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Model test study on the anti-saline effect of the crushed-rock embankment with impermeable geotextile in frozen saline soil regions

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ABSTRACT

In the road construction in frozen saline soil regions, treatments on both permafrost and saline soils are the main challenges to keep the stability of embankments. The crushed-rock embankment was proved to be an effective cooling measure to protect underlying permafrost layers from thawing. In this paper, as a countermeasure to salt migration and salt expansion, impermeable geotextile was added in the crushed-rock embankment. However, little research work has been done on the cooling and anti-saline effects. Thus, the tests of two embankment models, the crushed-rock embankment with impermeable geotextile and the ordinary filling embankment, were carried out to compare this novel embankment structure with ordinary one. The variation characteristics of temperature, moisture, salt and deformation were investigated, and it was found that their variations were a coupled process. The novel embankment structure showed an efficient cooling effect. Meantime, it can efficiently prevent water and salt from migrating to the upper soil layer. More importantly, it can efficiently alleviate frost heaving and salt expansion, and consequently avoid the appearance of longitudinal cracks. The results will provide a good reference to the widespread application of this novel embankment structure in frozen saline soil regions.

1. Introduction

Permafrost areas, seasonally frozen areas and saline soil areas account for about 22.4%, 55.0% and 2.0% of China's total land area, respectively (Zhou et al., 2000). In permafrost regions, embankment construction may break the heat balance between natural surface and atmosphere, and inevitably induce the warming or thawing of the underlying permafrost layers. Thaw settlement generally results in the instability or failure of road embankments. Thus, it is difficult to construct road embankments in permafrost regions. To protect underlying permafrost from thawing, some cooling techniques and measures have been innovated and put into practice, such as insulation (Wen et al., 2005a), crushed-rock interlayer (Lai et al., 2006; Zhang et al., 2006a), crushed-rock revetment (Zhang et al., 2006b), ventilation duct (Lai et al., 2004; Zhang et al., 2006c; Zhang et al., 2008), and thermosyphon (Pan et al., 2003; Wen et al., 2005b). Through field experiments, these cooling measures have been proved to be successful in protecting permafrost (Sheng et al., 2006; Wu et al., 2008; Xu and Goering, 2008). Compared with other cooling techniques and measures, crushed-rock interlayer separates embankment from ground, and consequently salt cannot migrate from ground to embankment. So, crushed-rock interlayer has possibility in preventing water and salt migration. But, its effect hasn't been confirmed by experiments.

Under the influences of freezing-thawing action and evaporation, salt may migrate from the underlying soil layers to embankments. A large number of tests and engineering practices indicated that due to the changes in soil temperature and moisture, it is rather easy to induce salt expansion and lead to salt expansion damage of the embankment (Li et al., 2009). Thus, special attention should be paid to saline soils in engineering construction. To ensure the stability of road embankments, a series of techniques were employed. Zhang et al. (2011) introduced a method of reinforcement by dynamic compaction replacement, presenting a good reinforcement effect on saline soils. Tan et al. (2011) proposed a series of measures applicable in saline soil regions, such as controlling the salt content and the compactness of filling materials, filling embankment, drainage, slope reinforcement. But, these techniques have no cooling effect, even aggravate thaw of underlying permafrost.

Thus, considering the advantage of crushed-rock interlayer, the crushed-rock embankment with impermeable geotextile was put

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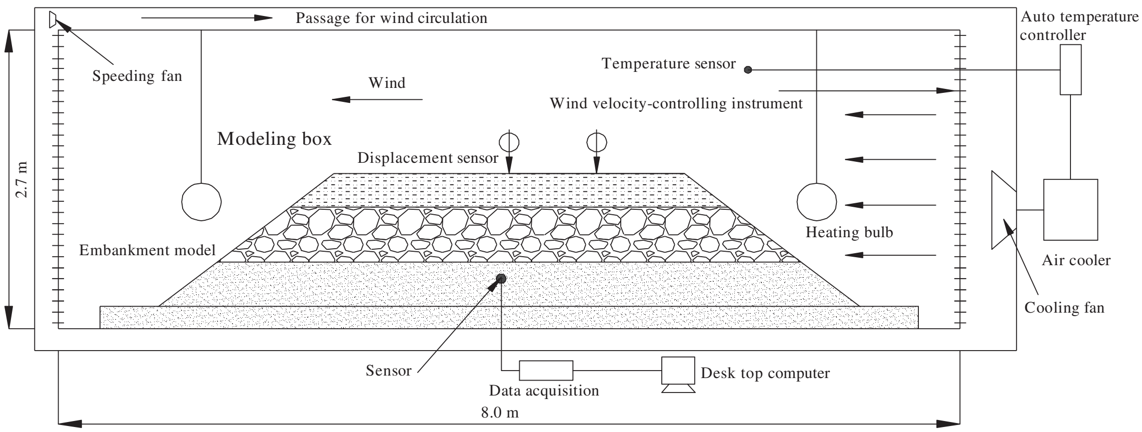

Fig. 1. A schematic diagram of the experimental equipment.

forward in this paper. The effect of the crushed-rock embankment with impermeable geotextile and the ordinary filling embankment on permafrost cooling and preventing saline under the same test conditions were investigated by comparing the temperature, the change laws of moisture and salt concentration, and deformation according to related specifications and an approximate similarity method. The research results show the crushed-rock embankment with impermeable geotextile to be suitable for using in frozen saline soil regions.

2. Experimental design

2.1. Experimental equipment

The experimental equipment was composed of four parts: a heat-insulation box, a ventilation system, a temperature-controlling system and a data-acquisition system, as shown in Fig. 1. The dimension of the box was 8.0 m × 1.9 m × 2.7 m. The ventilation system consisted of cooling fans, speeding fans, wind velocity controlling instruments and a passage for wind circulation. The wind direction was parallel to the longitudinal direction of the box. The temperature-controlling system consisted of a double head SANYO compressor (7.5 kW), an automatic temperature controller (precision: ± 0.3 °C) with a temperature sensor (precision: ± 0.1 °C), Freon circulation pipes and an evaporator. The temperature controller kept the inner ambient temperature closed near the design temperature. The data-acquisition system was composed of 46 temperature sensors (thermistor, precision: ± 0.05 °C), 16 Hydra Probe Soil sensors (manufactured by Stevens Water Monitoring Systems, Inc., operating temperature: -30–65 °C) which were used to measure temperature (precision: ± 0.6 °C), moisture content (precision: ± 0.003), and electrical conductivity (precision: ± 0.0014 S/m), 4 displacement sensors (manufactured by Shanghai TM Automation Instruments Co., Ltd. precision: ± 0.001 mm, measurement range: 0.001–50 mm), three data loggers (DT500, Datataker Inc., Australia), and a desktop computer. Data were automatically collected by the data loggers at an interval of 20 min.

2.2. Experimental models

In order to investigate the cooling and anti-saline effect of the crushed-rock embankment with impermeable geotextile, two physical embankment model tests were designed for comparison: one was the crushed-rock embankment with impermeable geotextile and the other one was ordinary filling embankment. The two test embankments had the same size. Fig. 2(a) shows the crushed-rock embankment with impermeable geotextile, while Fig. 2(b) presents the ordinary filling embankment. The two tests were designed according to related specification and an approximate similarity method (Zhang et al., 2008). The geometric size and time were 1/4.93 and 1/24.33 of the practical ones, respectively. The crushed-rock embankment with impermeable geotextile was divided into three layers. The lowest layer was saline soil containing high-content sodium sulfate with a thickness of 20 cm. The middle layer was crushed-rock interlayer with a thickness of 40 cm, and the grain sizes ranged from 15.3 cm to 22.6 cm. The upper layer was the undisturbed soil containing low-content sodium sulfate with a thickness of 20 cm. Impermeable geotextile was laid between the saline soil containing high-content sodium sulfate and crushed-rock interlayer, and permeable geotextile was laid between the undisturbed soil and crushed-rock interlayer. The interface between the undisturbed soil and the top surface of crushed-rock interlayer was taken as the upper boundary of data analyses while the one between the bottom surface of crushed-rock interlayer and soil containing high-content sodium sulfate was taken as the lower boundary of data analyses. The ordinary filling embankment was composed of two layers. The lower layer was saline soil containing high-content sodium sulfate with a thickness of 20 cm, and the upper layer was the undisturbed soil with a thickness of 60 cm. Meanwhile, saline soil containing high-content sodium sulfate had a good contact with the undisturbed soil. In order to compare the water and salt migration of the two embankments, the location in the ordinary filling embankment with the same height as the upper boundary of the crushed-rock embankment with impermeable geotextile was taken as its upper boundary of data analyses. And, the interface between the undisturbed soil and soil containing high-content sodium sulfate was taken as the lower boundary of data analyses. Fig. 3 is a photo of the two test embankments. Fig. 3(a), (b) and (c) are the two test embankments, impermeable geotextile and crushed rock layer, respectively.

The undisturbed soil was silty clay (water content 12.8%, dry density 1.92 $g{\cdot}cm^{-3}$) which was taken from Beiluhe on the Qinghai-Tibet plateau. The liquid limit and the plastic limit were 34.7%, and 19.2%, respectively. The plastic index was 15.5. The particle size distribution was shown in Fig. 4. The particle size had a range from 0.275 to 549.541 μm, the specific surface area was 1.5 $m^2{\cdot}g^{-1}$, and the mean volume diameter was 62.033 μm. The saline soil containing high-content sodium sulfate was silty clay, the water content was 25%, dry density was 1.92 $g{\cdot}cm^{-3}$, and the concentration of sodium sulfate was 7.0%.

In order to observe the variation characteristics of temperature, moisture, salt concentration and deformation, some sensors were placed in the mid-cross sections of the two test embankments, as shown in Fig. 2. According to the long-term observed results of the in-situ temperature conditions (Cheng et al., 2003; Niu et al., 2006), the annual average temperatures of frozen saline soil regions ranged from − 4.0 °C to − 6.5 °C, so the ambient temperature in the modeling box was designed as follows: