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The experiment study of frost heave characteristics and gray correlation analysis of graded crushed rock

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ABSTRACT

Traditionally, fine-grained fillings are considered to be susceptible to frost heave. However, most frost heave deformations appeared in the top layer of subgrade of the Harbin–Dalian high-speed railway (Harbin–Dalian HSR), the first HSR running across cold regions in China, indicating that graded crushed rock may also be prone to frost heave. In order to study the frost heave characteristics of graded crushed rock, a series of laboratory experiments on one-dimensional frost heave were conducted in a closed system. Frozen depth and frost heave deformation during the freezing and the moisture content distribution after freezing in a graded crushed rock sample were analyzed. Different factors critical to the development of frost heave, including cooling temperature, moisture content, fine content, and compactness, were used in orthogonal tests. Each factor had three levels. Experimental results showed that different amounts of frost heave occurred across various combinations of factors and levels. The Gray correlation method, which uses the frost heave ratio as a reference sequence and other factors as comparison sequences, was used to determine the correlation degree among these different factors and the optimal collocation which results in the development of frost heave in graded crushed rock. Results from this analysis indicated that moisture content produces the most significant effect on the frost heave ratio of graded crushed rock and that the moisture content of graded crushed rock should be maintained below 5% in order to prevent frost heave development in cold regions.

1. Introduction

The differential deformation caused by frost heave in cold regions can create dangerous conditions for the safe operation of a railway system, especially for a high-speed railway (HSR). Thus, anti-frost measures play important roles in the subgrade design of a newly built or existing HSR in a cold region. Frost heave mechanisms and anti-frost measures in fine-grained soil have been previously studied in detail. For example, Tian et al. (2010) conducted experiments to evaluate the moisture migration and frost susceptibility of fine-grained soils during freezing under dynamic and static loadings. Through freezing–thawing tests of silty clay, Zhao et al. (2012) indicated that for a closed system, the frost heave amount and frost-heave ratio of soil mass with the same water content and dry density increased as freezing temperature increased. Another study by Tezera et al. (2012) confirmed the hypothesis that ice lens formation was initiated by the cracking of the soil in the frozen fringe through frost heave tests with a fine-grained soil. The Takashi equation was adopted as a theoretical foundation to estimate three-dimensional frost heave by Hao et al. (2015), and an anisotropic parameter was proposed to distribute the frost heave ratio in the freezing direction and transverse directions. Zhou et al. (2014) found that in the early beginning of the freezing experiment, a small amount of pore water was discharged from the saturated silt and frost heave did not occur until the amount of the water intake due to cryosuction exceeded the amount of the pore water discharged. Zhou et al. (2013) introduced a new method called soil-bags (bags filled with soil) to prevent frost heave in clayey soil and found that soil-bags can effectively inhibit capillary water and film water migration. Traditionally, coarse soils are considered to be non-frost-heave or mildly susceptible materials. Wang (1986) showed a significant difference in moisture migration between fine-grained and coarse soils, and proposed that a fine-grained content of less than 0.05 mm can be used as a criterion to determine the susceptibility of coarse grained soil to frost heave. Results presented by Xu (1994) indicated that the frost heave ratio is less than 2% when the fine content in coarse grain soil is less than 12%, even under saturated conditions. The frost heave ratio was found to increase significantly when the fine content was greater than 12%. Chen et al. (1988) proposed a power function that can express the relationship between frost heave ratio and fine content, frost penetration rate in sandy gravel. Ye et al. (2007) showed that non-frost-heave soils, such as sand with fine content less than 5%, gravel with fine content less than 15%, and crushed rock, can be used to produce an anti-freezing subgrade layer.

The Harbin–Dalian HSR, whose construction work began on August 2007 and operated since December 2012, is considered to be the first HSR operating at high latitudes and low temperature in winter. The embankment of the Harbin–Dalian HSR adopted measures to prevent frost damage, including measures such as an insulation layer,

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waterproofing and using non-frost-heave fillings. For example, Group A and Group B soils (high quality and good filling materials in China HSR Construction Code) were used in the bottom layer, and graded crushed rock in the top layer of the subgrade bed. These measures were thought to be effective to protect the subgrade from frost damages. However, based on the observation of widespread seasonal frost heave in the Harbin–Dalian HSR subgrade since 2012, with the maximum frost heave reaching 20 mm in January 2013 (Zhang, 2013), Liu et al. (2012, 2014) found that in different parts of the roadbed of the Harbin–Dalian HSR during seasonal freeze–thaw cycles, the maximum seasonal frozen depths were all higher than those measured in the natural ground. The numerical simulation showed that the modified Group A and B soils do not improve the thermal state of the embankment. Based on site observation, Yu (2013) found that deformations of the Harbin–Dalian HSR occurred mainly at the subgrade bed which is composed of graded crushed rock and Group A and B fillings. Similar phenomena were also observed in embankment fillings on the culvert of the Qinghuangdao–Shengyang Passenger-Dedicated Line (Li, 2008) and on the subgrade of the Harbin–Qiqihar HSR (Tian et al., 2014 and Chen and Leng, 2014). For example, the monitoring results from 2012 to 2013 in the Harbin–Qiqihar HSR subgrade showed that a large proportion of the frost heave (85%) was less than 4 mm, the maximum amount reached 12.52 mm, and the deformation mainly occurred in the subgrade surface with large a moisture content. Thus, the frost heave mechanisms of these coarse fillings require more comprehensive studies in order to better explain the observed frost heave. Nie et al. (2013) conducted laboratory experiments on three-dimensional frost heave with graded crushed rock and showed that the frost heave ratio increased with increasing moisture content and increasing fine content. Wang et al. (2014) analyzed the results of frost heave tests for fine round gravel soils with different fine contents and found that the fine round gravel soil displayed little frost heave when the fine content was below 10%. Sheng et al. (2013a, 2013b) proposed that the cyclic dynamic loads can cause the development of the excess pore moisture pressure in the underlying subgrade soils, and result in the formation of ice and continuous frost heave. A soil that is only mildly susceptible to frost according to classification can still generate a significant amount of heave or heaving pressure under favorable environmental conditions. In the current study, laboratory experiments on one-dimensional frost heave were conducted in a closed system to study the frost heave characteristics of graded crushed rock, and more specifically the development of frozen depth, frost heave deformation, and moisture content distributions after freezing. Cooling temperature, moisture content, fine content and compactness were used as influence factors to design an orthogonal test to study frost heave deformations under different conditions. All the experiments were conducted in a close system. In the Harbin–Dalian HSR, the graded crushed rocks lie in the top layer of the subgrade. There are waterproof measures adopted above and beneath this top layer to prevent water intrusion, such as an insulation layer and a composite geomembrane. The frost heave still could be observed in the HSR. Thus, this paper assumed that there is no water supply (a closed system) in the layer of graded crushed rock.

Bao et al. (2012) and Zhao et al. (2007) showed that the gray relation analysis can be used to quantitatively study the influence factors in frozen soil and determine the inherent properties of a system with minimal experimental data and unknown systemic probability. Thus, the gray relation analysis was applied to experimental data to determine the correlation degree among different factors and the optimal collocation for the development of frost heave of graded crushed rock.

2. Test program

2.1. Physical properties test

Graded crushed rock used as a filling for the top layer of the subgrade for the HSR across cold regions in China were collected from the original rock material factory. The grain size distribution for this material is presented in Fig. 1. The maximum grain size was determined to be less than 30 mm.

A modified compaction test device was used for compactness experiments based on the *Code for Soil Test of Railway Engineering* (TB10102-2010) in China (Fig. 2). The dry density versus moisture content was tested for graded crushed rock with fine contents of 3%, 5% and 7%.

2.2. Frost heave test

In order to study the frost heave characteristics of graded crushed rock in a closed system, laboratory experiments on one-dimensional frost heave were conducted using one particular graded crushed rock sample (initial moisture content 7%, cooling temperature −5 °C, and compactness 0.97). Four factors were then chosen to study the frost heave characteristics of graded crushed rock under different conditions: factor A (initial moisture content), factor B (fine content), factor C (cooling temperature), and factor D (compactness). Each factor had three levels, as shown in Table 1. This type of arrangement is called an orthogonal test design (Bao et al., 2012) and allows for determination of the inherent properties of a system with limited experimental data and unknown systemic probability.

2.3. Test process

The frost heave experimental apparatus was comprised of a sample cell, upside and downside cold plates, constant temperature cold baths, cotton insulation, temperature sensors, and a data acquisition system (Fig. 3). The sample cell is made of organic glass with internal dimensions of 20 cm (height) × 15 cm (diameter). Two cold plates were placed in the upside (cold side) and downside (warm side) of the soil sample. Each cold plate was connected to a constant temperature cold bath in order to simulate unidirectional freezing conditions observed in the field. The insulation cotton was wrapped around the sample cell in order to reduce heat exchange between the sample and the external environment. The temperature of the constant temperature cold bath was controlled to an accuracy of 0.1 °C by a computer. Constant temperature antifreeze was circulated around the upside and downside cold plates with the cold bath to maintain a specific soil sample temperature. During the frost heave experiments, temperature sensors were installed inside the sample. Since the environmental temperature is critical to the accuracy of the test, experiments were conducted in a homoeothermic room with dimensions of 3.0 m (length) × 3.0 m (width) × 2.2 m (height). The temperature inside the room was maintained at 1 °C. Two fans were installed in the room to ensure a uniform air temperature.

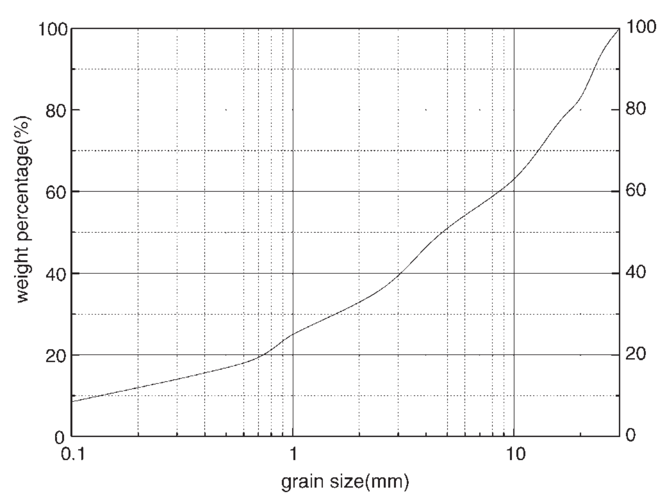

Fig. 1. Grain size of graded crushed rock.