Effect of stress and temperature history on creep behavior of straight and enlarged-base anchors in frozen silty soil

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ABSTRACT
The objective of this project was to study the pullout creep behavior of different types of anchors embedded in a frozen silty soil. A 16 mm diameter cylindrical steel rod and a hybrid anchor with an enlarged cone-shaped base were tested at temperatures ranging from -1.2 to -0.5°C. The data for the cylindrical anchors was found to be in close agreement with that reported in the literature. Important decreases in the creep rate were recorded for the enlarged-base anchor, particularly at -1.2°C. A significant reduction of the creep rate was also observed after rest periods following cyclic changes in temperature.

RÉSUMÉ
Le but de ce projet de recherche était d'étudier le comportement au fluage, en soulèvement, d'ancrages de différentes géométries dans un soil silteux gelé. Un ancrage cylindrique constitué d'une barre en acier de 16 mm de diamètre ainsi qu'un second encrage possédant une base élargie de forme conique ont été étudiés à des température de -1,2°C et -0,5°C. Les comportements au fluage de l'ancrage cyclindrique qui a été observés se sont montrés en accord avec les résultats obtenus dans une étude raportant des données d'essais de terrain. Des aténuations significatives des taux de fluage ont été observés lors des essais effectués sur l'ancrage ayant une base conique, particulièrement pour les températures de -1,2°C. Aussi, des réductions importantes des taux de fluage ont été observées après des périodes de repos lors de l'alternance de la température d'essai.

1 INTRODUCTION

The development of arctic regions in the northern portion of the province of Quebec, Canada, will unavoidably occur in the decades to come. This will lead to the construction of new hydropower plants and electrical distribution infrastructures beyond the 50th parallel. In order to reduce the cost of construction, engineers may choose to build guyed transmission towers in which guyed cables transfer uplift forces to the frozen ground, where deformation under constant loading (or creep) may be significant. It must also be emphasized that the mechanical response of this system may change with the rise of ground temperatures resulting from global climate warming.

The purpose of this paper is to present the results of an experimental study on the pullout response of two types of anchors embedded in a frozen silty soil at temperatures close to 0°C.

2 BACKGROUND

The presence of ice in permafrost allows for a phenomenon know as adfreeze strength, which results from the adhesion of two surfaces by ice. Depending on the temperature of the permafrost and the type of contact surface, adfreeze strength can be in order of 100 to 150 kPa at -1°C, and reach 200 to 300 kPa at -4°C (Andersland et al. 1978). In addition to adfreeze strength, ice rich permafrost is susceptible to a viscoplastic deformation, known as creep. This deformation is ascribed to a shear distortion of ice crystals in a connected ice matrix. Most laboratory creep studies have been conducted under uniaxial loading conditions. Figure 1 presents the commonly encountered stages of creep under uniaxial stress conditions at constant temperature. Stage I (primary creep) represents a creep rate that is decreasing in time, stage II represents a steady creep rate, and stage III represents creep rates that increase with time and often leads to failure. Creep is mainly influenced by soil temperature, applied stress, soil type and ice content. As a result, pile or anchor design in permafrost is often controlled by creep deformation criterion and not maximum load criterion.

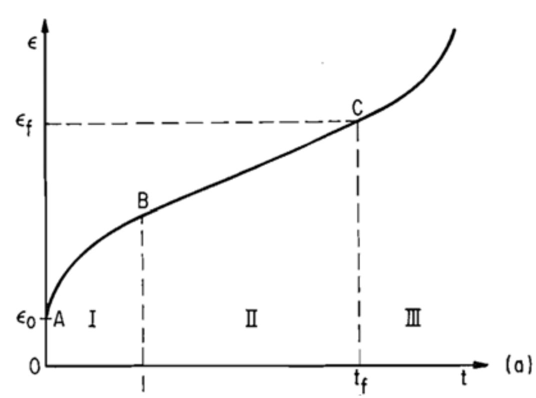

Figure 1. The three stages of creep behavior (Ladanyi 1972).

It is commonly accepted that creep rate in polycrystalline ice can be described by Glen's flow law:

$$\dot{\varepsilon} = B\sigma^{n} \qquad [1]$$

where $\dot{\varepsilon}$ is the axial or shear strain deformation rate, σ is the stress, *B* is the temperature dependent ice hardness parameter, and *n* is the creep exponent .

It is also commonly accepted that creep deformations (ε) are divided into two terms:

$$\varepsilon = \varepsilon^{(i)} + \varepsilon^{(c)} \qquad [2]$$

where $\varepsilon^{(i)}$ is the pseudo-instantaneous strain and $\varepsilon^{(c)}$ *is* the strain associated to creep law.

2.1 Type of anchors in permafrost

In permafrost engineering, anchors can be divided into two categories: surface anchors and deep anchors. In the case of surface anchors, also referred to as mass-gravity anchors, a weight of rock, a boulder pile or a granular embankment is applied over a deadman anchor or a steel frame. Although these anchors are not affected by creep, they must be installed in areas that are not affected by frost heave or seasonal thaw. In the case of deep anchors, the anchors are seated deep enough to avoid the effects of both frost heave and seasonal thaw. These latter types of anchors can be divided into three categories; i) plate anchors that are generally installed in excavated holes, which are backfilled with a soil-water mixture or a compacted moist soil that will refreeze in contact with the permafrost, ii) helical anchors with single or multiple helixes that can be screwed into the permafrost, and iii) grouted rod anchors that are placed in augered or drilled holes. In this type of anchor, anti-heave devices must be installed to avoid uplift forces in the seasonal freezing zone.

2.2 Studies of creep in permafrost

Johnston and Ladanyi (1972) conducted a field study on 18 grouted anchors installed at two different sites in the province of Manitoba, Canada (9 anchors at Gillam and 9 anchors at Thompson). Both sites lie within the discontinuous permafrost zone. The soil profile at the Thompson site consisted of stratified layers of silt and brown clay whereas the soil at the Gillam site was a brown to grey silty clay. The mean ground temperature at both sites was approximately equal to -0.55°C.

The anchors consisted of #14S reinforcing bars that were placed in 15 cm diameter boreholes, and grouted with a mixture of water, early-strength cement and clean medium-to-coarse sand to lengths varying from 2.5 to 3 meters. Of the 18 anchors, ten were tested with a constant axial load until failure and one was stage-loaded. Under sustained loading, anchors from both sites showed typical responses with distinct primary, secondary, and tertiary stages. Although the secondary stage creep was very short at larger loads, it was most prevalent at smaller loads. The test duration at the Thompson site varied from less than one hour to 4 hours (stage-loaded test lasted 110 hours) whereas it varied from 2 hours to about 1500 hours at the Gillam site.

3 MATERIALS AND METHODS

3.1 Experimental setup

In the current study, two different types of anchors were tested (Fig. 2). The first of these anchors consisted of a 16 mm diameter, 525 mm long, cylindrical steel rod. The second cone-shaped anchor consisted of a 60 mm long truncated cone with a 50 mm diameter base, which was threaded to a 16 mm diameter, 500 mm long, cylindrical steel rod. Threads were also used to join the upper portion of the anchors to a 30 mm ball joint.

The tests were conducted with a cylindrical steel container, a loading frame, and a pneumatic loading system with an air chamber and a pressure regulator. The container was 600 mm in diameter, 600 mm in height, and had a wall thickness of 10 mmThe anchors were connected to a steel plate using a ball-and-socket joint and the plate was attached to the load cell. This loading system was found to provide a constant load during anchor displacement.

Soil temperature within the container was measured on three level at three different points on a horizontal plane. The first thermistor was placed a few centimeters from the wall of the container, the second was placed close to the anchor whereas the third thermistor was set mid-distance between the latter two. The displacement of the anchor was measured with two linear variable displacement transducers (LVDT), and the applied load was measured with an electronic load cell. All of the data was recorded using a data acquisition system.

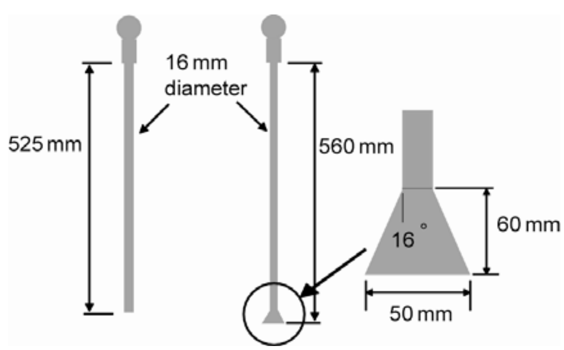

Figure 2. Geometry of the tested anchors.

3.2 Sample preparation

The silty soil consisted of an industrial limestone filler for which 100% of particles are smaller than 10 μm, and 18% are smaller than 1 μm. The median diameter of the material is equal to 3 μm. The limestone filler was mixed in a concrete mixer with a water content of 50%. A sufficient amount of soil (0.065 m^3) was prepared to ensure an anchor embedment of 200 mm.

In order to ensure adequate temperature control, the testing equipment was installed in a cold room, at -10°C. Six independently computer-controlled heating cables were used to control frost progression, and maintain constant temperature conditions. The samples were frozen from bottom to top to avoid large internal stresses. Three days were generally required to freeze the sample, and reach testing temperatures.

4 EXPERIMENTAL PROGRAM

The straight anchor was initially embedded in the sample, and then subjected to a series of constant loading tests at different temperatures. Upon completion, the sample was thawed, removed form the container, and thoroughly mixed. The cone-shaped anchor was then embedded in the soil and subjected to a series of creep tests that lasted for more than five months.

4.1 Creep tests on a straight anchor

The sample with the straight anchor was subjected to creep tests at temperatures of -1.2 and -0.5°C. Table 1 presents the applied loads for the different temperatures. At the end of the creep tests, a pullout test was performed at a temperature of -0.5°C using a step load of 0.25 kN/min.

4.2 Creep tests on an enlarged-base anchor

In order to observe the creep behavior of the enlarged-base anchor, the creep tests were conducted at alternating temperatures. Table 2 shows the different cycles of alternating temperature and loading conditions . As shown in Table 2, the temperature is set equal to -1.2°C during cycles 1, 3, 4 and 6 whereas the temperature of the other cycles is set equal to -0.6°C. With the exception of cycle 2a, the anchor was unloaded during temperature changes In the specific case of cycle 2a, a constant load of 1.5 kN was applied. The first serie of creep tests (cycle 1) was performed at a temperature of -1.2°C. For cycles 1 to 3, loads were applied for periods of time varying between 5 to 190 hours. In cycles 4 to 6, the load was applied for longer periods (up to 300 hours) . As with the straight anchor, a pullout test was conducted at the end of the creep tests.

5 RESULTS

5.1 Freezing of the laboratory silty soil

Initial freezing of the samples resulted in frost heave ranging from 70 to 80 mm at the center of the container. The straight anchor was also shown to move upwards by 30 mm whereas the enlarged-base anchor remained immobile. The enlarged part of the anchor may have locked all possible uplift movement during freezing, which occurred from bottom to top. Given these changes, embedment depths of 250 and 270 mm were used for the shear strength calculations of the straight and enlarged-based anchors, respectively.

Table 1. Experimental program for creep tests on a straight anchor.

Temp (°C)	Load (kN)	Duration (hrs)	Remark
-1.3/-1.1	2.0	35	
-0.5	1.0	24	
-0.5	1.25	22	
-0.5	1.,50	8	
-0.5	1.75	27	Test stopped when entering stage 3 creep

Table 2. Experimental program for creep tests on an enlarged-base anchor.

Cycle	Temp (°C)	Load (kN)	Duration (hrs)	Remark
1	-1.2	1.0	5,7	
		2.0	43	
		3.0	5,3	
2	-0.6	1.0	47	
		1.5	70	
2a	-0.6/-1.2	1.5	150	See note
3	-1.2	2.0	66	
		3.0	192	
		3.5	143	
	-0.6	Change of temperature/ no loading		
4	-1.2	1.5	23	
		3.0	192	
		4.5	311	
5	-0.6	1.0	40	
		1.5	313	
		2.5	245	
		3.0	185	
6	-1.2	1.5	48	
		3.0	216	
		4.5	311	
7	-0.6	1.0	71	
		1.5	24	

Note: Change of temperature with load applied

5.2 Straight anchor response

Table 3 presents the creep rate results for the tests on the straight anchor. As shown on figure 3, the temperature at the beginning of the test was not stabilized resulting in a slight change of the creep rate with time. Yet, after stabilizing at -1.1°C, the displacement is shown to be a linear function of time (constant creep rate). Figure 4a gives an overview of the applied loads and displacements at a temperature of -0.5°C whereas Figure 4b provides a detailed view of displacements smaller than 1 mm. The results show no primary creep stage for any of the load increments. After applying the final load, the creep rate remains constant for a few hours, and then increases significantly as it enters the tertiary creep phase.

Upon completing the creep test, the straight anchor was subjected to a pullout test. As shown in Figure 5, the anchor begins to slide as the load reaches 2.5 kN, and fails as it reaches 3.0 kN. These loads resulted in shear stresses of 200 and 240 kPa, respectively.

Table 3. Results of the creep tests on the straight anchor.

Temperature (°C)	Load (kN)	Shear stress (τ) (kPa)	Creep rate (mm/year)
-1.3/-1.1	2.0	160	134/178
-0.5	1.0	80	65
-0.5	1.25	100	78
-0.5	1.5	120	297
-0.5	1.75	140	1300[1]

[1]Evaluated just before entering into the tertiary creep phase.

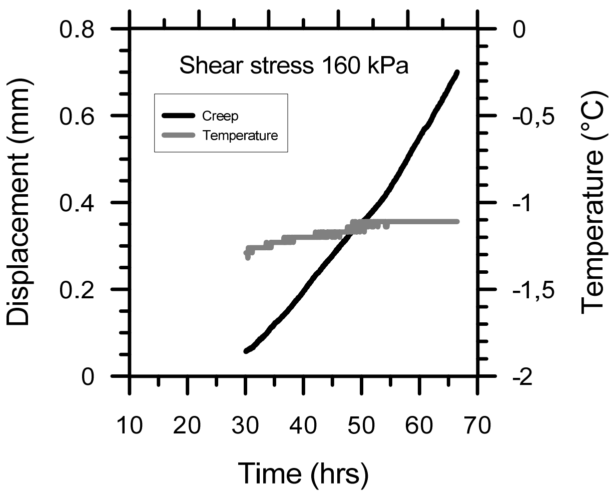

Figure 3. Creep test results for the straight anchor at a temperature of -1.3/1.1°C.

5.3 Enlarged-base anchor response

Figure 6 shows the evolution of the displacement, load and temperature with time during the creep test with the enlarged-base anchor. The total displacement is shown to be equal to 5 mm. The computed creep rates are given in Table 4. It must be noted that displacements often stabilised with time at temperatures of -1.2°C. Loads of 1,5 or 2 kN resulted in very small displacement variations, making creep rate evaluation difficult.

Figures 7 and 8 show the typical response of the enlarged-base anchor at temperatures of -0.6 and -1.2°C,respectively. As shown, significant displacement occurs at each load increment. At a temperature of -0.6°C, the anchor rapidly reaches a constant creep rate whereas the creep rate decreases with time at a temperature of -1.2°C.

The decrease in creep rate is most noticeable at an applied load of 3.0 kN. As expected, the temperature has a significant effect on the creep rate.

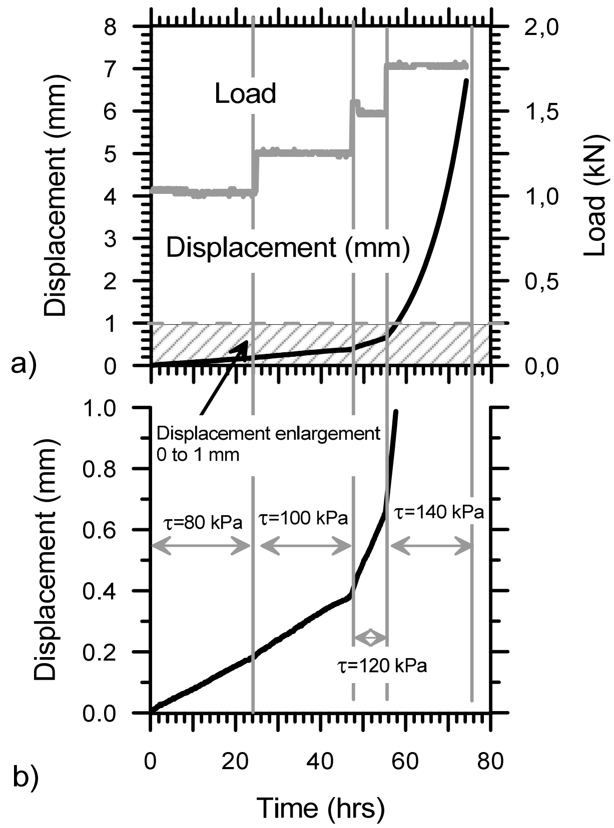

Figure 4. Creep test results for the straight anchor at -0.5°C.

For instance, the creep rate at 3 kN decreases by a factor of 6 as the temperature decreases from -0.6 to -1.2°C.

5.4 Repeated loading

As mentioned above, the test with the cone-shaped anchor consisted of seven load cycles with alternating temperatures. Figure 9 shows the results during different cycles at a temperature of -0.6°C. The results for the straight anchor are also shown for comparison purposes. The response of the cone-shaped anchor during cycle 5 is highly influenced by cycles 3 and 4. In fact, the creep rate during this cycle is approximately 5 mm/year at an applied load of 1.5 kN whereas it was equal to 60 mm/year during cycle 2. It must be noted that the creep rate decreases to 2 mm/year during cycle 7

Figure 10 presents the results for three load cycles at a temperature of -1.2°C. As shown, the creep rate decreases with time and almost reaches zero at an applied load of 3 kN. Cycles 3 and 4 also lead to very similar displacements. At an applied load of 4.5 kN, the creep rate is significantly different during cycles 4 and 6.

Significantly different creep rates are observed at the same temperature and load. This can most probably be ascribed to changing soil properties in the vicinity of the base of the anchor.

Figure 11 shows the results of the pullout The displacements are generally negligible at loads smaller than 3 kN. Although the displacement rate increases as the load reaches 6 kN, the anchor does not fail.

6 DISCUSSIONS

6.1 Straight anchor

In the case of the straight anchor, the pullout strength is clearly the result of the adhesion of the anchor surface and frozen soil. This can be substantiated by comparing the results with those of Johnston and Ladanyi (1972). As generally suggested in the literature, the displacement rates are normalized by dividing the results by the radius of the anchor. As shown in figure 12, the creep test results obtained in this study are in a good agreement with those found in Johnston and Ladanyi (1972). The data is generally well described by a power law in which the exponent is equal to 8.

It must be noted that the lack of initial, or pseudo-instantaneous, displacement upon loading is most likely ascribed to the rigidity of the 16 mm diameter steel anchor.

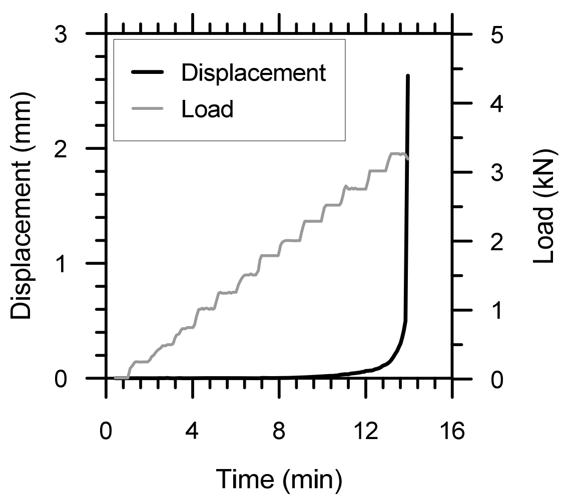

Figure 5. Pullout test on the straight anchor at a temperature of -0.5°C.

6.2 Cone-shaped anchor

The cone-shaped portion of the anchor has a significant effect on creep behavior. As previous highlighted, the creep rate of the cone-shaped anchor was more than 5 times smaller than that of the straight anchor at an applied load of 1.5 kN. The effect of the cone-shaped portion of the anchor is even more significant at a temperature of -1.2°C. In addition to the smaller creep rates, the displacement of the cone-shaped anchor was shown to be nonlinear rather than linear. This nonlinear response is similar to that found for power-installed screw anchors at the Thompson site (Johnston and Ladanyi 1974), and can be ascribed to pseudo-instantaneous strain. It is thus not ascribed to the adfreeze strength on the straight portion of the anchor for which the bond is essentially brittle (Ladanyi and Thériault 1990). The resistance of the anchor can therefore be ascribed to its cone-shaped base. Despite the fact that it has a cone shape, an analogy can be made with the behavior of a screwed anchor for which the base resembles that of a plate or cylinder. Figure 13 compares the normalised creep rate as a function of stress (Q/A) for both cone-shaped and screwed anchors. In contrast to that shown earlier for a straight anchor, the relation is shown to follow a hyperbolic law. The normalised creep rate for cycle 2 is generally similar to that observed for a 15 inch screwed anchor. The smaller displacement rates of the 8 and 10 inch screwed anchors, on the other hand, are most likely due to the difference in shape and rigidity of the anchor.

In short, the response of the enlarged-base anchor is similar to that found for screwed anchors. In addition, the response of the anchor is found to be highly dependent on temperature and loading conditions, which may alter the properties of the frozen soil. The manner in which permafrost properties evolve with stress and temperature is still unclear and warrants further investigation.

Table 4. Creep test results for the cone-based anchor

Cycle	Test temperature (°C)	Load (kN)	Creep rate (mm/year)
1	-1.2	1.0	*
		2.0	*
		3.0	**
2	-0.6	1.0	35
		1.5	58
3	-1.2	2.0	*
		3.0	4
		3.5	6
4	-1.2	1.5	*
		3.0	3
		4.5	8
5	-0.6	1.0	1.3
		1.5	5.5
		2.5	17
		3.0	20
6	-1.2	1.5	*
		3.0	0.8
		4.5	1.7
7	-0.6	1.0	1
		1.5	2

Note: * small displacement variation
** test stopped during creep attenuation

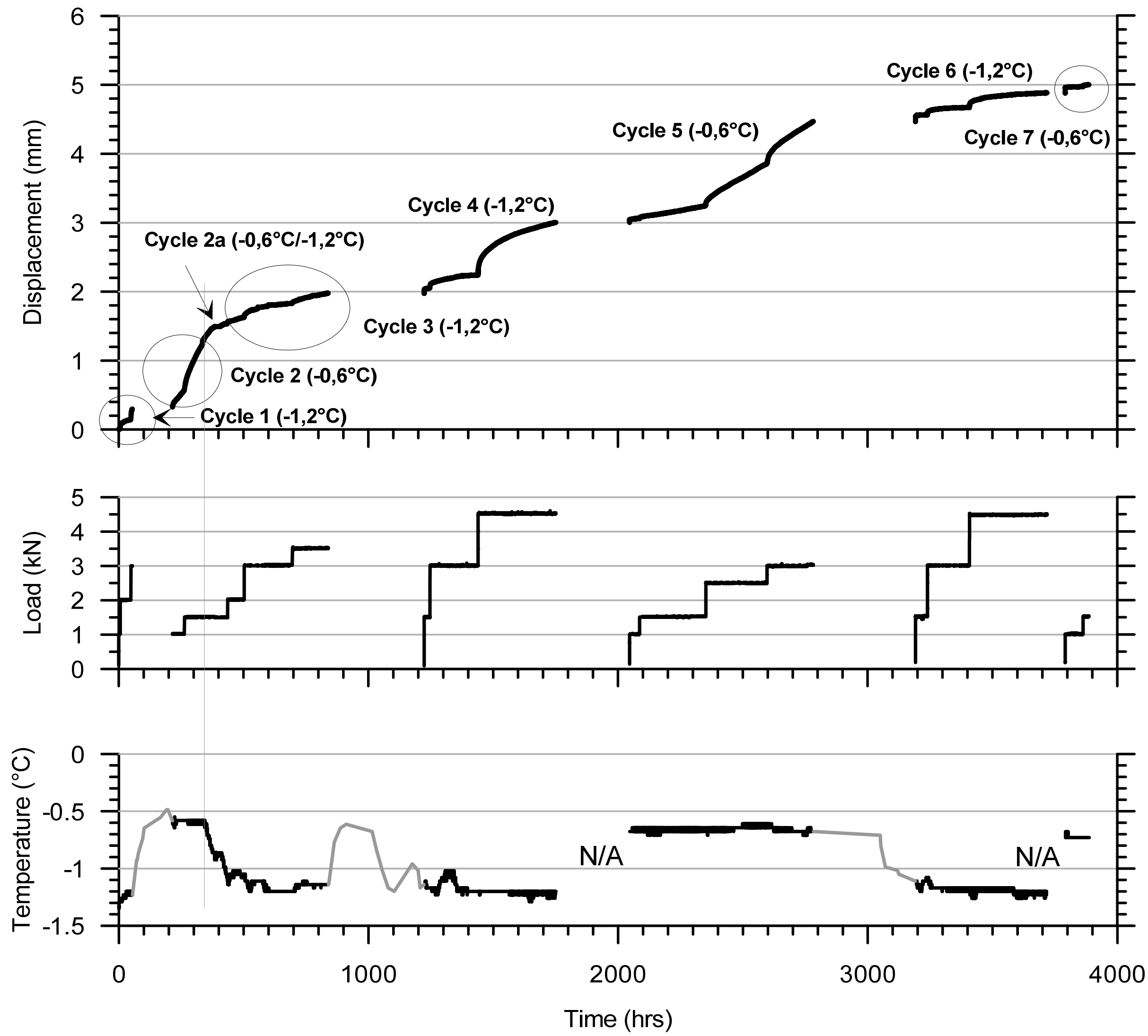

Figure 6. Summary of the creep tests on the enlarged-base anchor.

7 CONCLUSION

The creep tests with a straight, 16 mm diameter, steel anchor were found to be in close agreement with that published by Johston and Ladanyi (1972). The results can be summarised as follows:

- Linear creep behaviour at temperatures of -1.2 and -0.5°C;
- Creep rates at -0.5°C were sensitive to load changes ;
- The relation between shear stress and creep rate was well described by a power law in which the exponent is equal to 8;
- Beginning of stage III creep was observed at an applied load of 1.75 kN and a temperature of -0.5°C.

The creep tests with a cone-shaped anchor lead to the following observations:

- Creep rates were much smaller than that observed with a straight anchor;
- Pseudo-instantaneous deformations were observed upon loading;
- At a temperature of -0.6°C, constant creep rates were obtained after a short period of time;
- At a temperature of -1.2°C, creep rates decreased with time and often reached values close to zero;
- The creep response was a function of load history;

Although more research is needed to fully understand the effect of both temperature and load cycles, the results of this study indicate that enlarged-base anchors are well-suited to warm permafrost conditions.

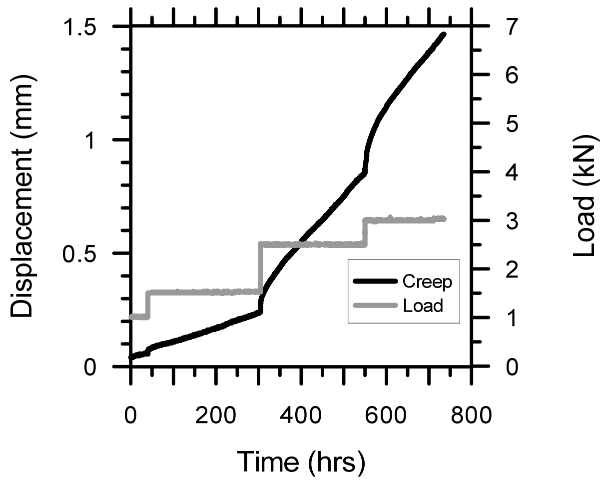

Figure 7. Typical creep behavior of the enlarged-base anchor at a temperature of -0.6°C (cycle 5).

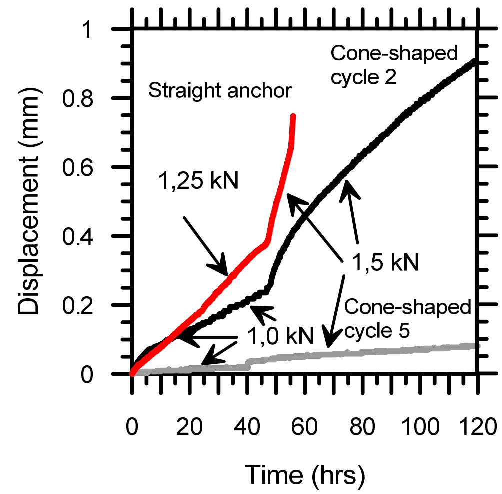

Figure 9. Effect of different loading cycles on the creep behaviour of the cone-based anchor at a temperature of -0.6°C.

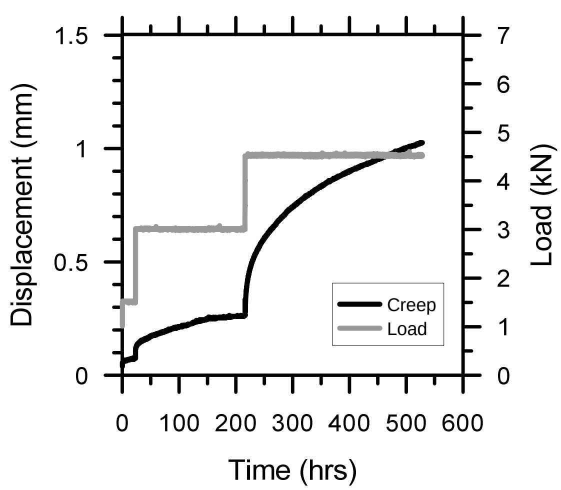

Figure 8. Typical creep behavior of the enlarged-base anchor at a temperature of -1.2°C (cycle 4).

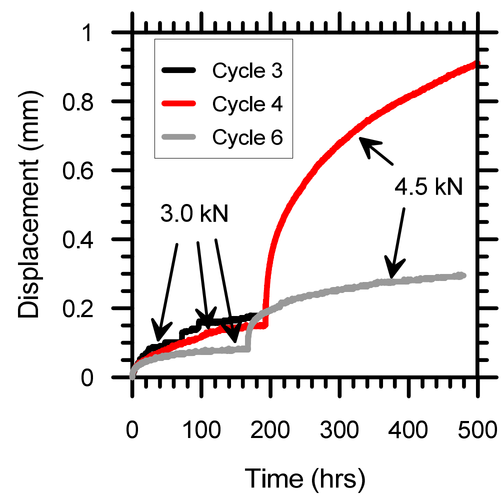

Figure 10. Effect of different loading cycle on creep behavior; coned-base anchor, temperature of -1,2°C.

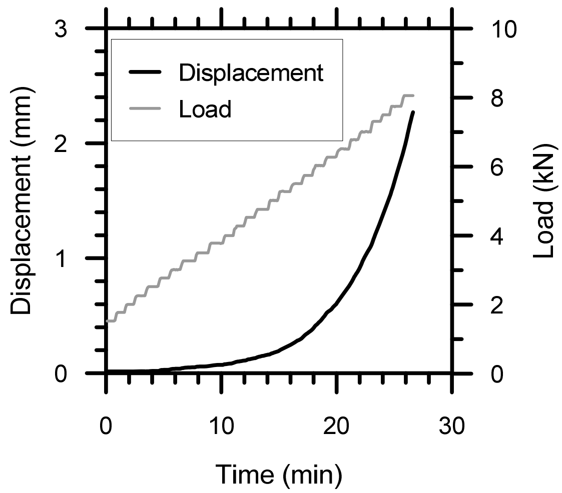

Figure 11. Pullout test on enlarged-base anchor at -0.6°C.

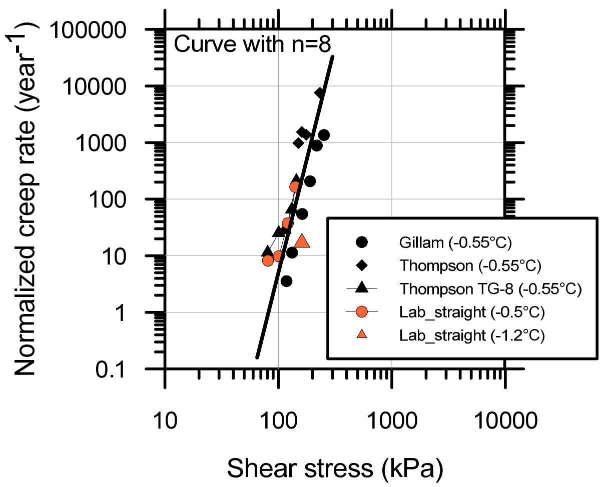

Figure 12. Creep behavior on straight anchor; comparison between data from Johnston and Ladanyi (1972) and our study.

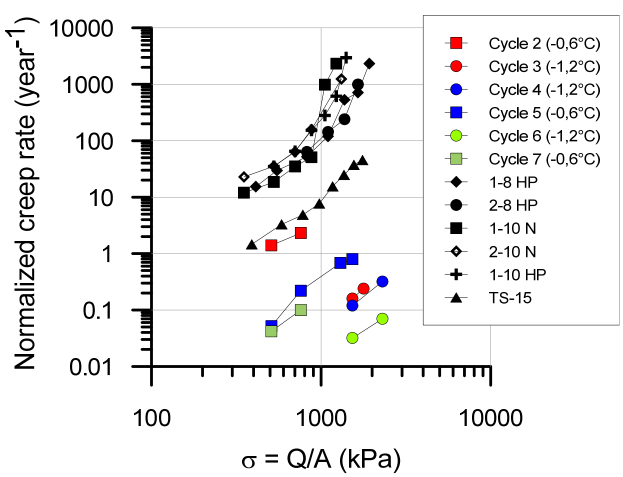

Figure 13. Creep behavior of screwed anchors from Johnston and Ladanyi (1974) and the enlarged-base anchor of our study.

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