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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

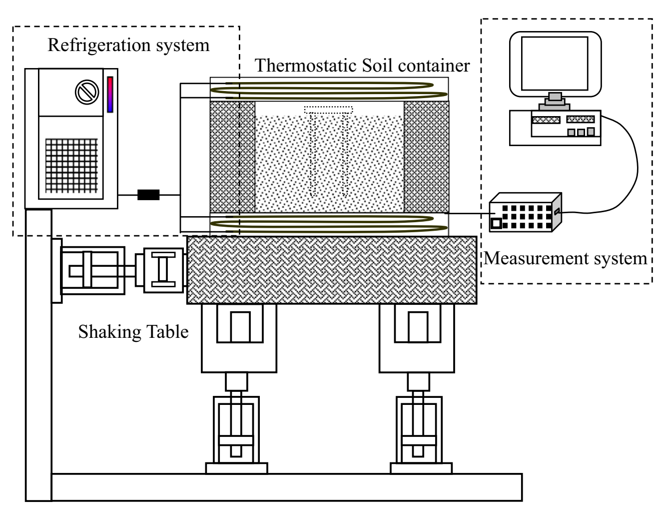

Fig. 1. Shaking table test system.