deal with and solve the related problems of engineering structures in cold regions. However, the research on the dynamic characteristics of frozen soil mainly focuses on the dynamic parameters of different frozen soils in the small deformation range and the dynamic strength and dynamic stress-strain relationship in the large deformation range. The research on the seismic response of bridge pile foundations in frozen soil areas is still in the exploratory stage. In the permafrost region of the Qinghai-Tibet Plateau, there are intense crustal tectonic activities and frequent strong earthquakes. Only from 1980 to 2010, there were 33 earthquakes with MS 6.0 to 6.9 and four earthquakes with MS 7.0 to 8.5 in the Qinghai Tibet Plateau and its surrounding areas. The strong earthquakes not only caused a large-scale surface rupture zone in the permafrost region but also caused certain damage and potential danger to the infrastructure projects and the safety of personnel and property in the region. Therefore, it is of great significance to study the performance of bridges in permafrost regions. In this paper, the thermal characteristics of the cast-in-place pile foundation of QTP in permafrost regions with temperatures (>1°C) are studied by field observation and numerical simulation. The observation of the temperature field shows that the peak temperature of the pile foundation appears two days after concrete pouring, and the positive temperature of the pile foundation lasts for 21 days. 93 days after grouting, the temperature at different depths of the pile foundation decreased to below 0°C. However, 224 days after pouring concrete, the temperature of the pile foundation is still higher than that of the natural foundation. Based on the
measured data, a three-dimensional numerical model is established to analyze the thermal disturbance and freezing process. In reference [1, 2], a method for evaluating the stability of piles in permafrost regions is proposed. The bearing capacity of the pile foundation in permafrost regions is caused by the freezing strength of the pile-soil interface and the bearing capacity of the pile bottom. According to the formation mechanism of the bearing capacity of the pile foundation in a permafrost region, the thermal stability of the bearing capacity of the pile foundation in permafrost region is evaluated by the stability ratio of the frozen zone and the freezing strength of the pile-soil. Using this method, the bearing capacities of single and double piles in typical humid permafrost areas and underground permafrost areas with warm groundwater are studied. The correctness and effectiveness of the evaluation method are proved by comparing it with the field-measured values. In reference [3], in order to study the influence of foundation freezing and thawing on the stress state of the pavement structure in permafrost regions, the finite element model of continuously reinforced concrete pavement (CRCP) in permafrost regions was established by using the finite element software COMSOL. Based on the coupled action theory of moisture and heat stress field, the effects of material parameters of base and subbase, thickness and modulus of concrete slab, and reinforcement ratio on the combination of CRCP pavement were studied. Reference [4] experimentally compared the resistance capacity of two opposing rotating mechanically excited monopiles buried in dry sand and saturated sand, made a small physical model, and completed the experimental work in the laboratory. The physical model includes two small motors with an eccentric mass of 0.012 kg and an eccentric distance of 20 mm, representing two opposing rotating machines, an aluminum shaft with a diameter of 20 mm as a pile, and a diameter of 160 × 160 mm pile cap. Test work was carried out taking into account the depth ratio (L/D; length to diameter) of the pile and the operating frequency of the rotating machinery. Twenty-four trials were conducted in medium-density fine sand with a relative density of 60%. The results show that, in the process of mechanical work, due to the existence of dynamic skin friction resistance, the pile tip load ratio and the working frequency are both reduced, whereas in saturated soils, for small (L/D) ratios and low operating frequencies, the kinetic friction is affected by water, which acts as a lubricant, resulting in increased pile tip loads.

In previous studies, due to the excessive displacement of bridge piers and abutments during the earthquake, the main damage form after the Yushu earthquake was beam collapse. For the study of pile foundations in permafrost areas, more is to explore the role of pile foundations in seismic forces in warm weather, or to analyze the pile foundations and their supported bridges and other structures in previous strong earthquakes, but for pile foundations in permafrost areas. At the same time, because the physical and mechanical properties of frozen soil are more sensitive to factors such as ground temperature and dynamic load, the in-depth study of the characteristics of pile foundations in frozen soil dynamics and frozen soil environments has become the seismic

1.1. Seismic Damage Characteristics and Causes of Bridge Pile Foundation in Yushu Permafrost Region. In recent years, China has carried out large-scale infrastructure construction in cold regions, such as the Qinghai-Tibet highway, Qinghai-Tibet railway, and the planned Sichuan Tibet railway. These traffic projects have passed through permafrost regions for thousands of kilometers, but most permafrost along traffic projects in cold regions is extremely fragile. When they are disturbed by earthquakes, they are bound to cause changes in ground temperature and the thickness of the freeze-thaw layer [5–9], resulting in typical seismic damage characteristics of bridge pile foundations, and the causes of seismic damage are inconsistent, as follows:

(1) The displacement of pile foundation pier with soil causes the upper structure to fall. Different from the conventional thawed soil, the static and dynamic mechanical properties of frozen soil are significantly different from those of unfrozen soil. The mechanical properties of frozen soil are extremely sensitive to external action. Under the coupling action of water, heat, force, and other factors, it has significant temperature control, rheological, and creep properties. As a result, the mechanical properties of pile foundation in frozen soil are significantly different from those in conventional soil, especially under the action.

(2) The pile moves or sinks continuously. In order to protect the fragile ecosystem and reduce the impact of the adverse geological environment on the subgrade, the bridge is often used to lead the road in the first stage of the project. However, after a strong earthquake, the change in the freeze-thaw layer will affect the dynamic characteristics of the site soil layer, which will cause seismic damage to the continuity of the pile foundation in cold regions [10–15].

(3) Soil softening causes pile sinking, which leads to bridge deck and beam damage [11, 16–19]. Under the strong earthquake, due to the influence of the inertial force of the bridge superstructure, the pile foundation will move relative to the soil, and even the separation and softening of the soil around the pile will appear on the interface between the two. At the same time, the strong nonlinearity of the soil makes the influence of the pile-soil dynamic interaction on the seismic response of the bridge structure more...
1.2 Simulation Analysis of Mechanical Nonlinear Characteristics of Bridge Pile Foundation in Yushu Permafrost Region

1.2.1 Source of Simulation Data and Experimental Environment Settings

(1) The soils used for this simulation analysis are the foundation pit soils of a station on the Yushu Expressway (Gongyu Expressway) in the plateau permafrost area. The length of the foundation pit is 234.7 m, the width of the standard section is 20.7 m, the buried depth of the bottom plate is about 17.74–19.25 m, and the buried depth of the Fushi is 3.9 m. The ground depth of the test soil sample is about 7–9 m. The soil sample taken from the foundation pit will be exposed to the sun, crushed, and screened, and a variety of soil samples will be selected as the frozen soil for the static and dynamic strength and dynamic parameter tests and the dynamic characteristics tests of the model pile foundation in the subsequent frozen soil environment [20–26].

(2) Generally, the pile foundation is made of large-diameter reinforced concrete. Because the model concrete pile is prone to be broken and destroyed, the steel pipe is selected to replace the model pile. Meanwhile, considering the brittleness of the model pile material in the low temperature environment and the large frozen soil stiffness, etc., in order to ensure the smooth implementation of the simulation [27–32], and prevent the situation that the pile body above the soil surface is cut off before the pile body is obviously displaced in the initial stage of horizontal dynamic loading and before the pile body is obviously displaced in the frozen soil, the simulation selects the Q235 seamless steel pipe with an outer diameter of 30 mm, a wall thickness of 3 mm, and a length of 700 mm as the model pile. The elastic modulus $E = 206$ GPa, the similar density ratio of 0.94, the similar bending stiffness ratio of $4.3 \times 10^7$, and the similar force ratio of $6.02 \times 10^5$, among which the length of the Q235 seamless steel pipe in the embedded soil is 550 mm, and the steel pipe with the same steel sheet material is used as the bottom part. Similar density ratio, similar flexural stiffness ratio, and similar stress ratio refer to the density ratio, flexural stiffness ratio, and stress ratio of two similar pile foundations [33–35].

(3) $C = 40$ and $C_g = 1$ shall be used for the geometric similarity ratio of simulation model. $C$ is the size of the original pile foundation, and $C_g$ is the size of the simulated pile foundation.

(4) Considering the universality of the simulation contents, the size of the prototype pile and the building materials in the actual project are comprehensively considered in the simulation design, and 40:1 is proposed to be the control condition for the geometric scale of the model simulation pile. [36–40].

(5) In the light of the actual situation of market materials [41–45], it is equipped with high-density and closed sample containers (Jinri Sealing Material Technology Co., Ltd., the maximum sample size is $1300 \text{ mm} \times 1300 \text{ mm}$), actuators (Series 244 actuators of Zhongji Test Equipment Co., Ltd.), presses (Shandong Gaomi High Forging Machinery Co., Ltd., Model JB21-160 presses), cycling refrigeration equipment (Jiangsu Haisi Temperature Control Equipment Co., Ltd., high and low temperature integrated circulation machine), and numerical control equipment for testing machines (Jinan Tianshun CNC Co., Ltd., XY)-208 series angular strength tester, numerical control spring tension tester and large scale tension tester).

1.3 Simulation Experiment Steps

In this study, in order to explore the seismic response and mechanical nonlinear characteristics of the bridge pile foundation under static and dynamic loads, first, the seismic response mode of a frozen soil pile foundation bridge structure is analyzed. The qualitative analysis of the dynamic coupling characteristics of a frozen soil pile foundation bridge structure in a frozen soil environment under seismic wave input is the premise and foundation of its mechanical nonlinear characteristics.

1.3.1 Modeling of Frozen Soil-Pile Foundation

According to the parameters set above, prepare samples of frozen soil, make steel boxes with lateral restrictions of $400 \text{ mm} \times 400 \text{ mm} \times 600 \text{ mm}$, put the soil into the steel boxes, bury the soil into the above set up good pile foundation, stick strain sheets on the surface and internal steel bars of the pile foundation, put the whole model into the freezer, and freeze the combined cycle refrigeration equipment. Several such frozen soil-pile foundation models can be made according to different temperatures. The top of the pile foundation can be compared with the bridge pier and superstructure by a press. The final frozen soil-pile foundation model is shown in Figure 1.

1.3.2 Test Plan

(1) When the permafrost reaches the plastic freezing state, the same vertical seismic wave is input. According to different loading methods, the vibration spectrum of the pile foundation and the corresponding time interval, the stress and deformation of the concrete and internal reinforcement were measured.

(2) When the loading mode of the input seismic wave is the same and the seismic wave intensity is different, the system provides nonlinear stress for the model pile foundation according to the set load amplitude
and working frequency, and the force is applied to the pile head by the valve-controlled actuator. The simulation control system collects the current load of the pile foundation and outputs the control signal after comparing with the set value, referring to the load effect of the bridge pile foundation and soil (Figure 2). By controlling the extension of the piston rod of the actuator to adjust the load on the pile head, the vibration frequency and displacement of the pile foundation, as well as the change and transfer law of the bearing capacity of the pile foundation, are measured.

(3) When the axial compression ratio is fixed and the strength of frozen soil is fixed, the input angle of the seismic wave shall be adjusted, the reference point of frequency shall be marked at the unearthed position of the pile foundation, and the vibration frequency and displacement under the corresponding seismic wave of the pile foundation shall be determined.

At points a, B, and C, according to the acceleration sensor, combined with the interaction between beam pile foundation and soil, the displacement time history curve is obtained, and the stress distribution nephogram is generated as shown in Figure 3, and the displacement distribution nephogram is generated as shown in Figure 4.

It can be seen from Figure 3 that stress concentration occurs at the bottom of the bridge pile foundation, i.e., point C, and the maximum principal stress is about 9000 kPa.

It can be seen from Figure 4 that the maximum settlement occurs at point B, that is, at the upper soil near the pile foundation. The maximum settlement is $0.5 \times 10^{-3} \text{ m}$, and the settlement decreases with an increase in the distance from the pile.

(4) Analyze the above results to judge the main factors affecting the ultimate bearing capacity of pile foundation.
The influence of temperature on the bearing capacity of pile foundations is studied under the same conditions of axial compression ratio and input seismic force. The input of the seismic wave is driven into the displacement of the seismic wave by applying the acceleration field to form the application of the seismic wave. When the seismic wave is input, the stress and strain devices collect a set of data every one second to measure the relationship between temperature and frozen soil strength, the temperature range is between \(-10\)–\(10\) degrees Celsius.

The commonly used models for describing the side friction of piles are the linear elastic model, the hyperbolic model, and the triple-fold model. The triple-fold model is suitable for analyzing the side friction of piles under various soil properties. Therefore, only a single pile model needs to be poured according to a certain proportion. When a single pile foundation is obtained, the change rule between the strength of frozen soil and the bearing capacity of a single pile can be observed by adjusting the proportion between the spacing of piles and the diameter of piles.

In this design, the single pile loading method is the main method. After the simulation is completed, the soil sample shall be taken out, the instrument shall be cleaned, the simulation environment shall be reset, and all instrument readings shall be restored to zero.

The coupling effects of frozen soil, pile foundation, and structure are analyzed by the model in Table 1. The seismic response stress of soil in different frozen soil area is studied.

2. Results of Simulation Experiments

2.1. Seismic Response Characteristics of Single Pile under Different Temperature Effects. Because the frozen soil area in the Yushu area has obvious seasonal change characteristics, the freezing mainly occurs from October to April of the next year, and the period from mid-June to early September is the safe period without frozen soil, and the average period without frozen soil is 173 days, and the period without frozen soil under an 80% guarantee rate is less than 5 months. Therefore, in the simulation experiment, without considering the annual maximum freezing depth, three identical single-pile models are made according to the above steps (1)–(6). Under the condition of constant load loading,
three frozen soil environment temperatures of −5, −2, and 2 are set, and the test operation method and specification are the same as in the above scheme. Therefore, the variable is single, and the seismic response of a single pile affected by different temperatures is special. The results are shown in Figure 4.

It can be seen from Figure 5 that in the same permafrost environment, the time of constant load application remains unchanged. For a certain loading moment of −5°C permafrost pile foundation, the tensile and compressive strains of the pile body change sharply along the pile depth. Similarly, the tensile and compressive strains of the pile body under −2°C and 2°C also have this trend, but it is obvious that the fluctuation of the pile body under −2°C and 2°C is lower than −5°C, indicating different permafrost environments. With the decrease in temperature, the displacement curve of a single pile fluctuates more.

2.2. Seismic Response Characteristics of Single Pile Influenced by Different Seismic Waves Loading Methods. When a significant earthquake occurs, the energy released by the source propagates around the ground in the form of a seismic wave and causes vibration on the ground. After different geological, transmission paths and topography, the seismic wave not only has a time lag but also its spatial characteristics will change. Therefore, the failure state of a single pile foundation of a bridge is divided into pile 1, pile 2, pile foundation 3, and pile foundation 74. In the four parts, the seismic response characteristics of the single pile foundation of the model are analyzed respectively, and the analysis results are shown in Figure 6.

As can be seen from Figure 6, among the four pile foundations, the failure probability of a single pile foundation of a bridge varies with the change of failure grade and its value is negatively correlated. No matter what the state of the bridge single pile failure probability, its change presents a nonlinear increase with the increase of seismic strength, and is related to the damage level, showing a certain regularity: when the bridge pile foundation just begins to bear the seismic wave loading force, because of its own bending deformation, it resists the external load, and with the continuous increase of the upper horizontal load, the stability of the pile body increases. With the increase of deformation degree, the rock and soil around the pile are squeezed by the pile foundation to produce rock and soil resistance, which has resistance to the further deformation of the pile foundation. With the continuous increase of seismic wave loading force on the pile foundation, the displacement of the pile foundation continues to increase, and the pile foundation begins to transition from elastic deformation to plastic deformation. At the same time, the squeezing effect on the rock and soil around the pile is more significant, and the rock and soil begin to change from elastic deformation to plastic deformation. When the deformation of the pile body is too large or the rock and soil beside the pile lose the resistance to the pile foundation, the pile foundation will reach its horizontal ultimate bearing state.

2.3. Test on Seismic Response Characteristics of Single Pile with Different Soil Materials. Taking the ultimate bearing state as an example, the analysis results of the seismic response characteristics of a single pile in different frozen soil materials are shown in Table 2. The calculation formula for the vector linear seismic response coefficient of a pile foundation is as follows.

By using the method of variance maximization, the subjective and objective weights between pile spacing and pile diameter are reasonably distributed, so that the bearing weights of pile groups can meet the consistency test conditions. According to the weight vectors \( U = [u_1, u_2, \ldots, u_m] \) and \( V = [v_1, v_2, \ldots, v_m] \) of pile group bearing capacity, the two pile vectors are linearly combined into the integrated weight to obtain \( w = \alpha U + \beta V \) and \( \alpha, \beta \geq 0, \alpha^2 + \beta^2 = 1 \).
The linear combination expression of two pile foundation vectors based on variance maximization is as follows:

$$
\text{max } Z = \sum_{m} \sum_{n} (r_{ij} - \tau_{ij})^2 (\alpha u_i + \beta v_j),
$$

where $r_{ij}$ represents the frozen soil strength and pile group bearing threshold, the arithmetic mean value of frozen soil strength and pile group bearing threshold is expressed by $\tau_{ij}$. The following Lagrange function calculation method [33–35] is used to optimize the linear combination expression of two pile foundation vectors and obtain the optimal solution:

$$
L(\alpha, \beta) = \sum_{m} \sum_{n} (r_{ij} - \tau_{ij})^2 (\alpha u_i + \beta v_j) + \lambda (\alpha^2 + \beta^2 - 1).
$$

The expression of vector linear seismic response coefficient of pile foundation can be obtained by calculating the partial derivative of Lagrange function:

$$
\alpha = \frac{1}{\sqrt{1 + \sum_{j=1}^{m} \sum_{i=1}^{n} (r_{ij} - \tau_{ij})^2 u_i / \sum_{j=1}^{m} \sum_{i=1}^{n} (r_{ij} - \tau_{ij})^2 v_j}}.
$$

According to the above vector linear seismic response coefficient of pile foundation, the seismic response characteristics of a single pile with different soil materials are analyzed. The analysis results are shown in Table 2.

As shown in Table 2, under the influence of soil materials in permafrost regions, the response coefficients of most single piles are between 0 and 1, indicating that most of the

<table>
<thead>
<tr>
<th>Pile material</th>
<th>Soil material</th>
<th>Loading mode</th>
<th>Vector linear seismic response coefficient of pile foundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile foundation 3</td>
<td>Barite powder</td>
<td>Vertical static load (P wave)</td>
<td>0.6</td>
</tr>
<tr>
<td>Pile foundation 4</td>
<td>Silt</td>
<td>Vertical static load (P wave)</td>
<td>0.5</td>
</tr>
<tr>
<td>Pile foundation 5</td>
<td>Medium sand</td>
<td>Vertical static cutting (P wave)</td>
<td>1.6</td>
</tr>
<tr>
<td>Pile foundation 6</td>
<td>Fine sand</td>
<td>Vertical static load (P wave)</td>
<td>0.25</td>
</tr>
<tr>
<td>Pile foundation 7</td>
<td>Fine sand</td>
<td>Cyclic dynamic load (L wave)</td>
<td>0.25</td>
</tr>
</tbody>
</table>
above materials can meet the seismic requirements of bridge pile foundations to a certain extent.

3. Conclusions

Based on the model simulation analysis, considering the bearing capacity and ultimate displacement of the pile foundation when the contact between the single pile foundation and the frozen soil is nonlinear, the dynamic BNWF model is used to simulate the seismic response and mechanical nonlinear characteristics of the bridge pile base in the Yushu permafrost region, and the mechanical nonlinear characteristics of the pile foundation under different temperatures, different seismic loading modes, and different frozen soil materials in the Yushu region are determined.

(1) The dynamic displacement load relationship of a single pile foundation is affected by the frozen soil temperature. When the materials of the bridge pile foundation are different, the seismic inertia force will cause large lateral displacement of the pile foundation, which is easy to cause the structure to overturn.

(2) The pile foundation is strongly affected by the surface seismic wave. In uniform frozen soil, the seismic response characteristics of a single pile foundation with different seismic wave loading methods have a certain regularity.

(3) With the decrease in temperature, the displacement curve of a single pile foundation fluctuates more in different permafrost environments.

However, only the seismic wave input mode and the single pile mode are considered in this paper. Therefore, in future research, the influence of freezing and thawing of upper soil on pile group structure should be comprehensively considered, especially the analysis method of base seismic response and mechanical nonlinear characteristics under the joint input of transverse and vertical seismic waves.

Data Availability

No data are available for this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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