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Warming effects on permafrost under earthquake motions and seismic stability of pile foundation of dry bridge

Z. J. Wu[1], A. L. Che*[2] and T. Ghen[1]

A series of shaking table tests for the 1 : 100 scaled model of the pile foundation in the Qingshui river Bridge along the Qinghai–Tibet Railroad were conducted on condition that the soil temperature around pile was below 0°C. The change of temperature around the pile foundation during the earthquake motions was monitored, and the warming effects on the permafrost were obtained. Applying dynamic finite element analysis method, the characteristics of seismic response of the pile foundation were analysed. In the dynamic time history analysis, the artificial seismic waves were used as the input ground motions. The effects of the peak acceleration and frequency characteristic of input ground motions on seismic stability of the pile foundation of bridges at the unstable permafrost areas of high temperature and high ice content were determined. The distributions of dynamic displacement, acceleration and earth pressure were studied and the dynamic stability of the pile foundation of bridges was evaluated.

Keywords: Permafrost, Pile foundation, Warming effects, Temperature, Seismic stability

Introduction

In China, the permafrost mainly distributes on the Qinghai–Tibet Plateau, where the tectonic movement is strongly active, and there has been a frequency of earthquakes and many strong events occurred in this area. The permafrost is a very special soil, and it is quite sensitive to temperature changes, as physical, chemical and engineering features are inherently unstable and correlated with temperature. Variation in temperature is one of the most important factors that influence the mechanical properties of permafrost and also the one that affects the bearing capacity of foundations in permafrost areas.[1] However, in the past decades, the annual average air temperature on the Qinghai–Tibet Plateau has increased by 0·2–0·4°C per year, and the permafrost has presented a regional degenerate state, because global warming is getting more serious. The degenerate of permafrost indicates that its strength will decrease gradually;[2] moreover, with the additive effects of earthquakes, it brings much more potential risk to safe operation of the Qinghai–Tibet Railroad (QTR).

In order to keep the stability of the permafrost as foundation of the QTR, there are many bridges constructed instead of embankment, also named as dry bridge, at the unstable permafrost areas of high temperature and high ice content. Several dynamic triaxial tests on frozen soil indicate that the temperature will increase under cyclic motions.[3] This increase in temperature will decrease the strength of permafrost and influence the stability of pile foundation in the permafrost areas. Under seismic dynamic motions, the shaking table tests for the scale model of piles were carried out when the soil temperature around model piles was below 0°C. The interaction between piles and frozen soil was studied, and the characteristics of the seismic response of the pile structure were analysed; moreover, the effect law of dynamic loading response of piles on temperature and strain around piles was achieved, and the stability of the pile foundation of bridges at the unstable permafrost areas of high temperature and high ice content was evaluated as well.

Shaking table tests for scale model of pile foundation in frozen soil

Brief introduction of test

The shaking table is a one-direction electrohydraulic servo vibration table, of which the working area is 2 × 2·2 m, the maximum loading is 4·5 t, the maximum acceleration is 1·0 g, the maximum velocity is 100 cm s^{-1} and the effective frequency range is between 0·5 and 20 Hz. In order to control the temperature of frozen soil accurately, a thermostat was specially designed for containing the scale model of piles and frozen soil around them. Its outer diameter is 80 × 80 × 50 cm, and inner diameter is 50 × 50 × 35 cm. There was an insulating material, 15 cm thick heat, designed as lining around the box, and spiral copper

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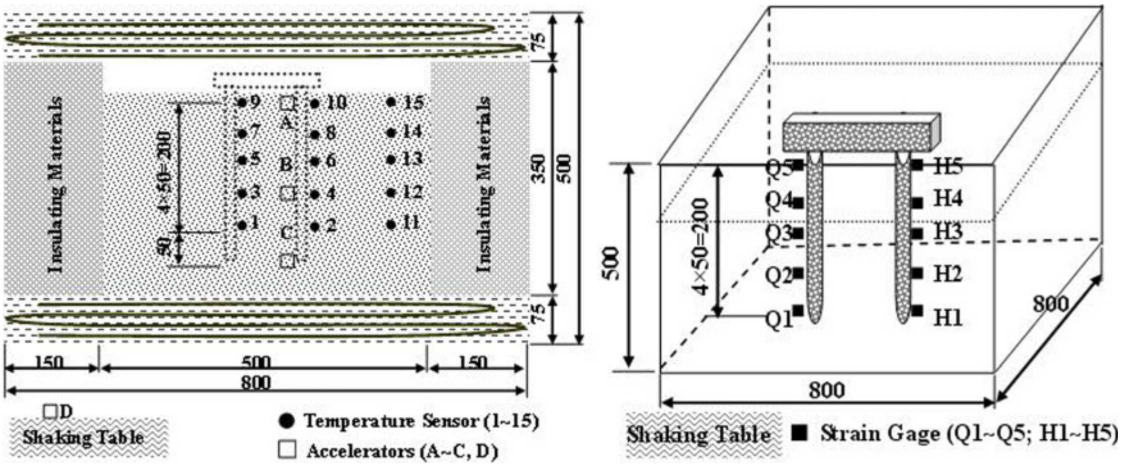


1 Layout of measuring points of temperature, acceleration and strain

tubes were set at the bottom and top of the box for hypothermic alcohol circulation. The temperature of frozen soil in the thermostat was controlled by a cold soaking circulating refrigerating machine.

The prototype was the pile foundation of the Qingshui river Bridge, which is a typical dry bridge and also the longest one along the QTR. This bridge locates at high earth temperature and extremely unstable permafrost area, where the annual average earth temperature is between −0·2 and −0·5°C, and the table of permafrost is 2–4 m under surface ground. This scale model for shaking table tests was a 1 : 100 scale to the prototype, of which the length of piles is 25 cm, the diameter is 1·5 cm, the interval between two piles is 3·3 cm, the penetration depth of pile is 22 cm and the thickness of pile cap is 1·5 cm, whose strength is as strong as that of the C30 concrete, and the proportion of cement and sand is 1 : 3. The soil around piles came from where the Qingshui river Bridge locates, the rate of water content is 20%, according to the test *in situ*, and the density of frozen soil is 26·0 kN m^{-3}.

The temperature, acceleration and strain were monitored while shaking. Figure 1 shows the layout of measuring points.

A series of shaking table tests were performed, of which the amplitudes of the input seismic waves were set according to a 7 degree basic earthquake (0·10 g), an 8 degree basic earthquake (0·20 g) and a 9 degree basic earthquake (0·40 g) respectively. Before shaking, the soil and pile foundation in the thermostat were kept in frozen for 72 h, and on the condition that the temperature of the soil maintained stably at a range between −0·5 and −1·5°C for 6 h as well. During operation of the test, the cold soaking circulating refrigerating machine kept on working in order to maintain soil temperature without being influenced by environmental temperature. To avoid the change of temperature at different operating cases, there was an interval of 5 min between every case during test.

Test results

Under the horizontal loadings of the sine wave (100, 200 and 400 gal), the Qinghai–Tibet artificial wave (167 gal) and the Wenchuan earthquake motion (184·9 gal) respectively, the foundation model demonstrates shear deformation response. The maximum shear strain of the model foundation is $\sim 3\times10^{-4}$. The maximum shear strain of the pile is up to 6×10^{-4}, which appears at the lower part of the pile, because of the stiffness difference between soil and pile structure.

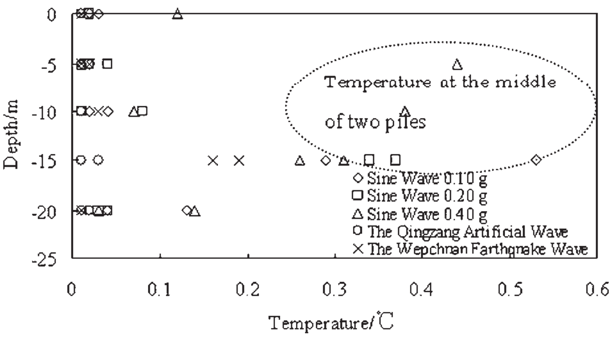
The increases in temperature at foundation soil and soil around piles under different motions are as shown in Fig. 2. With increasing input acceleration, the increase in temperature becomes more significant, especially at the middle of two piles (15 and 25 cm in depth). Because the mechanical energy concentration is induced by libration between two piles, when the energy transfers into thermal energy, it causes an obvious increase in temperature. Also because of the friction between pile and soil, the temperature increases here as well. However, the free foundation is influenced rarely by shaking. After shaking, the maximum increase in temperature is up to by 0·5°C; this increase response is influenced by the density of soil foundation and location.

Finite element dynamic simulation and stability analysis

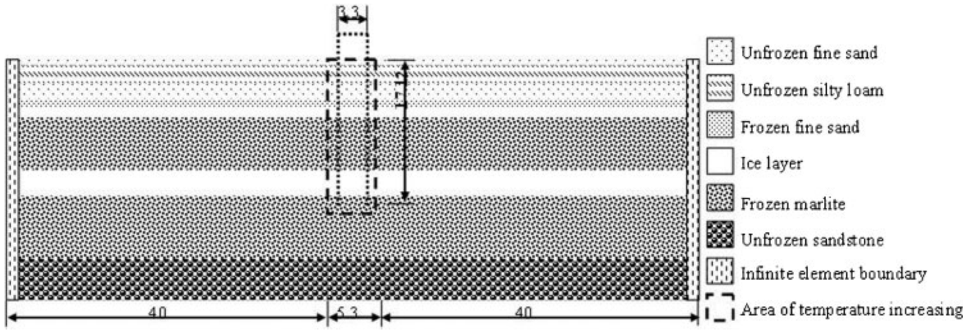
The two-dimensional equivalent linear time history dynamic analysis was used for the numerical simulation of seismic response of the pile foundation of the Qingshui river Bridge. The dynamic stability of the pile foundation and the effects of temperature increase on it were analysed as well.

Analysis methods

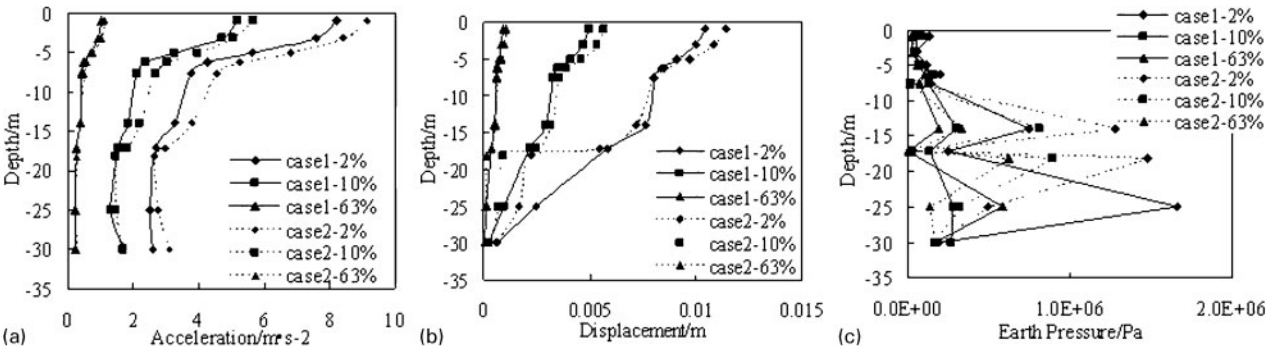
The dynamic response characteristics of free field soil and its non-linear were taken into account, when the two-dimensional finite element dynamic analysis method was employed. The values of the dynamic shear modulus



2 Response of temperature increase at soil foundation and soil around piles under different motions



3 Ground structure model (in m)



a acceleration; *b* displacement; *c* earth pressure

4 Distribution of maximum response along depth

and damping ratio, obtained while the maximum displacement occurred during elasticity calculation, according to its dependence on strain,[4,5] were applied during the dynamic analysis proceeding. The analysis model is shown in Fig. 3, where the foundation is set into plane strain element (linearly equivalent), the structure is beam element (linear) and joint elements are taken between soil and pile. The boundary condition uses the infinite element boundary. The whole model has 2508 elements and 2580 joint points.

Artificial seismic waves with exceedance probabilities of 62·5, 10 and 2% respectively in 50 years, developed by Xiaojun Li, Professor of Chinese Earthquake Administration, were used as input seismic motions, of which the peak ground accelerations of the motions are 26, 167 and 326 gal respectively. Table 1 shows the soil parameters under natural state and temperature increase at the permafrost areas at the Qingshui river Bridge.[1]

Effects of temperature increase on dynamic response and stability of pile foundation

According to the boreholes and temperature data at the Qingshui river Bridge, the soil temperature of surface layer, which locates between the ground and 6·2 m underground, is influenced obviously by seasonal change of air temperature. In the numerical simulation, there were two cases studied: case 1 was on natural conditions in warm seasons according to the temperature on site, and case 2 was subjected to a temperature increase of 0·5°C around the pile foundation after shaking.

Acceleration response characteristics

Figure 4*a* shows the distribution of maximum acceleration along the depth of the two cases. The acceleration of the permafrost foundation causes increasing response, and the acceleration at ground surface is five times as much as that at the bottom. Because of low stiffness at the surface layer, where the soil is fine sand and silty loam, there is an obvious difference in stiffness with the marlite layer underneath, and the soil temperature is influenced obviously by seasonal change of air temperature, the acceleration increases remarkably at the boundary of the surface layer and marlite layer underneath. The pile foundation, therefore, presents the shear response. It is important to note that the load force of the pile foundation at the ice layers shows an obvious phase difference under large earthquakes (case 2, 2%), after the temperature increase in permafrost around the piles.

Table 1 Soil parameters under natural state and temperature increase at permafrost areas at Qingshui river Bridge

Lithology	Soil type	V_s, m s^{-1}	Density ρ, kN m^{-3}	Poisson ratio μ	Dynamic elastic modulus, MPa
Fine sand	Unfrozen	192	19	0·47	216
	Frozen	302	19	0·47	468
Silty loam	Unfrozen	196	19	0·47	216
	Frozen	313	19	0·47	502·2
Ice layer	Unfrozen (with some clay components)		9	0·3	50
	Frozen		9	0·3	900
Marlite	Unfrozen	964	28	0·2	10 300
	Frozen	1153	28	0·32	10 300
Sandstone	Unfrozen		27	0·27	15 600

Displacement response characteristics

As shown in Fig. 4*b*, the displacement of the two cases, as a whole, increases from the bottom to the surface. It indicates that the permafrost foundation shows obvious shear response under the horizontal seismic motions. The maximum relative displacement is up to 12 mm. Because there are ice layers in the permafrost, the relative displacement increases remarkably and shear strain changes greatly at the boundary of ice layer and the others. When the temperature increases around the piles, the material parameters of ice layer change obviously, where the soil shear strain around the pile increases greatly.

Dynamic earth pressure response characteristics

Figure 4*c* shows the maximum dynamic earth pressure distribution along the pile, where the axial force acting on the side of pile increases along depth. The distribution of pressures is distinctly different at frozen and thawing situation, especially at the soil layer near ice layer. This change in dynamic earth pressure will greatly influence the stability of the pile foundation of bridges at the permafrost areas along the QTR under long term warming effect.

Conclusions

1. Under seismic motion loading, the frozen soil foundation of scale model shows temperature increase response. The increase places include the areas around piles and in the middle of these two piles, and the maximum increase in temperature is up to by $0{\cdot}5^{\circ}$C.

2. Seismic response of permafrost layer and pile foundation is obviously sensitive to the increase in temperature, and the response values increase with increasing acceleration input. At the boundary between surface layer and marlite layer underground, where the relative displacement increases, the shear strain changes sharply, and the amplification effects of acceleration are remarkable.

3. The ice layers in the permafrost influence the acceleration, displacement and dynamic earth pressure response remarkably, especially when the earth temperature increases; however, these responses will demonstrate much more complexity situation.

4. Temperature is an important factor to influence the seismic stability of pile foundation of dry bridges along the QTR. Therefore, when we design and construct bridges at the permafrost areas of high temperature and high ice content, active and scientific methods should be taken to control the soil temperature around pile foundation.

Acknowledgements

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