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Stability of pile foundations base on warming effects on the permafrost under earthquake motions

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Abstract

The Qinghai–Tibet Railway (QTR) is approximately 1142 km long, of which 275 km are underlain in warm permafrost regions (mean annual round temperatures range from 0 °C to 1.5 °C), where the stability of the embankment would be greatly affected by minor temperature variations. Furthermore, since the Qinghai–Tibet Plateau (QTP) is in an active seismic zone, special attention needs to be paid to the relationship between earthquakes and soil temperature. Using a refrigeration system, 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 for soil temperatures of below 0 °C around the pile. The results indicated that the seismic mechanical properties are extremely sensitive to soil temperature. The change of temperature around the pile foundation during the earthquake motions was monitored, and the warming effects on the permafrost were assessed. In addition, the seismic stability coupled with the effect of soil temperature of the pile foundation in the Qingshui-river Bridge was evaluated.

Keywords: Permafrost; Shaking table tests; Soil temperature; Seismic stability; E09; E12

1. Introduction

In China, the distribution of frozen soil is extensive and the probability of earthquakes is high. The permafrost in the Qinghai–Tibet Plateau (QTP) is the largest of the permafrost areas, with the thickest frozen soil layer and lowest temperature among the mid-low latitudinal zones in the northern hemisphere. It ranges from the north of the Kunlun Mountains to the south of Himalaya Mountains, and has an area of about 1500,000 km^2, which is equivalent to 70% of the total area of the permafrost region in China (Tong and Li, 1983). The region is also characterized by its very active tectonics, with a relatively high frequency of earthquakes, and indeed many of the strong events have occurred in the QTP area. In particular, on the 12th of May in 2008, there was an 8.0 magnitude earthquake in the west of QTP (He et al., 2008) in Sichuan province; on the 14th of April in 2010, there was a 7.1 magnitude earthquake in the west of QTP in Qinghai Province. The second of these earthquakes resulted in a 50 km long L-shaped rupture zone with on the ground and many cracks in the Qinghai–Tibet highway (Wang et al., 2010; Zhang et al., 2010). Though the QTR is a 100-year grand plan

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designed for generations to come, it is subject to both static and seismic loadings during its operation. Therefore, it is an important and urgent to study on the seismic response of the railway and highway in the permafrost regions.

However, the permafrost is a very special soil with mechanical properties very different from those of unfrozen soil. It is made up of soil skeleton, water, air and ice (Wu and Liu, 2005). Since ice is one of its components, it is sensitive to temperature changes: its physical, chemical and engineering features are inherently unstable and correlated with temperature. Vinson et al. (1978) discussed the behavior of frozen clays under cyclic axial loading. In particular, the relationships, between the dynamic modulus of elasticity of frozen soil and confining pressure, negative temperature, strain amplitude and water content, were analyzed in detail; Hyodo et al. (2013) determined the mechanical properties and dissociation characteristics of methane hydrate-bearing sand under high pressure and temperature by triaxial tests; Tokimatsu et al. (1995) investigated the dynamic properties of frozen sand by in-situ dynamic experiments; Zhao et al. (2003) researched the dynamic characteristics of frozen soil; Wang et al. (2004a, 2004b) discussed the seismic responses of embankment in cold regions. It has been shown that variations in temperature is one of the most important factors which determine the dynamic mechanical properties of permafrost and also the one which has the most effect on the bearing capacity of foundations in permafrost areas. 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 degenerative state as global warming becomes more serious (Cheng, 2001). The degeneration of the permafrost is a clear indication that its strength will decrease gradually. When this is considered together with the added effects of earthquakes, the potential risk to the safe operation of the Qinghai–Tibet Railroad (QTR) is clearly greater.

In order to maintain the stability of the permafrost as foundation of the QTR, many bridges, referred to as dry bridges, were constructed instead of embankments in the instable permafrost areas of high temperature and high ice content (Cheng et al., 2009). The geo-temperature under the foundation of the QTR is a crucial factor determining the performance of the railway (Cheng et al., 2008; Qin et al., 2009; Wang et al., 2001). The in-situ monitored temperature shows that the geo-temperatures of the underlying permafrost are warming toward 0 °C (Wang et al., 2001; Ma et al., 2008). There is therefore considerable concern that, as the scenario of climatic warming unfolds, the permafrost beneath the railway's embankment will thaw in the coming decades, and that this will cause significant settlement issues and even cripple this key transportation route. It is, however, very difficult to mitigate these concerns because of the limitations in terms of technical knowledge and funding. Few papers have been published on the dynamic properties of the frozen soil due to the complexity of the problem, the limits to the testing conditions and because the frozen soil tends to thaw under dynamic loading. The seismic response of foundation in permafrost regions is a complex thermal-dynamic interaction process. In this investigation, a refrigeration system was used in the shaking table tests to determine the variation in temperature during earthquake motions. Based on the results of the shaking table tests, the interaction between piles and frozen soil was studied, and the characteristics of seismic response of the pile structure were analyzed.

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

In order to reduce the risk of structure failure in a permafrost environment, the thermal stability of the ground has to be the main goal (Harris et al., 2009). The challenges in the shaking table test system are (a) a refrigeration system to keep the soil temperature around model piles below 0 °C; (b) measuring the changes in temperature. The test system is composed of a shaking table, a thermostatic soil container, a refrigeration system and a comprehensive data acquisition system (Fig. 1).

2.1. Shaking table

A unidirectional electro-hydraulic servo shaking table made by Japan Saginomiya Corporation was used in the Xi'an University of Architecture and Technology. Its size is 2 m × 2.2 m, loaded weight 45 kN, maximum acceleration 1.0 g, maximum speed 100 m/s. The regular waves and irregular waves can be used as input motions, and the effective frequency range is 0.5 Hz to 20 Hz.

2.2. Soil container

A thermostatic soil container was developed to reliable and accurately control the temperature of the frozen soil, which was designed as lining around a box with insulating material, as shown in Fig. 2. The outer diameter of the box is 80 cm × 80 cm × 50 cm, and the inner diameter is 50 cm × 50 cm × 35 cm. The model ground was constructed from silty loam sampled from site at the K1026+102 section of the Qingshui-river Bridge. Based on the results of field tests, the

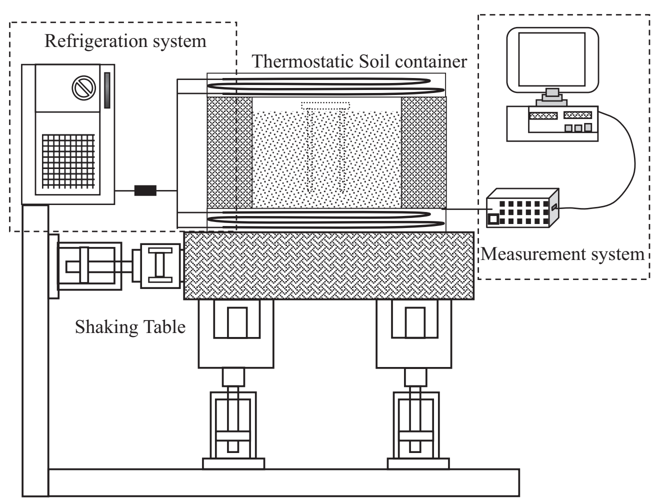

Fig. 1. Shaking table test system.

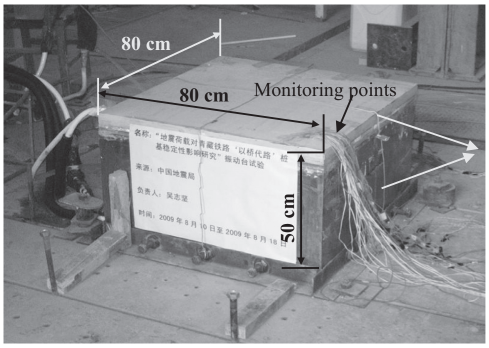

Fig. 2. Soil container.

remodeled sample was made to the following criteria: moisture parameter $w=21\%$, density $\rho=21.5$ kN/m^3.

2.3. Scaled model

The prototype is the pile foundation of the Qingshui-river Bridge, which are a typical dry bridge and also the longest one along the QTR. This bridge is located at high earth temperature and in an extremely unstable permafrost area, where the annual average earth temperature is -0.2–-0.5 °C, and the table of permafrost is 2–4 m under the surface ground. The pile model for the shaking table test was a 1/100 scale to the prototype, with a length of 25 cm, a diameter of 4.0 cm, a 6.0 cm interval between the two piles, a penetration depth of 22 cm, and a 2.0 cm thick pile cap. The pile model was made of cement and sand of proportions 1:3, and with a strength comparable to that of C30 concrete.

2.4. Refrigeration system

In order to control the temperature of frozen soil accurately, a thermostat was especially designed in order to contain the scale model of the piles and frozen soil around them. There was an insulating material designed as lining around the soil container, and the spiral copper tubes were set in the bottom and top of the box for hypothermic alcohol circulation. The temperature of the frozen soil in the thermostat was controlled by a cold soaking circulating refrigerating machine made by China Hangzhou Xuezhongtan Corporation, of dimensions 600 $W\times730$ $D\times980$ mm H, with a temperature range of -30–$+90$ °C, and a temperature fluctuation range of ±0.1–0.5 °C.

2.5. Temperature measurements

The measurement points are shown in Fig. 3. Fifteen temperature sensors are set in the ground, five are set in middle of the model, five are set around the piles and five are set in side of the ground to monitor the temperature response while shaking. A thermistor temperature sensor developed by the State Key Laboratory of Frozen Soil Engineering at the Chinese Academy of Sciences was used (Fig. 4a). The minimum temperature resolution was 0.02 °C. The temperature data recorder was a dataTaker DT500 made by Thermo Fisher

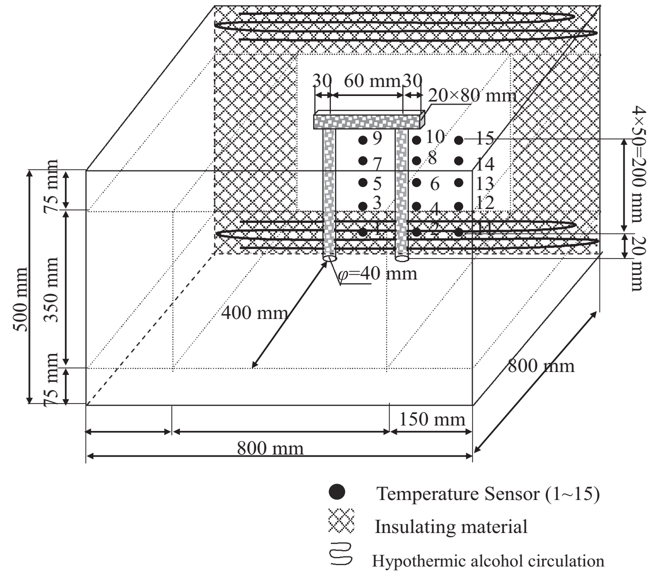

Fig. 3. Layout of the measuring points of temperature.

Scientific Australia Pty Ltd, with a minimum sampling of 1.0 s. The DT500 has 10 differential channels for three-wire and four-wire connections, and an expansion module by an external CEM channel (Fig. 4b). In the shaking table tests, the sampling was 2.0 s.

3. Temperature response during earthquake

A series of shaking table tests was performed, including sine sweep tests and random vibration tests, as shown in Fig. 5a and b. The sine-sweep tests were carried out under the following conditions: the amplitude of acceleration was 100 gal, 200 gal, 400 gal, and the alternating frequency was 0.5–20 Hz, which is 0.5 Hz, 0.7 Hz, 0.9 Hz, 1.0 Hz, 3.0 Hz, 5.0 Hz, 7.0 Hz, 9.0 Hz, 11.0 Hz, 13.0 Hz, 14.0 Hz, 16.0 Hz, 18.0 Hz and 20.0 Hz, respectively, with 30 cycles for each frequency, after 10 s the shaking was started for each frequency, as shown in Fig. 5a. The random vibration tests used the recorded horizontal accelerations at the Wenxian Seismic Station, Gansu Province (104.48°N, 32.95°E) during the Wenchuan great earthquake, with a maximum acceleration of 184.9 gal, after 10 s the shaking was started, as shown in Fig. 5b. Before shaking, the soil and pile foundation in the thermostat was kept frozen for 72 h, and the temperature of the soil was stably maintained at a temperature range between -0.5 °C and -1.8 °C for 6 h as well. During the operation of the test, the cold soaking circulating refrigerating machine was kept working in order to maintain the soil temperature without being influenced by the environmental temperature. To avoid the change of temperature at different operating cases, there was an interval of 5 min between every case during the test.

Fig. 6 shows the temperature distribution of the pile foundation when the earthquake was about to take place. Fig. 7 shows the temperature maximum changes of the pile foundation during the earthquake. From these figures it is clear that the temperature states of the underlain frozen soil around

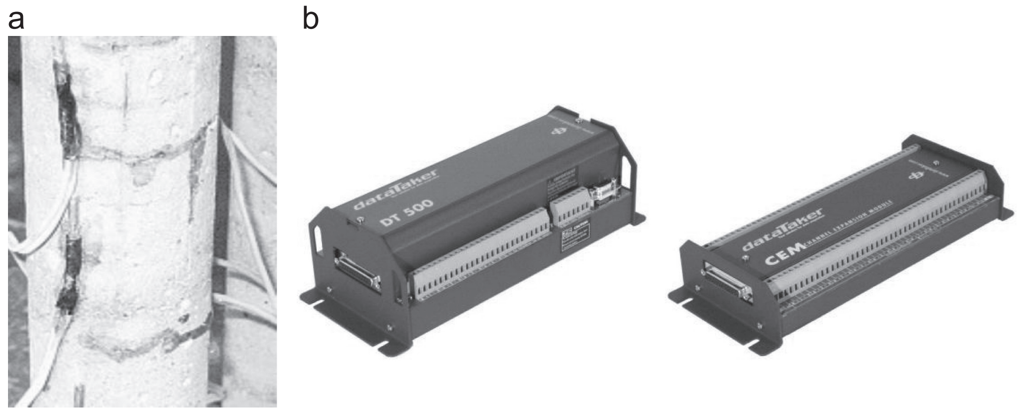

Fig. 4. Temperature measurement. (a) Thermistor temperature sensor (b) temperature data recorder- DT500&CEM.

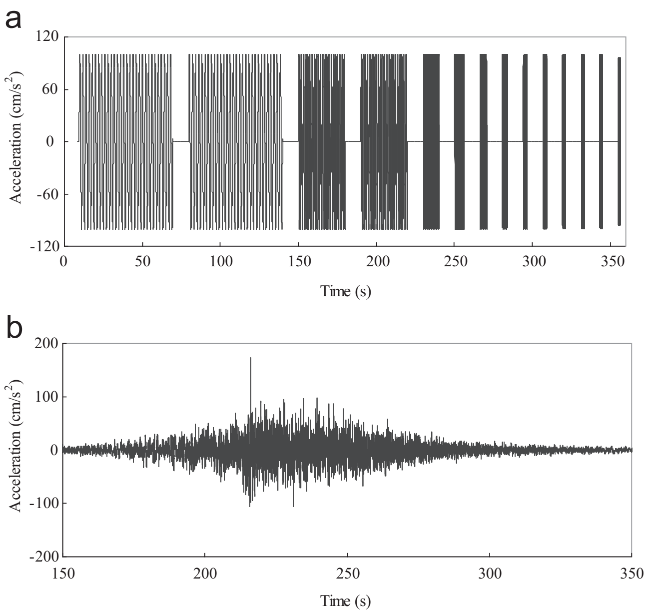

Fig. 5. Input motions in shaking table tests. (a) 100 gal, (b) Wenchuan Earthquake.

the pile foundation changed: the maximum warming reaches 0.53 °C, 0.38 °C, 0.38 °C, 0.18 °C during sine-sweep100 gal, 200 gal, 400 gal and the Wenchuan Earthquake, respectively, which was distributed in the lower part of the file foundation. Compared with temperature changes during different input motions, the warming effect expanded upward as the acceleration increased. It can therefore be concluded that a thick layer of warm frozen soil will form around the pile foundation with very unstable mechanical properties. The potential for large deformation to occur under static and seismic loadings is therefore quite clear.

4. Stability of pile foundations coupling the temperature field and the dynamic field

The seismic response of pile foundations in permafrost regions is a complex thermal-dynamic interaction process. Therefore, research on the seismic problem of pile foundations in permafrost regions should be combine with the results of site temperature monitoring, warming effect shaking table tests and dynamic parameters tests. Here a temperature field is established by superimposing the site temperature monitoring data and the warming effect results from the shaking table tests. Based on the dynamic characteristics of permafrost, a thermal-dynamic coupled model is proposed. Subsequently, the seismic response of pile foundation of the Qingshui-river Bridge of QTR is analyzed and the stability is evaluated under seismic loading.

Based on the superimposing temperature field, the Newmark-β was adopted as the time integration scheme. Then, the step of seismic analyses on pile foundation in permafrost regions can be summarised as follows.

(1) Compute the temperature fields when the earthquake is taking place.
(2) Determine the dynamic mechanical parameters relative to temperature according to temperature distribution computed by the above step.
(3) Compute the initial stress distribution in the pile foundations under gravity and bridge loading.
(4) Under the initial stress distribution based on static analysis, compute the seismic responses of pile foundations when the earthquake is about to take place.
(5) Analyze the results and evaluate the reliability of the pile foundations from a safety perspective.

4.1. Temperature field

The Qingshui-river Bridge along the Qinghai–Tibet Railroad is located in the Kunlun southern foot of the Chumaer-river plateau area, at an elevation of 4450–4520 m in permafrost region. It is the longest dry bridge along the QTR: the total length is 72 km and mileage is K1019 + 266.51 – K1030 + 986.51. The major adverse geological phenomena at the bridge site can be summarized as follows: the soil below the upper limit of the ground strata contains mostly multi-ice, rich-ice, full of ice frozen soil and an ice layer, the layer is thick while the ice layer is shallow, and the bearing capacity of the underlying marlstone is low.

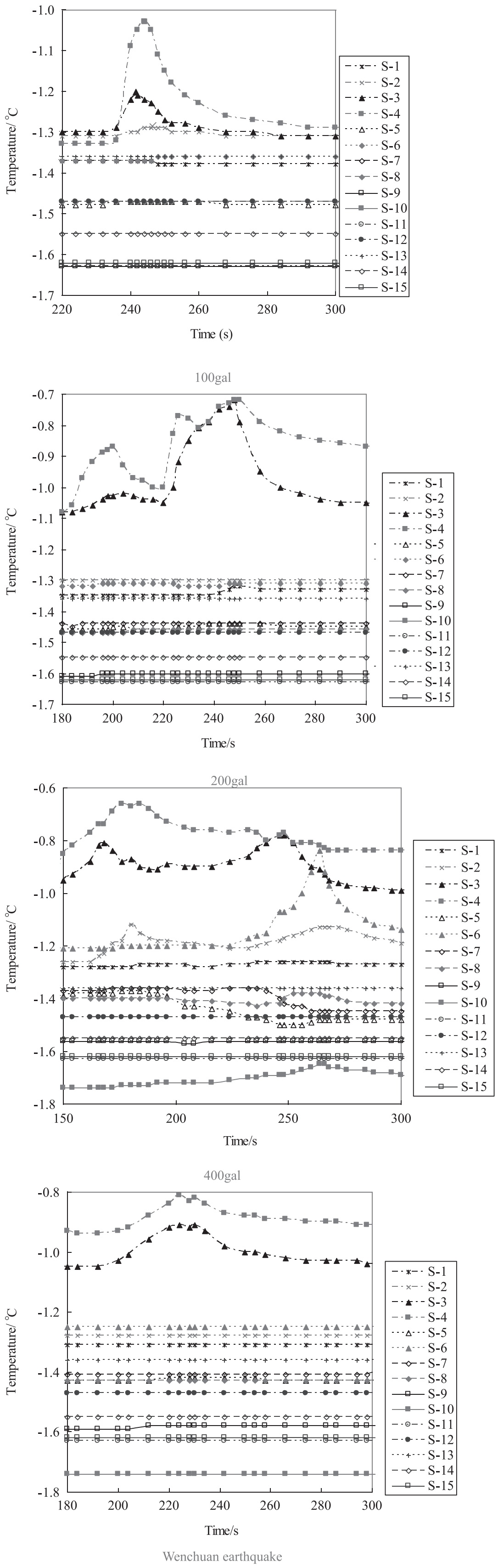

Fig. 6. Temperature distribution of the pile foundation during earthquake.

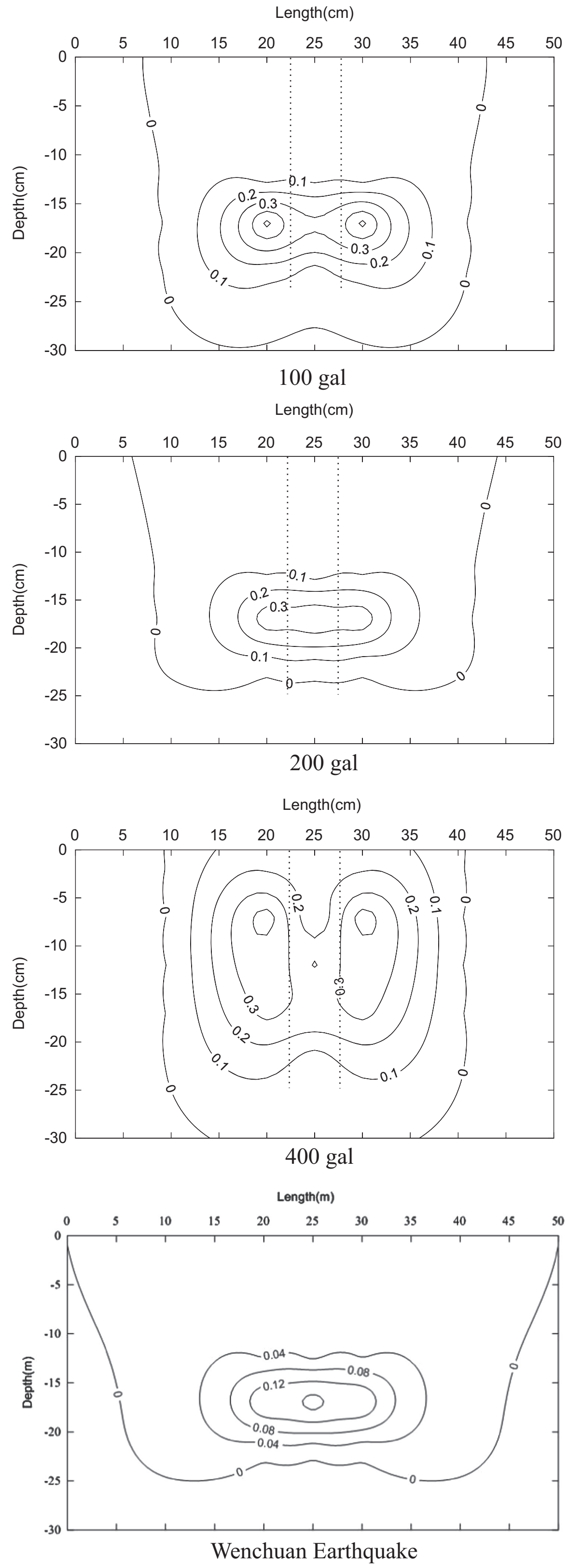

Fig. 7. Temperature maximum changes of the pile foundation during earthquake.

Three 25 m deep boreholes were drilled at the K1026+102 section of the Qingshui-river Bridge from November to December in 2007. The distance from the left (Lhasa direction) pile foundation of the cross-section was 0.5 m, 1.2 m, 11.2 m, respectively. On two occasions each month, continuous

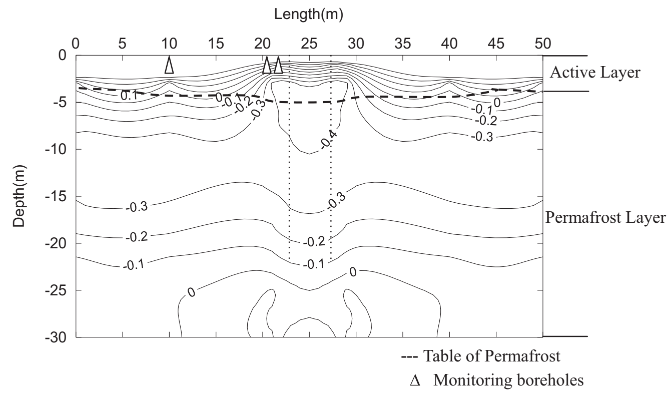

Fig. 8. Distribution of average ground temperature of the monitoring profile from 2008 to 2009.

artificial temperature monitoring was conducted. Fig. 8 shows the distribution of average ground temperature of the monitoring profile from 2008 to 2009. The ground temperature in the section is basically shown the negative gradient type, which can be considered in an endothermic thermal state, and the permafrost has a very high thermal instability. The upper limit of permafrost in this section is 3.2–5.3 m, and thickness of permafrost is 19.5–20.0 m. The minimum temperature is observed at a depth of 8–15 m, and the upper ground temperature is influenced by the atmospheric boundary layer in annual cyclical changes.

A thick layer of warm frozen soil around the pile foundation was found in the shaking table tests. The maximum temperature changes in the distribution for each input motion in the shaking table tests was scaled to the prototype and superimposed to the site temperature monitoring data. Then the temperature field of the pile foundation ground was obtained equivalent to a 5° basic earthquake (0.10 g), a 6° basic earthquake (0.20 g), and a 7° basic earthquake (0.40 g), using the results from the sine-sweep 100 gal, 200 gal and 400 gal (Fig. 9). It is shown that the warming effect led to an increase in the ground temperature around the piles rises to 0 °C or more during an earthquake, and that the upper limit of permafrost around the piles moved down during the earthquake, resulting in significant frozen-thaw deformation.

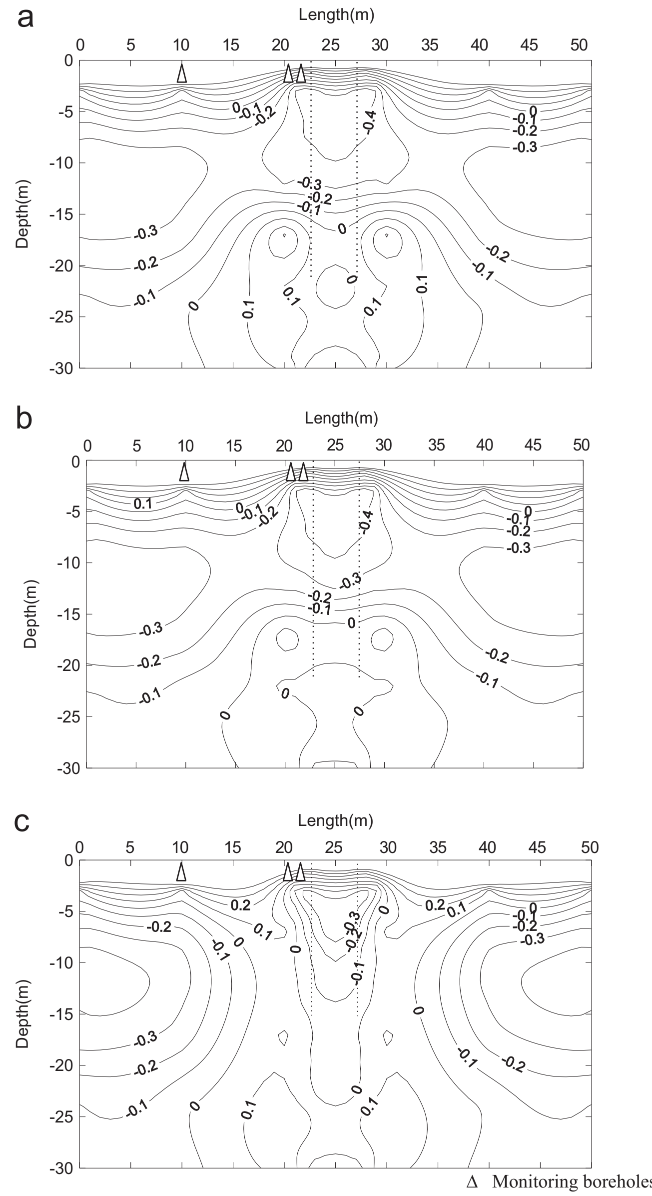

Fig. 9. Temperature field of the pile foundation ground during earthquake. (a) 5° basic earthquake, (b) 6° basic earthquake, (c) 7° basic earthquake.

4.2. Dynamic numerical computation and stability analysis

The monitoring section (K1026 + 102) of the Qingshui-river Bridge was used as an example to carry out a seismic analysis which was simplified to a 2D plane case in a 30 × 50 m area. The computational model used is shown in Fig. 10. The boring sample was comprised of fine sand, silty loam, ice layer and weathered Marlite, as well as sandstone in the computational domain. According to results of the shear wave velocity tests in 14 sections along the Qinghai–Tibet Railway, it is possible to average the shear wave velocities of each layer, both frozen and unfrozen (Wang et al., 2005, 2007). A series of dynamic triaxial tests with cycle refrigeration system for remolded fine sand, silty loam and weathered Marlite which sampled from site at K1026 + 102 section of the Qingshui-river Bridge were conducted using 5 sets of temperatures as normal atmospheric temperatures, −0.5°, −1°, −2°, −5° (Wu et al., 2003; Zhao et al., 2006). Based on the constitutive relationship of material properties against temperature change, the dynamic elastic modulus, dynamic damping ratio and dynamical strength were obtained. The physical and mechanical parameters varied with temperature as shown in Table 1. The mechanical properties of frozen soil are closely connected with temperature, and its strength and deformation changes considerably with minor temperature variations. As such, temperature distributions were first determined by the shaking table tests results. Then, the seismic response of pile foundations was analyzed by employing corresponding mechanical parameters relative to the temperature conditions of the pile foundations. The mesh consisted of plane elements and beam elements. In the dynamic analysis, a viscous boundary was adopted to prevent

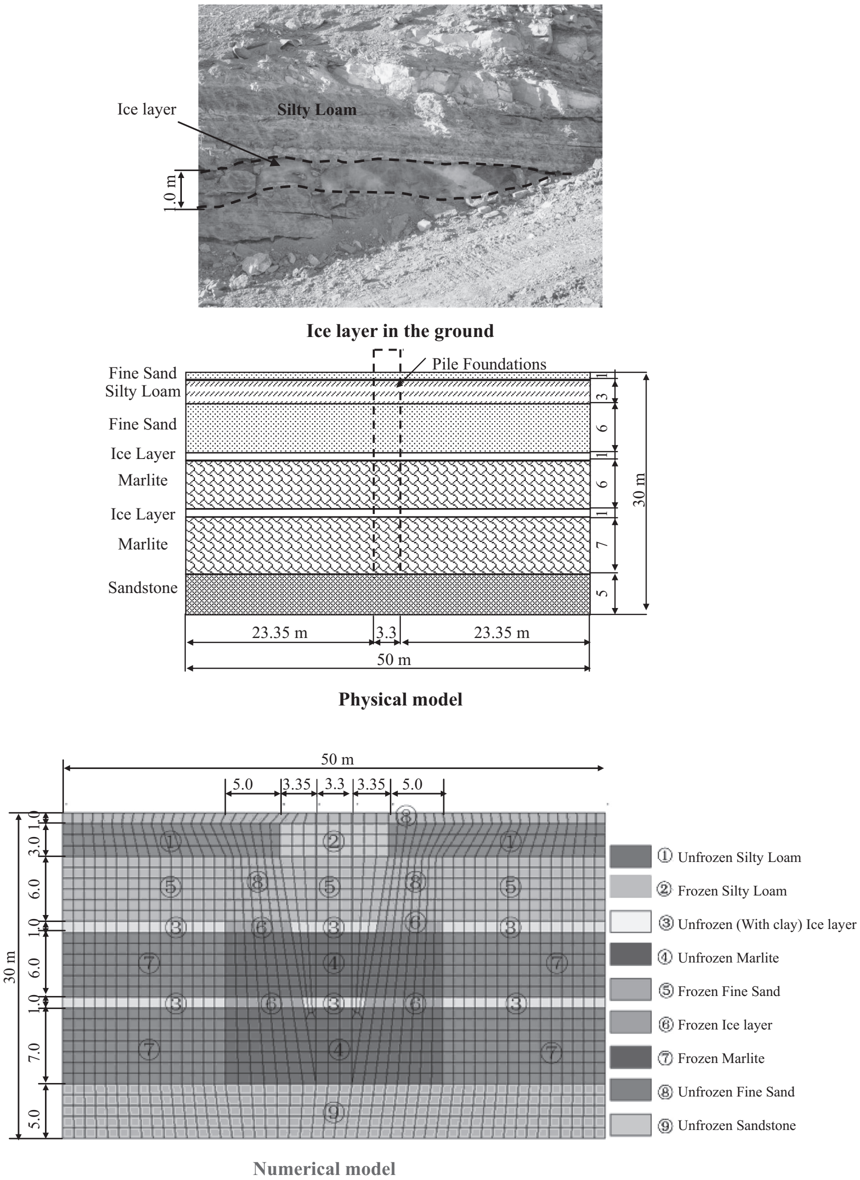

Fig. 10. Pile foundations model.

the reflection of outward propagating waves back into the model and because they do not allow the necessary energy radiation.

In order to evaluate the dynamic stability of the pile foundations, the EW and UD accelerations used here are those which were recorded at the bedrock in the Wenxian Seismic Station, Gansu Province (104.48°N, 32.95°E) during the Wenchuan great earthquake, where is 249 km away from the epicenter. The maximum accelerations used were 428 cm/s^2 in the EW direction and 423 cm/s^2 in the UD direction, respectively (Fig. 11). The EW and UD acceleration records were used as horizontal and vertical motions input from the bottom of the model in the calculations. When $\Delta t = 0.005$ s was used, $f = 7.0$–10.0 Hz and a duration $t = 158$ s was predominant.

Because the seismic response in the region around pile foundations is the matter of most concern, the numerical results in 30×50 m region are given. The acceleration response of the pile foundations is mainly horizontal under horizontal and vertical seismic loading. The contour of maximum horizontal acceleration is shown as Fig. 12. It was found that the maximum values appear at surface of the ground at 16.86 m/s^2 and the minimum values appear between the two ice layers at 2.4 m/s^2.

Similarly, the contour of the vertical displacement of the pile foundations is given in Fig. 13 when the earthquake was just over. The uneven rather than symmetrical settlement distribution of the displacements of the pile foundations reflects the phase differences around the pile foundations.

5. Summary and conclusions

A thermal-dynamic coupled model for seismic response analysis of pile foundations in permafrost regions was developed and applied to the seismic stability analysis of pile foundations of QTR that may experience strong earthquake

Table 1
Mechanical parameters of media in pile foundations model.

Physical variable	Soil type	Shear velocity V_s (m/s)	Density ρ (kN/m^3)	Poisson ratio μ	Dynamic elastic modulus E (MPa)	Dynamic cohesion c (MPa)	Dynamic friction angle φ (°)
Fine sand	Unfrozen(8)	192	19	0.47	216	0.190	2.49
	Frozen(5)	302	19	0.47	468	0.018	16
Silty loam	Unfrozen (1)	196	19	0.47	216	0.246	1.165
	Frozen(2)	313	19	0.47	502.2	0.015	15
Ice layer	Unfrozen (With some clay components)(3)		9	0.3	50		
	Frozen(6)		9	0.3	900		
Marlite	Unfrozen(4)	964	28	0.2	1.03×10^4		
	Frozen(7)	1153	28	0.32	1.03×10^4		
Sandstone	Unfrozen(9)		27	0.27	1.56×10^4		
Reinforced concrete		3500	24.5	0.3	3.0×10^5		

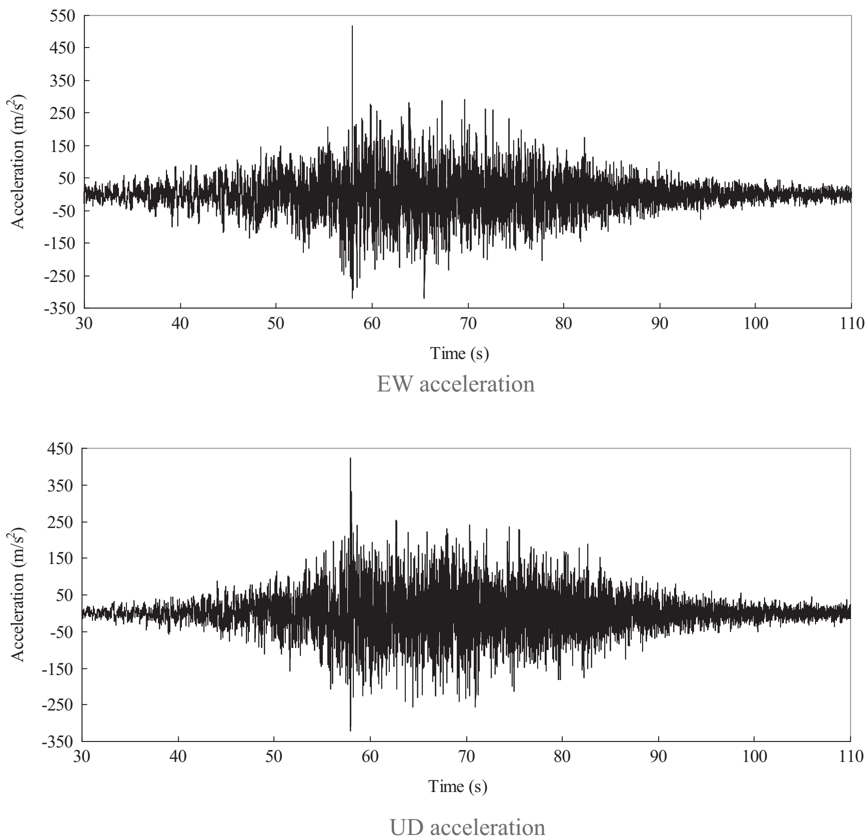

Fig. 11. Earthquake records during the Wenchuan great earthquake.

motion. Through shaking table tests and computations, the following conclusions were obtained.

1. The frozen soil foundation in the scaled model shows a temperature increase response under seismic motion loading. The temperature states of the underlain frozen soil around the pile foundation changed during an earthquake, and the maximum warming was as much as 0.53 °C, and this occurred at the lower part of the file foundation.
2. Based on the shaking table test results of temperature distribution, it was found that a thick layer of warm frozen soil appeared around the pile foundations of the QTR. The stability of the pile foundations of the QTR will be seriously threatened by this layer of warm frozen soil.
3. The ice layers in the permafrost have a strong influence on the acceleration and displacement response, especially while the earth temperature increases. These responses, however, are the result of a much more complex situation.
4. Temperature is an important factor which influences the seismic stability of pile foundation of dry bridges along the QTR. Therefore, it is important to design and construct bridges at permafrost areas with high temperature and high

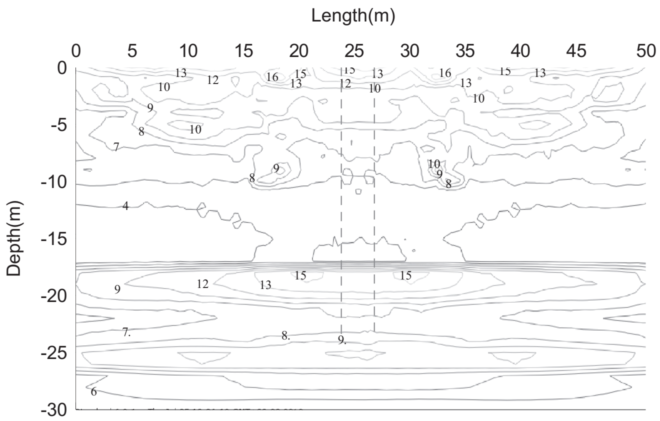

Fig. 12. Horizontal accelerations of the pile foundations when earthquake is over.

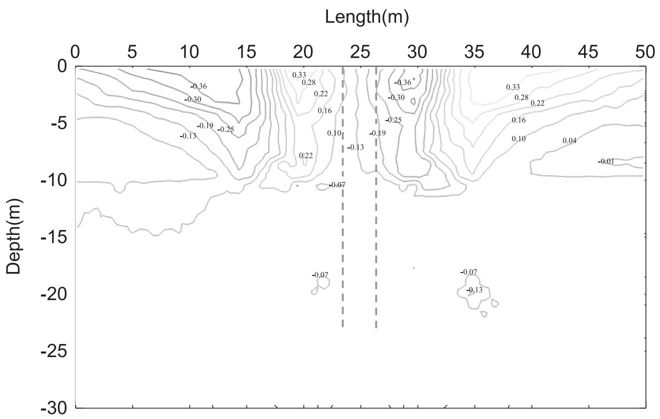

Fig. 13. Vertical displacements of the pile foundations when earthquake is over.

ice content after taking this scientific approach into consideration, and control ling the soil temperature around pile foundation.

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