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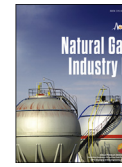

Research Article

An open frozen–heave test on the pipeline foundation soils in the permafrost regions[☆,☆☆]

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Abstract

In the Da Hinggan Mountains, the safe and smooth operation of shallowly buried oil pipelines is threatened greatly by the frozen–heave damage derived from frozen soil. At present, a closed frozen–heave simulation test is often carried out in China, with water content and dry density of samples being assumed to be constant. However, an open frozen–heave test, all the factors of which change as the test goes on, can reflect the real frozen–heave damage more accurately. In this paper, the open frozen–heave test was carried out on five types frozen soil along the China–Russia Crude Oil Pipeline to measure the frozen–heave factor and water content of each soil sample and accordingly analyze their relationship. Besides, its test results were compared with that of the closed frozen–heave test. Then, the normal frozen–heave force was measured by using the displacement limiting method, and this measurement was compared with the result of the static equilibrium test. Finally, a difference significance test was conducted. It is shown that the frozen–heave factor of the open test is higher than that of the closed test; the frozen–heave factor of fine grained soil has a significant effect on the frozen–heave factor of soils, and the frozen–heave factor increases as the capillary effect or the swabbing action of soil increases; the frozen–heave factor of coarse grained soil is mainly dependent on the mud content, and it is lower than that of fine grained soil; the value of frozen–heave force is in close relation with the test methods and the sample height; it is indicated that the open frozen–heave test is more applicable to the investigation on the frozen–heave of the foundation soils of pipelines in the Da Hinggan Mountains. It is concluded that the soils for the cushion and digging/packing layers of the pipelines in the permafrost regions shall be acted by the gravel or detritus with lower mud content, and waterproof and draining pipeline jetty shall be made from the clay soils with a higher plasticity.

Keywords: Open frozen–heave test; Closed frozen–heave test; Displacement limiting method; Static equilibrium method; Frozen–heave factor; Normal frozen–heave force; Regression analysis; The *t* test

1. Introduction

The China–Russia Crude Oil Pipeline is one of the four major strategic energy channels for China and also a strategic route for the import of crude oil by land in the northeast of China. The pipeline crosses the permafrost zone in the northern Da Hinggan Mountains. This region is characterized by extensive vegetation and abundant precipitation, criss-crossing surface water systems, and extremely active groundwater, especially shallow groundwater. The permafrost here is relatively thin. The average annual ground temperature

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is generally high, and the seasonal temperature difference changes greatly. The maximum freezing-thawing depth of the active layer exceeds 3.5 m, or even 5 m locally. There is an extremely harsh permafrost environment. Many researches have been made on the permafrost along the China–Russia Crude Oil Pipeline in China, and a conclusion has been made that the thaw settlement of frozen soil is the main factor affecting the normal pipeline operation. Jin Huijun et al. [1] argued that the differential thaw settlement and frozen–heave of oil pipeline in the permafrost region are the key technical problems in pipeline engineering. The Permafrost Physics Laboratory of Jilin University conducted a thaw settlement test on several typical undisturbed frozen soil samples along the China–Russia Crude Oil Pipeline [2–6] and many closed frozen–heave tests on several typical soils in the seasonal permafrost region along the pipeline [7–11]. They worked out *The Frozen Soils Test and Frozen Damages Investigation* [12]. However, the operation of the China–Russia Crude Oil Pipeline is not affected by the thaw settlement of frozen soils. Instead, serious deformation and destruction caused by freezing have occurred. Even some parts of the pipeline in the northern section are arched to the surface and broken, causing oil leakage. It shows that frozen–heave damage that occurs to seasonal active layers poses the greatest threat to the safety and stability of shallowly buried oil pipelines as light linear structures. At present, a closed frozen–heave simulation test is often carried out in China [13–15]. The authors conducted an open frozen–heave test instead to study the frozen–heave sensitivity of frozen soil along the China–Russia Crude Oil Pipeline. The open test results are compared with the closed test results in 2007 to analyze the advantages and disadvantages of the open frozen–heave test in studying the frozen–heave of the foundation soils, so as to provide reference for the design and research of the double track of the China–Russia Crude Oil Pipeline.

2. Open frozen–heave test

2.1. Properties of test soils

The soils used for this frozen–heave test were mainly taken from the vicinity of Tahe County along the China–Russia Crude Oil Pipeline. Having gone through steps like air-drying, crushing and removal of oversized soils, the test soils were subject to the test of physical and mechanical indexes in accordance with relevant regulations [16]. The physical and mechanical indexes of each soil are shown in Table 1, where No.2 soil was taken from the front edge of the second terrace in the Songhuajiang River in Taolaizhao, Jilin Province.

2.2. Test instruments and equipment

One-way freezing and temperature drop rate control are two basic requirements of a standard frozen–heave test. The instruments and equipment used need to simulate the one-way frozen conditions under the action of semi-infinite body surface cold source and should be able to control the temperature drop rate. To meet the requirements above, the instruments and equipment used in this test mainly consist of the following components:

1) A temperature control system: an incubator and cold bath devices. The incubator provides a constant temperature environment for the test. It is made of stainless steel clip insulation materials and is equipped with a small refrigeration compressor, a light bulb, a fan and a temperature controller inside. The cold bath devices control the end temperatures of samples, and the main equipments are DC3030 and THD2015 low-temperature and thermostatic tanks, and the accuracy of all the equipments is up to 0.1 °C.
2) A temperature measurement system: The test used a thermocouple with PZ158 or a PZ126 DC digital voltmeter or a thermistor with FLUCK187 or a 287 digital multimeter to measure the temperature of soil samples.
3) Sample boxes: Each container of soils is made from a PMMA tube, a steel pressure plate, rods and a copper top cover.
4) A water supply device: It is a Mariotte bottle connected with the base of the sample tube.
5) Deformation measurement devices: The deformation readings were measured by a dial gauge or a displacement meter. The normal frozen–heave test used a BHR-4 load sensor and a GGD-331 peak ergometer.

2.3. Selection of test methods

Depending on the presence of moisture, frozen–heave tests are classified into a closed test and an open test. The advantage

Table 1
Basic physical and mechanical indexes of test soils.

Samples	Liquid limit	Plastic limit	Plasticity index	Relative density	Grain fineness distribution/mm								Name
					>20.0	10.0	5.0	2.0	0.5	0.25	0.075	<0.075	
No. 1	27.5%	17.2%	10.3	2.69									Silty clay (including sand)
No. 2	33.8%	20.8%	13.0	2.70									Silty clay
No. 3	26.0%	17.7%	8.3	2.68					4.4%	4.0%	24.7%	66.9%	Silt (sticky sand)
No. 4				2.65				16.5%	29.4%	17.5%	32.9%	3.7%	Medium sand
No. 5				2.64	22.4%	18.6%	14.5%	15.4%	8.2%	2.6%	6.3%	12.0%	Fine grained soil breccia