Development of a Core Barrel for an In Situ Measurement of the Thaw Consolidation Behavior of Permafrost

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Abstract: In permafrost areas, environmental changes, such as infrastructure, building, and climate change, have effects on the thermal regime of soil and can initiate permafrost degradation. As a result, this will lead to the degradation of the mechanical properties of the soil. Thus, good knowledge of permafrost characteristics is essential to make the right decisions during the design and construction phases of a project and to anticipate potential problems related to climate change. The goal of this project was to improve our capacity to characterize thaw-sensitive permafrost by developing a drilling tool that is able to carry out in situ tests. In partnership with the Mechanical Engineering Department of Laval University, an oedometric core barrel was designed, and a prototype was built. As the core barrel is modular, it is easy to clean and maintain. Once the barrel has penetrated frozen soils, thawing is initiated by an electric heating element. A pneumatic cylinder then allows the user to set a consolidation pressure, and drainage occurs radially along the first 20 cm of the core. The drained water is discharged at the top of the drill hole, and information on the thaw consolidation behavior is recorded during the test. The complete testing procedure can be made during the in situ drilling operation. In order to validate the testing procedure, laboratory tests were made in pure ice and synthetic permafrost reconstituted in barrels. The testing program has allowed improvement of the initial design of the equipment as well as the test procedure. The reliability of the thaw settlement/consolidation tests was evaluated for fine and coarse soils.

Keywords: Core barrel; Permafrost; Settlement; Testing; Thaw.

1 INTRODUCTION

The existing procedure used to evaluate the thaw sensitivity of a permafrost soil consists of a coring phase and a testing phase. Retrieving an intact frozen core has always been a challenge. Friction and heat must be controlled during the coring process. Heavy duty drill rigs can operate triple wall core barrels with a refrigerated system. The drilling power of these rigs limits coring problems and provides quality cores, but they have poor mobility and high operation costs. Another option is to use light-weight portable drill rigs. With these drills, thin core barrels can provide good results in ice-rich soils (Calmels et al. 2005). However, they encounter difficulties with pure ice, fine grained soils with low ice content, or hot sandy permafrost. The Cold Regions Research and Engineering Laboratory (CRREL) core barrel performs well in ice-rich fine-grained soils but encounters difficulties when coring in soils with pebbles. Its performance improves when it is mounted on a bigger drill rig (7 hp) (Brockett and Lawson 1985). After coring, the sample must be kept frozen during transportation to the laboratory. For remote study sites, the transportation is done by plane. The deploying logistics for these test campaigns are therefore costly.

In order to allow in situ thaw consolidation testing, a special core barrel has been designed and built at Laval University (Quebec City, Canada). Instead of investing in means to retrieve high quality samples and ensure their transportation to the laboratories, a core barrel is used to carry out the thaw consolidation tests down the hole and produce thaw consolidation profiles with depth. The information is likely to support decision-making processes in the design, construction, and maintenance stages. The proposed testing tool and its performance are described in this paper.

2 DESCRIPTION OF THE TOOL

The oedometric core barrel is design to work in the first few meters of permafrost. It can be operated by a light-weight 8 hp drill. It does not need drilling fluids to operate. The coring head is adapted to core from sandy to silty frozen soils.

The core barrel looks like a hollow stem flight auger. The overall length of the barrel is 130 cm when the coring and the driving heads are fitted. The nominal diameter is 30 mm and the external diameter is 76 mm. The cores formed are 326 mm high. The thaw consolidation test is made on the 190 mm of the top of the core.

The core barrel is made of four subassemblies: the coring head, the lower part, the upper part, the reading tube and the driving head. Torque transmission between the subassemblies is done by slot assemblies and shoulder screws. The coring head combines two chisel-edge cutters and a thin-wall coring tube for a clear cut in the frozen soil and for the conveyance of the cuttings.

The lower part is where the thaw consolidation takes place. It contains the core chamber made of several layers. The core is in contact with a sintered stainless steel tube filter. The filter is fitted in a stainless sheath around which an electric heater is set. The space left between the heater and the external tube of the barrel plays the role of thermal insulation and thereby prevents the surrounding soil from melting, as the test is ongoing.

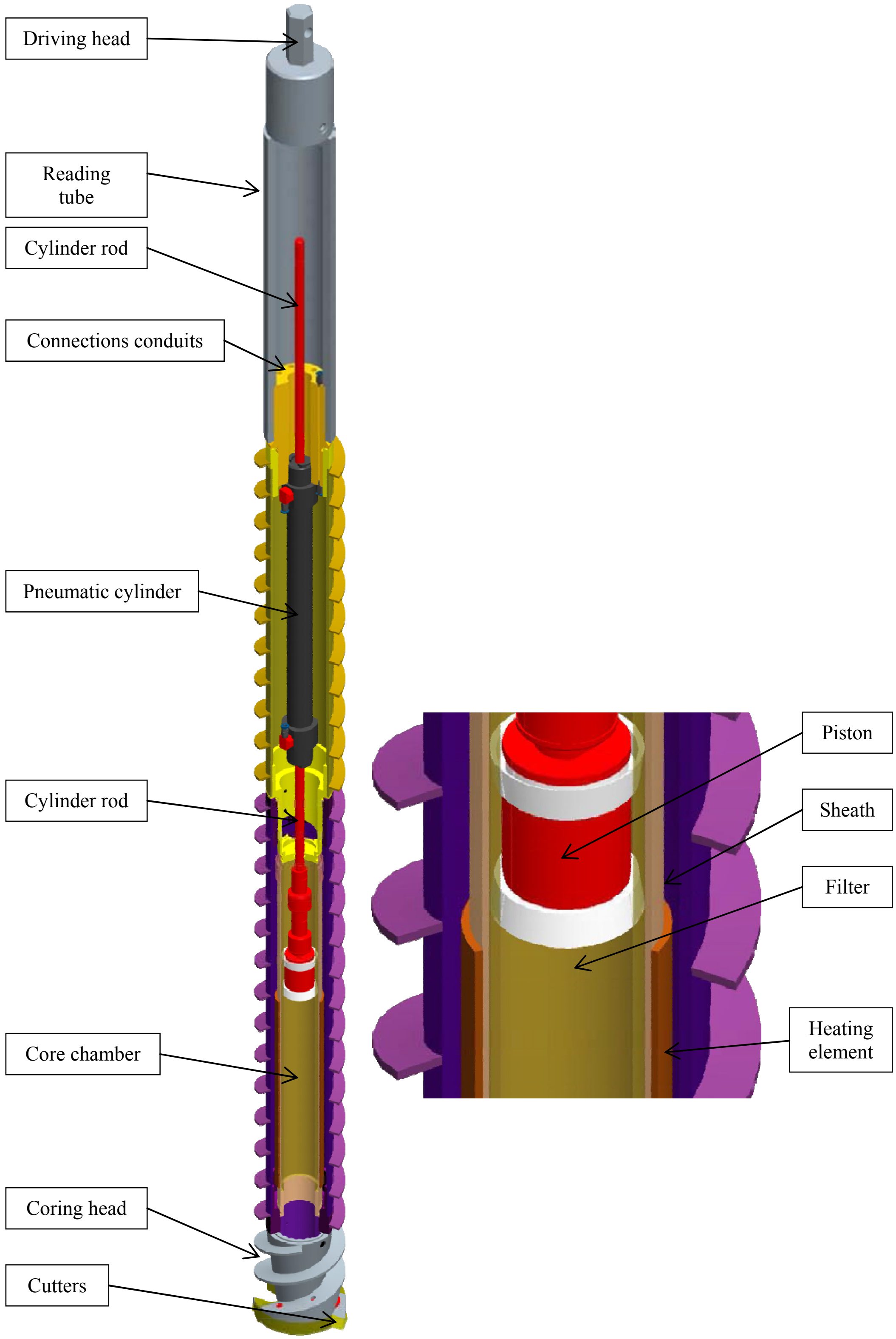

Figure 1. Core barrel view.

The upper part of the core barrel includes the mechanical components required to apply the selected pressure on the sample. A rod type pneumatic cylinder generates this pressure. The cylinder moves a piston that can slide into the core chamber and apply a pressure on the sample. On the other side of the cylinder rod, the displacement of the piston can be read visually or using a displacement transducer. The driving head has been designed to be compatible with the driving system of the Minuteman drill rig but it could be adapted for running with other drill rigs.

In order to protect the electric parts and to avoid rejecting the drained water directly outside the core barrel, where it may freeze, the parts in contact with the drained water are water-sealed. A tube guides the drained water from the lower part to the surface.

The actual version of the core barrel is a laboratory prototype version. The displacement of the piston is monitored by a camera to ensure a continuous reading. The heat regulation is controlled externally by a power supply and a data acquisition system and software.

2.1 Procedures

The following paragraphs describe the principle and the procedure developed for a thaw consolidation test.

A hole is drilled into the active layer with conventional methods. Casing installation is recommended to stabilize the hole and prevent infiltration of groundwater. Once the permafrost is reached, the core barrel is installed on the drill rig, and the coring operations begin. When the core barrel is fully augered in permafrost, the drilling operations are stopped and the thaw-consolidation test begins. The sample is then thawed by the electric heating element and is radially drained under the pressure chosen by the user and applied by the piston. The drained water is expelled to the surface through a channel when the piston comes back. If needed, the rest of the sample can be brought back to the surface.

Among the procedures tested to gradually assess the barrel performances, two procedures will be described. Depending on the drill rig settings and the core method, the height of the core may not be equal to the core chamber capacity. An expansion of the core caused by warming of the frozen sample may appear. This problem will not be discussed in this paper but a proper setting of the drill and the experience of the operator can minimize this effect. However, when it occurs, it must not be neglected when calculating the settlements. Therefore the procedures always begin with the measurement of the height of the core. This is done at the end of the coring operations, by moving the piston to reach the top of the core.

The first procedure is called the single loading thawing test. After measuring the height of the sample, the soil is thawed and then a pressure of 168 kPa is applied on the sample. 168 kPa corresponds to the remaining pressure in the sample after considering that the pneumatic circuit in under a pressure of 6.5 bar and that the pressure needed to overcome the friction is of 2 bar. In this case, the friction of the piston against the wall is assumed to be the same for all tests. The second procedure is a multi-loading thawing test. Before each coring, an assessment of the friction resistance of the piston against the filter is made by measuring the pressure needed for the piston to move in the empty filter. This will be necessary in the calculation of the actual load applied. Once the coring is done and the core is measured, it is thawed under a first loading step. When the piston reaches a stable position for two minutes, the load is increased to a new step.

The first procedure was executed on a silty frozen soil and the second procedure was executed on a sandy frozen soil. The soils characteristics and the composition of the barrels are given Table 1 and 2.

Table 1. Soils Characteristics

							Content			
Soil Type	Gs	e_0	W_{sat} (%)	W_L (%)	W_P (%)	W_{barrel} (%)	Gravel	Sand	Silt	Clay
Silt	2.79	nc	nc	34.7	22.2	40	9.60	31.7	49.9	8.81
Sand	nc	0.65	24	nc	nc	24	1.9	97.2	0.9	

Table 2. Description of Test Barrels

Silt barrel					Sand barrel				
Depth (mm)			Thickness (mm)	Layer type	Depth (mm)			Thickness (mm)	Layer type
0	to	52	52	Ice	0	to	24	24	Ice
52	to	130	78	Silt (w=0.4)	24	to	80	56	Sand (w=0.24)
130	to	170	40	Ice	80	to	102	22	Ice
170	to	240	70	Silt (w=0.4)	102	to	144	42	Sand (w=0.24)
240		…		Silt	144	to	164	20	Ice
					164	to	203	39	Sand (w=0.24)
					203	to	220	17	Ice
					220	to	265	45	Sand (w=0.24)
					265	to	290	25	Ice
					290	to	325	35	Sand (w=0.24)
					325	to	…		Ice

2.2 Results of Laboratory Tests

Results of tests using the first procedure are shown Figure 2, for four thawing tests. For comparative purposes, a test done in a pure ice barrel is plotted in the same graph. Since the test equipment is designed for radial outflow consolidation, the displacement is plotted against the time raised to 0.465 to process the consolidation data (McKinlay 1961, Trautwein 1981). The tests were made on samples of different heights. This is why a difference of vertical displacement between the tests can be seen. The sample heights are given Figure 2.

Two stages can be viewed for tests on the silty soil. The first one is the drainage of the excess ice of the sample: the displacement rate matches the one of the pure ice test. This stage describes the behavior of the test cell in drainage. The second stage shows a slower displacement speed which correspond to the consolidation of the sample. The length in time of the tests didn't allow us to see a third stage which would correspond to the secondary consolidation stage. Therefore the method to estimate the consolidation rate (McKinlay 1961) couldn't be applied.

Nonetheless, the ordinates of the intersection point of the tangents to the linear parts of the curves were assumed to be representative of the amount of excess ice in the sample. The method, called "tangent method" was applied to the tests and compared to the settlement expected due to the excess ice. Owing to the expansion of the sample in the core barrel and in order to estimate the ice lenses thickness in the sample, two assumptions were made. The first assumption was that the expansion ratio was homogeneous in the sample. The second one was that the expansion occurred only for the soil layers. The relative error between the theoretical and the measured settlements were of 9%, -23%, 0%, 2% for the first assumption and 13%, -10%, 9%, 9% for the second assumption. Even if no reason was found for a possible error during the second test, excluding this test and finding a correction factor could improve the method reliability.

The vertical strains against the applied pressures of eleven multi-loading thawing tests are presented Figure 3. The heights of the samples tested are given in the figure's legend. The data shown on this figure has been processed to eliminate aberrant data points. Indeed, the expected initial thaw settlement due to the excess ice drainage was of about 37 %. Yet some measurements showed smaller settlement values. Because these inconsistencies occurred at low pressures, the given explanation is that the friction between the piston and the filter has the biggest influence when the pressure applied is low. To correct the curves obtained, a filter parameter was chosen. The points corresponding to the pressures under the initial pressure needed to move the piston were removed.

To compare the results obtained, compression indexes, C_c, were calculated according to equations 1 and 2. It should be noted that under field conditions, the void index e_0 can't be measured, thus only the modified compression index $C_{c\varepsilon}$ can be calculated. Since all the tests can give a result at 130 kPa, the comparison of the settlement level has been made at that pressure. At 130 kPa, the mean vertical settlement ε_v was of 51.9 % with a

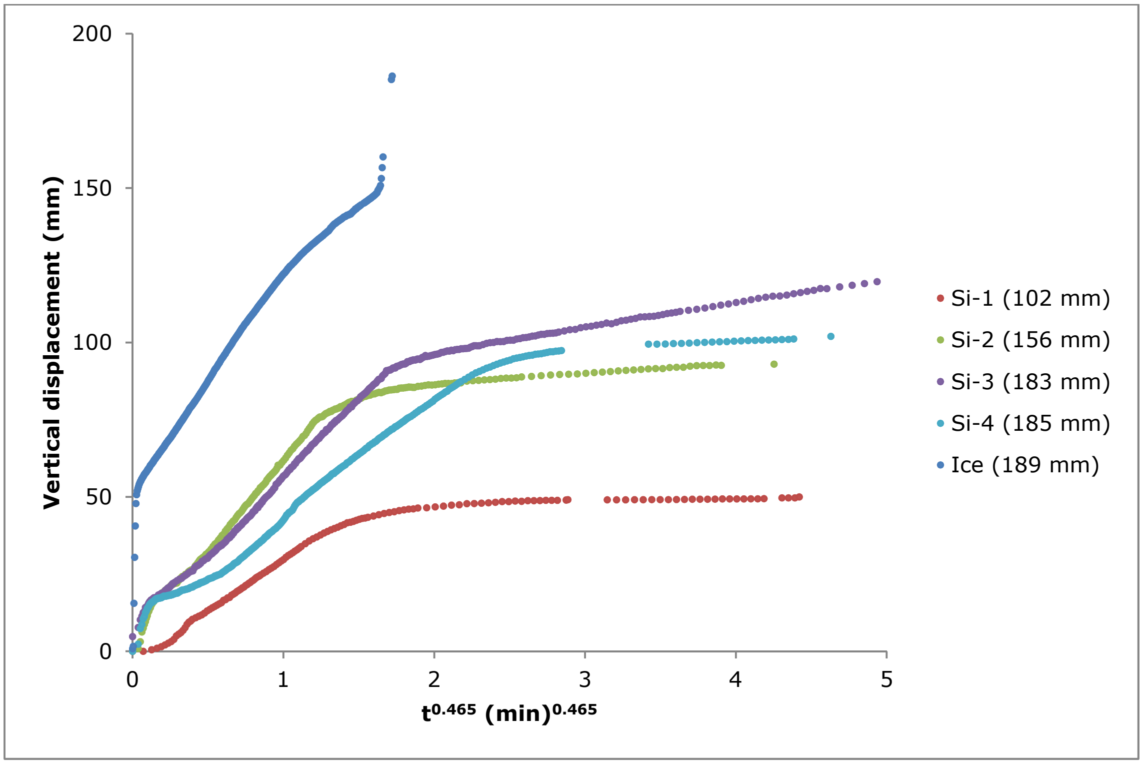

Figure 2. Single load thaw consolidation test on silty frozen soil. Vertical displacement against time at 0.465 power.

standard deviation of the mean value of 8 %. Two tests gave settlement values beyond one standard deviation of the mean value. With respect to the compression indexes, the mean value was 0.31 with a standard deviation of the mean of 0.16. Again, two tests, different from the previous ones, gave compression index values beyond one standard deviation of the mean value. The calculation of the compression indexes was made through the determination of the void index of the sample.

Compression index values were compared to a reference value obtained with a standard consolidation testing oedometer. The sand was saturated but unfrozen. This test gave a compression index of 0.066 therefore 4.7 times less than the mean value obtained with the core barrel. The reason for this difference has not been clearly identified. Nonetheless, one explanation could be that more than 190 mm of soil might have thawed during the test. However, this can’t be the only reason for the compression index difference. Even if the real thaw front reached the end of the core, the values obtained would still be about double the reference value. The high compression indices can also be caused by the very low dry density of the soil placed in the testing barrels compared to the soils placed in the oedometric cell.

$$C_c = C_{c\epsilon}\,(1 + e_0) \qquad [1]$$

Where C_c = compression index, $C_{c\varepsilon}$ = modified compression index, e_0 = initial void ratio

$$C_{C\epsilon} = \frac{\Delta \varepsilon_v}{\log\left(\frac{\sigma'_2}{\sigma'_1}\right)} \qquad [2]$$

Where $C_{c\varepsilon}$ = modified compression index, $\Delta H/H_0$ = vertical strain

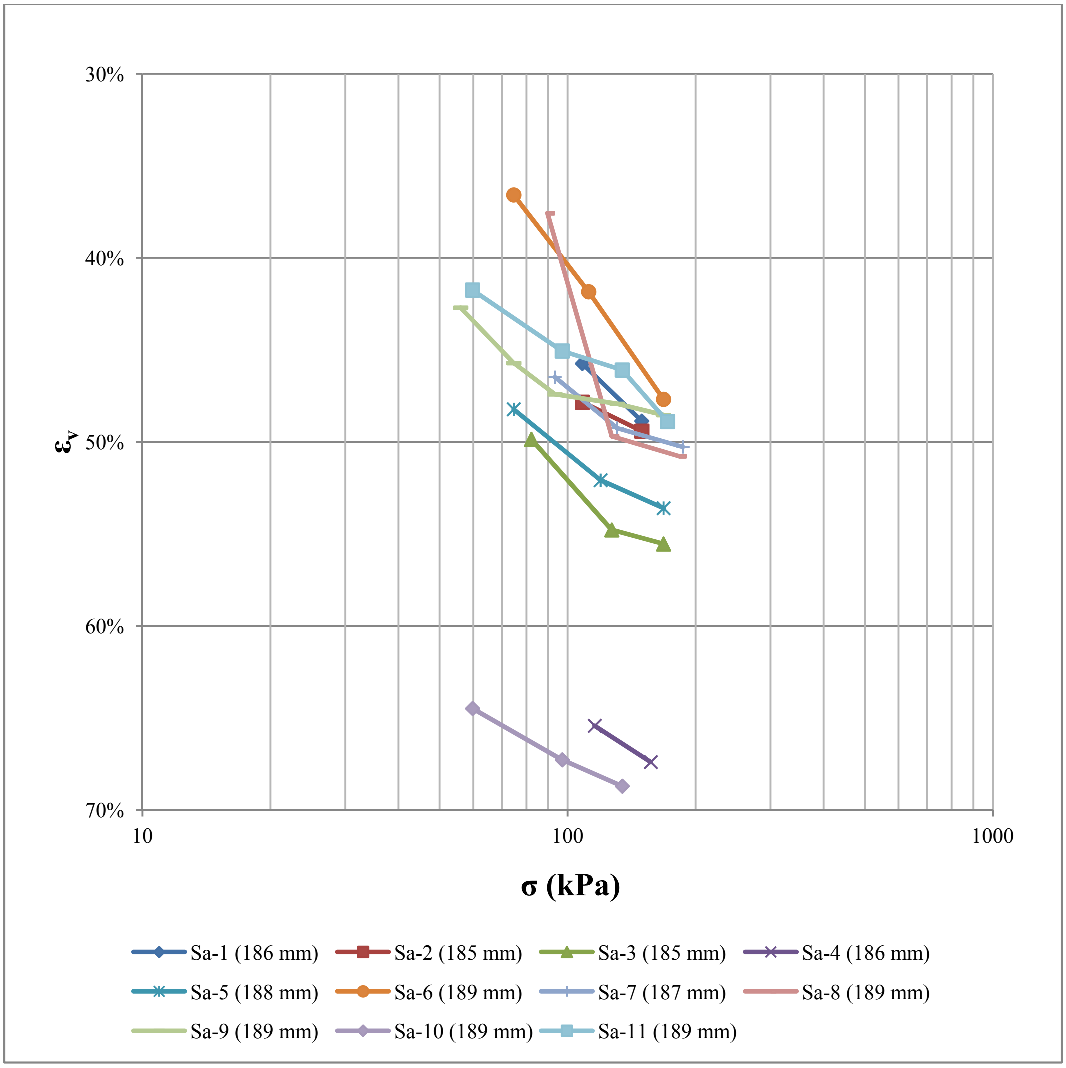

Figure 3. Settlement curves. Vertical strain against applied pressure.

3 IMPROVEMENT

The laboratory tests allowed us to notice ways to improve the core barrel. Small changes in the design would make the handling easier and accommodate the prototype to field conditions. An important evolution is to design the rods so the tool can go down the hole, after the casing is done. These rods will have to allow electric and the pneumatic connection with the surface.

With regard to the thaw consolidation testing cell, the electric resistance could be changed for a thinner etched foil element heater to gain space. The temperature measurement system will gain in stability if the new resistance is supplied with direct current.

To avoid the need to filter the data while performing a multi load thaw consolidation test, the friction between the piston and the filter has to be reduced as much as possible. A way to do that would be to use a filter with an asymmetric construction. These kinds of filters have two layers. In this case, the inner layer has a very low permeability, thus a better surface quality. To keep an interesting pressure reduction with a radial outflow, the outer layer has a high permeability. This technology wasn't used for the first prototype version because it is 1.5 times more expensive than the normal sintered porous filters.

Using a different filter technology would allow the cell to function at low pressures and would improve the system's efficiency by reducing the friction losses. Yet, another problem is that the core barrel can't indicate the real pressure applied to the sample. A pressure sensor in the piston would solve that lack of precision.

Another step in the evolution of the tool would be the monitoring of the displacement of the piston. With the current version, the displacement data is visually recorded. This implies setting up a camera in order to have a continuous recording of the piston's position. The installation of a displacement sensor would simplify the piston's position acquisition.

4 CONCLUSION

The goal of the project was to develop a core barrel that was able to perform in situ thaw consolidation testing. The prototype has an auger with two flights and a coring head that provides two cutting effects. The thaw consolidation test under the selected stress level can be fully executed and documented using the core barrel. The laboratory tests conducted on ice-rich silt highlighted the ability of the tool to make a single loading thaw consolidation test. Unfortunately, the loading time was not long enough to estimate the consolidation rate. However, the consolidation was observed, and the settlement expected (due to the ice excess) was evaluated. The multi-loading tests carried on ice-rich sand provided vertical strain against the pressure applied. After data processing, which was necessary because of inconsistencies caused by the friction of the piston against the filter, compression indexes were calculated. The results compared to a standard consolidation test showed higher values. In both situations, the repeatability was good. Further development of this work may include the determination of correction factors. Several ways to improve the core barrel were discussed. Reducing the level of uncertainty of the real applied pressure is a high-priority improvement. All other improvements involve the general design and should be carried out to enhance the handling and the ability to work on the field.

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