IX Simposio Nacional sobre Taludes y Laderas Inestables
Santander, Junio 2017
E.Alonso, J. Corominas y M. Hürlimann (Eds.)
CIMNE, Barcelona, 2017

INFLUENCE OF THE CLIMATE CHANGE ON THE EVOLUTION OF SOIL BEARING CAPACITY: AN EXPERIMENTAL STUDY ON THE EFFECTS OF FREEZING/THAWING CYCLES

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ABSTRACT

One of the consequences of global warming is the increasing of the phenomenon of cyclical freezing / thawing of the soils.

This preliminary experimental study aims to understand and quantify the variations in the behaviour of a silty soil subjected to a cycle of freezing / thawing through a series of laboratory tests. After a soil characterisation, shear and oedometric tests are performed before and after freezing on several soil specimens. The results, which are temporary and not exhaustive, are deduced from the oedometric curves and Mohr-Coulomb diagrams obtained. Some comments can be drawn from the superimposition of the oedometric curves and Mohr-Coulomb diagrams of the soil before and after freezing.

All tests are carried out according to Swiss standards.

1. INTRODUCTION

In the current context of global warming, it is important to better understand the phenomenon of soil freezing / thawing. The swelling of the soil during its freezing phase and its shrinkage during thawing phase can cause enormous damages to the built environment. Therefore, it is necessary to find a way to quantify the changes in the characteristics of a frozen soil when it is thawing (Dysli, 2007).

The phenomenon of thawing, as a consequence of global warming, affects permafrost (permanently frozen soils). In Europe, the Alpine regions are mostly characterised by the presence of permafrost. Switzerland, according to its geographical position and geomorphology, is clearly very concerned by this phenomenon.

Transport infrastructures, mountain chalets and ski areas facilities are the most exposed elements, because of the possible loss of bearing capacity of the underlying soils during thawing. These structures were probably designed based on the characteristics of frozen underlying soils, without taking into account the phenomenon of thawing and its possible consequences. The effects of cyclical variations of the characteristics of soils can also cause fatigue problems on the infrastructures mentioned above.

This experimental study attempts to quantify the variations of the characteristics of a silty soil subjected to a cycle of freezing / thawing. At first, a characterisation of the soil studied is carried out in terms of (i) granulometry, (ii) Atterberg limits, (iii) optimal water content at which the soil achieve its maximum dry density (Proctor test) and (iv) Bulk density. Then, oedometric and shear tests are performed in order to have the shear strength and the compressibility properties of the soil before freezing, as reference case. After this characterisation phase, oedometric and shear tests are carried out on the soil after a cycle of freezing / thawing. This procedure is performed on various specimens in order to find a correlation in the obtained results. Finally, the variations of the soil characteristics are deduced by superimposing the obtained shear curves and oedometric curves before freezing and after a cycle of freezing /thawing.

2. SOIL CHARACATERISATION

The soil studied was collected from the washing sludge of a lacustrine gravel. A full characterisation of the soil was necessary before testing the effects on the soil of a cycle of freezing / thawing. Firstly, the distribution of particles sizes of the soil was determined with a full granulometric analysis (screening and sedimentometry). Then, the laboratory test to define critical water contents of the soil (plastic limit and liquid limit) were performed. Before realising the specimens for shear and oedometric tests, the Proctor compaction test was carried out to find the optimal water content for saturated soil and dry soil. All the specimens and the subsequent tests were carried out with the optimal water content for saturated soil.

The bulk density was measured and then the samples were realised, estimating an original soil depth of 3.5 meters. Several shear tests were carried out and compared in order to validate the method used to realise the soil specimens and guarantee the regularity of the measurements.

Granulometry

The granulometric curve of the soil studied is between 0.002 mm and 0.3 mm, which means that the silt component is approximately the 99% of the soil. Silts are very sensitive to the effect of frost and that is the reason why this type of soil was chosen to carry out this study.

Atterberg Limits

Three Atterberg limit tests were carried out on the soil. An average value was calculated starting from the obtained results for the two limits, providing a value of 18.1% for the plasticity limit and 29.1% for the liquidity limit. The plasticity index I_P is 11%.

Bulk density

The measurements of this soil property were performed by hydrostatic weighing. In order to obtain the variation of the Bulk density according to the water content, several tests were carried out with four different water content values: 14%, 16%, 18% and 20%. As a result, the Bulk density presented a little variation between 1.98 g/cm^3 and 2.05 g/cm^3. Therefore, for all the following tests, the assumed value of Bulk density for the soil studied is 2 g/cm^3, which corresponds to 20kN/m^3.

Proctor test

The Proctor compaction test was carried out in a Proctor mold type A in 3 layers of 25 shots each, with a hammer of 2.5 kg and a drop height of 305 mm. The optimal water content of the moist soil is about 18%, and 16% for the dry soil.
However, the 18% water content does not correspond to the 100% degree of saturation of the soil. The value of the solid particle density γ_s is generally between 26 and 27 kN/m^3. According to these values, the degree of saturation S_r was calculated, giving as results S_r = 93% with γ_s = 26 kN/m^3 and S_r = 88% with γ_s = 27 kN/m^3. In order to achieve a 100% degree of saturation, the required water content should be between 20.3% and 21.5%. The average of these two values was taken into account for the following tests, i.e. a water content of 20.9%.

3. TESTS BEFORE FREEZING (REFERENCE CASE)

In order to have a reference case of the shear strength and the compressibility properties of the soil before freezing, a shear test and an oedometric test were performed.

3.1 Compressibility properties

The oedometric test was performed with 18 loading stages of 24 hours each. These are the stress values (in kPa) used for the test: 5, 10, 20, 40, 70, 40, 20, 10, 25, 50, 100, 200, 400, 800, 400, 200, 100, 50. The initial stress of the drill core was about 70kN/m^2 (depth estimated at 3.5 meters and Bulk density of 20 kN/m^3).

The initial void ratio deduced from this trial is:
e_0 = 0.603.
The compression index is:
Cc = -0.0563.
The swelling index is:
Cs = -0.00473.

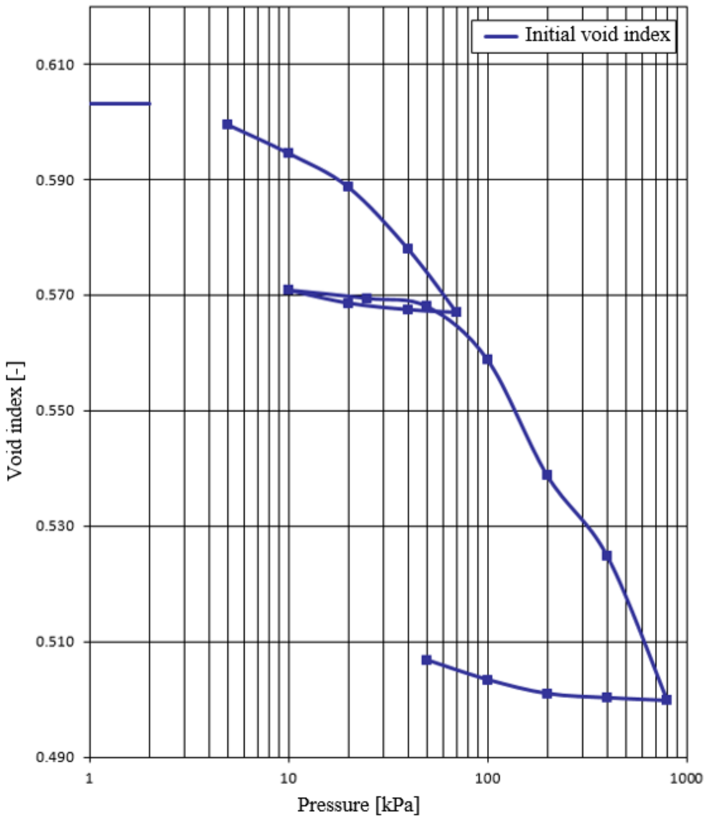

Fig. 1 Oedometric curve before freezing.

3.2 Shear strength

The values of shear stress, normal stress and water content *w* considered for performing the shear test are presented here below:

Point	Shear stress [kPa]	Normal stress [kPa]	*w* [%]
1	45.56	68	21.84
2	75.56	136	20.98
3	103.61	204	20.90

Table 1 Parameter values for shear test.

Cohesion *c'* and internal friction angle φ of silty soil at a water content *w* = 20.9% were determined from the Mohr-Coulomb diagram (Fig. 1). As a reminder, the cohesion is the ordinate at the origin of the regression curve and the angle of internal friction is the slope of the curve. This soil therefore presents a cohesion *c'* = 16.9 kN/m^2 and an angle of internal friction φ = 23.1°.

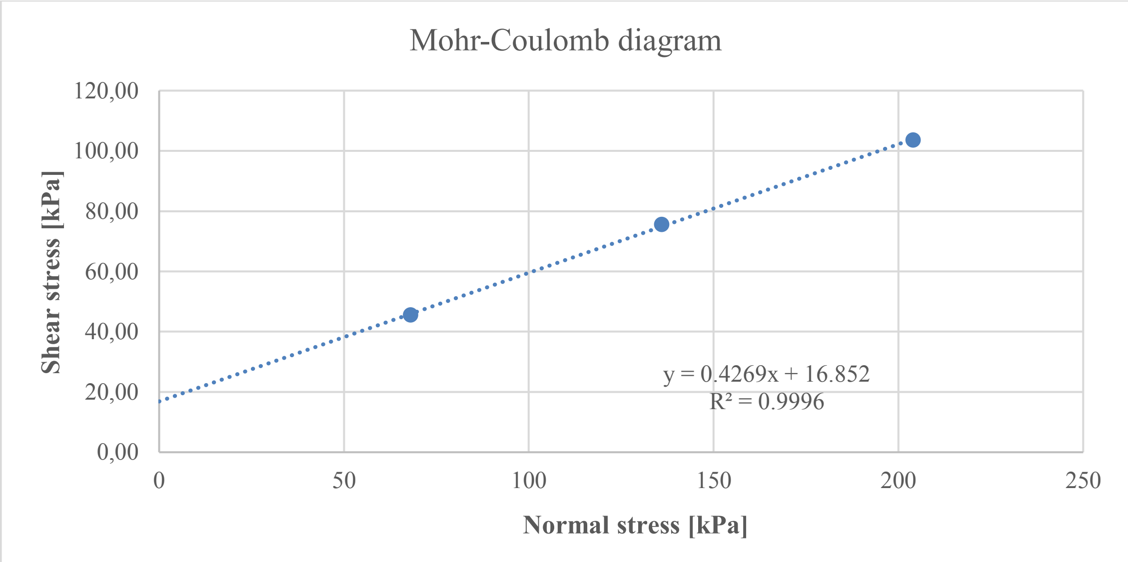

Fig. 2 Mohr Coulomb diagram.

4. TESTS AFTER FREEZING

After the soil characterisation and the definition of the shear strength and the compressibility properties of the soil before freezing (reference case), the specimens prepared were frozen in an air-conditioned cabinet. Firstly, a first group of specimens were kept in the cabinet for 3 days; then a second group of specimens was tested after 18 days of freezing.

4.1 Visual description of specimen condition after frost

After the freezing phase, many ice lenses appeared on the frozen specimen. They are clearly visible on the whole surface of the drill core. Numerous vertical cracks also appeared. The overall appearance of the frozen drill core can be described as "cracked".

Fig. 3 Specimen before freezing (left) and frozen (right).

Fig. 4 Specimen after freezing.

The evidence of the cracks seemed minor after thawing, but the voids in the specimen are greater than before freezing. Since they strongly weaken the soil, precautions had to be taken to handle the specimens and keep them intact for the realisation of the tests. Unfortunately, many drill cores were too deteriorated to achieve something. About 50% of the collected frozen specimens were in these conditions, or even completely destroyed by the freezing (Fig. 5).

Fig. 5 Cracks induce by freezing (left) and specimen destroyed by freezing (right).

Note that the specimen opened in two from top to bottom. The degradations due to ice were too strong. The split in two of the drill core was recorded in a short video.

4.2 Compressibility properties

3-days freezing oedometric tests

The first experiments were carried out after a 3-days freezing phase.

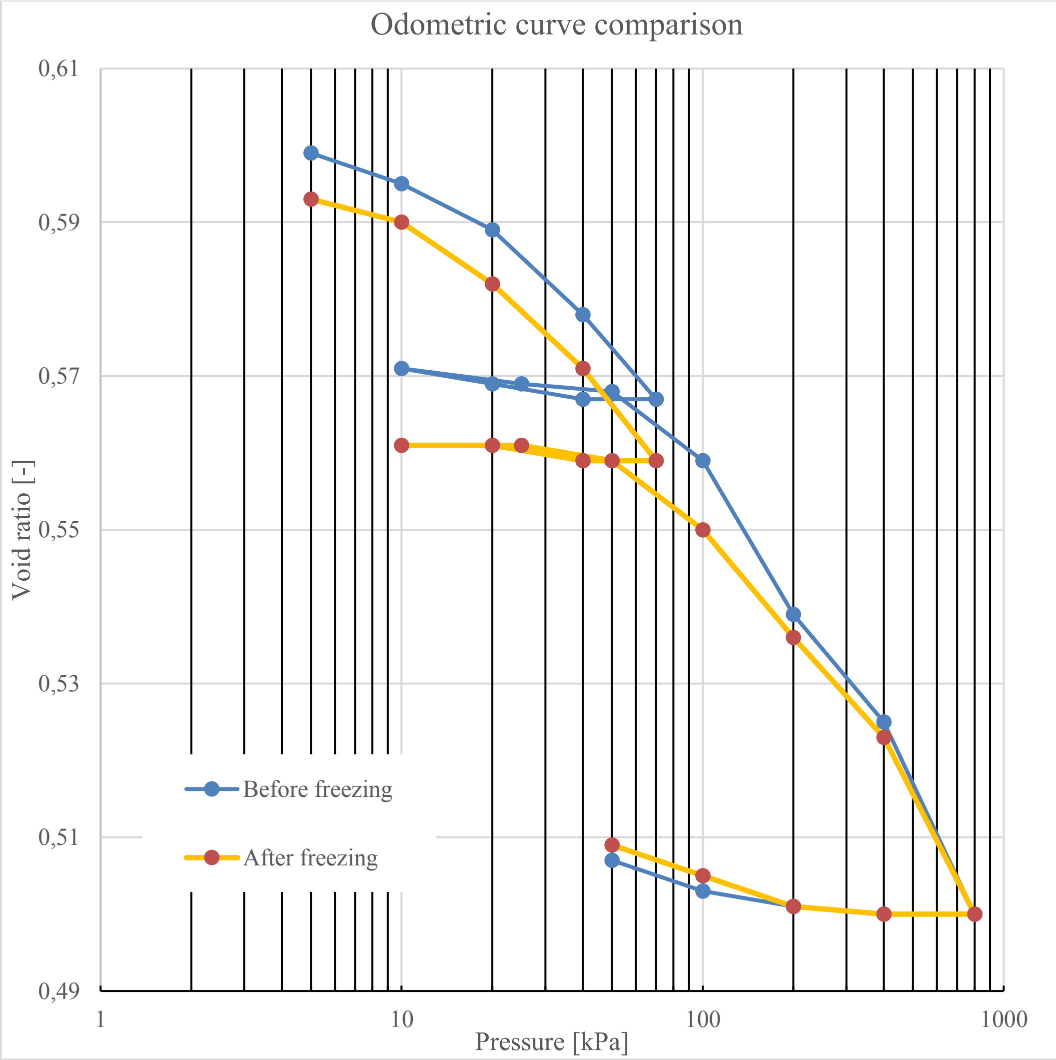

Fig. 6 Comparison between oedometric curves before freezing and after 3 days of freezing.

We can see from these two oedometric curves that the differences between the test before freezing (in blue) and the test after freezing (in yellow) are minimal. Here below a summary of the characteristics calculated from these tests according Vulliet et al. (2016).

Parameters	Before freezing	After freezing
e_0	0603	0595
C_s	-0.00473	-0.00367
C_c	-0.0563	-0.0639

Table 2 Index summary

18-days freezing oedometric tests

Since the difference was minimal probably due to a too short freezing time, it was decided to extend the duration of the freezing phase to 18 days.

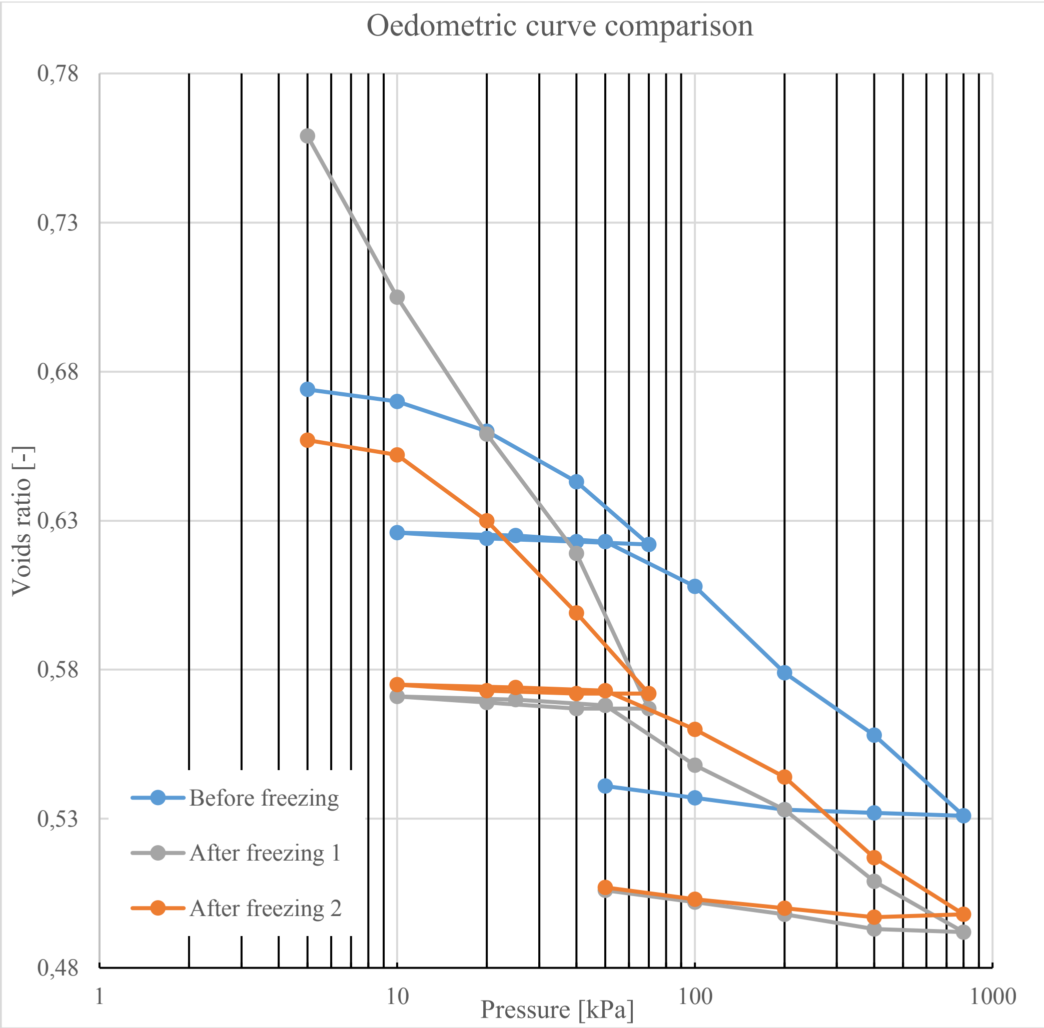

Fig. 7 Comparison between oedometric curves before freezing and after 18 days of freezing.

Test	Before the freezing	after the freezing 1	After the freezing 2
e_0	0680	0818	0675
C_s	-0.00473	-0.00473	-0.00355
C_c	-0.0875	-0.0631	-0.0623

Table 3 Index summary

The oedometric curve after a freezing / thawing phase 1 has a different appearance. First, the initial void ratio increases from 0.68 to 0.818, an increase of almost 20%.

Fig. 8 Specimens with voids caused by the ice lenses.

The initial void ratio of the second test after 18 days of freezing is close to the initial state.

The behaviour of the curves on the bearing discharge is identical. The swelling index C_s, which is the slope of the approaching hysteresis cycles, varies very little. The two curves after 18 days of freezing are very well superimposed between the pressure values of 50 kPa and 800 kPa. This is confirmed by the determination of the compressibility index, whose deviation is less than one thousandth. The effect of the prolonged freezing is identical on the two curves. At 800kPa of stress, the void ratio of the two tests carried out after the freezing decreases. The index is 0.531 for the unfrozen soil and increases to 0.492 (after freezing / thawing test 1) and to 0.498 (after freezing / thawing test 2).

4.3 Shear strength

It was relatively difficult to carry out these tests because the specimens are greatly weakened by the residual voids left by the ice lenses, as mentioned above (v. Paragraph 4.1). The drill cores can be destroyed very easily, sometimes just because of the effect of gravity.

Performing the shear test on the frozen soil was even more difficult. Indeed, the preparation of the soil specimen can damage the material. This is why only one such test was carried out. The test gave a cohesion $c' = 62.9$ kN/m^2 and an internal friction angle $\varphi = 27.1°$.

The first test carried out on the ground after an 18-day gel phase gave a very high internal friction angle $\varphi = 47°$. The results obtained for the three shear tests carried out after 18 days of freezing and 24 hours of thawing, as well as their graphical representation, are presented here below.

Test No. 1: $c' = 21{,}9$kN / m ^{2,} $\varphi = 47°$
Test No. 2: $c' = 5{,}4$kN / m ^{2,} $\varphi = 27°$
Test No. 3: $c' = 21{,}1$kN / m ^{2,} $\varphi = 21.9°$

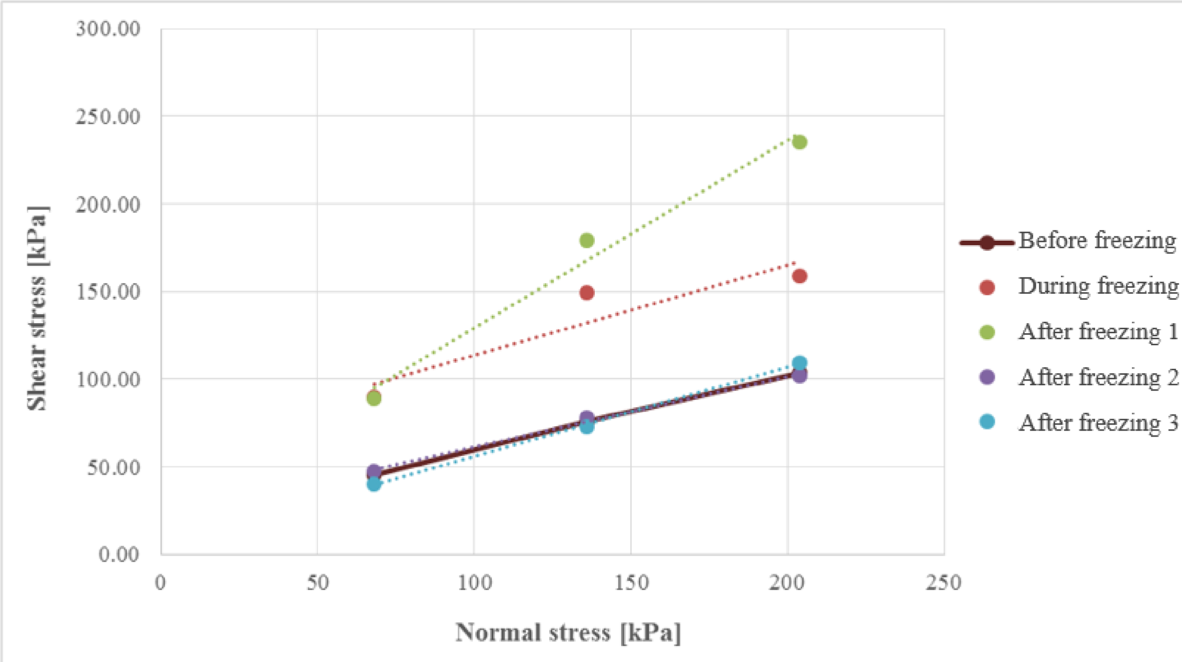

Fig. 9 Shear tests results after 18 days of freezing.

5. DISCUSSION

The overall state of the drill cores after the freezing phases is poor; strong degradations are visible on all the specimens.

Concerning the results of the oedometric tests, the increase of the initial void ratio of the first specimen subjected to freezing / thawing is probably due to the presence of an ice lens during the collection of the specimen (Fig. 8). The first part of the curve represents the settlement of this void. Because of this, for the calculation of the compression index C_c (the slope of the blank compression line), the first loading steps were not taken into account. In order to be consistent in the comparison procedure, the same was made for the second specimen subjected to freezing / thawing (After the freezing 2). This second specimen presented an initial void ratio close to the one of the soil before freezing because he contained less voids left by ice lenses. The increase in initial void index is local, it is even more important in areas where ice lenses have been formed. Out of these areas e_0 does not vary in a meaningful way. However, it must be taken into account that the tested specimens are very small comparing to the entire drill core. The large voids left by the formation of the ice lenses do not close completely once the ground has been thawed, which is why the index of voids on the entire drill core is greater after freezing.

The effect of the freezing on the swelling index C_s is insignificant according to these first tests, but it is supposed to be confirmed by further tests. The effect of the prolonged freezing is identical on the two curves: the soil, therefore, has greater compressibility after a prolonged freezing phase compared to its initial state. This is most likely due to the voids left by the ice lenses developed during the freezing phase.

The oedometric test could not be carried out on the frozen ground because of the lack of the appropriate equipment to carry out this test in a cold room. Since the test is relatively long, the soil would have been thawed at the end of the test.

Apart from the first part, the two after freezing tests show quite similar curves, both from the point of view of the void ratio (at the different stages of the second loading) and of the swelling and compression indices. By comparing the curves before and after the freezing it seemed as if there is a translation of the initial curve downwards. This behaviour suggests a greater compressibility of the silt after a freezing phase, which is due to the remains of ice lenses developed during the freezing of the soil. Additional oedometric tests are planned to be performed.

Regarding shear tests, the increase of cohesion and internal friction angle of the frozen soil is easily explained by the freezing of the soil. As comparison, the values of cohesion and angle of internal friction of the non-frozen soil were: $c' = 16.9$ kN/m^2 and $\varphi = 23.1°$. In frozen conditions the cohesion of the soil increased by more than 250%, and the internal friction angle increased by 17%. The very high value of the internal friction angle of the first specimen after freezing was surprising. Nevertheless, the test was carried out according to the rules and to Swiss standards and the trend curve had a correlation of 98.2%. One possible cause of this value of the angle could be the presence of a residual ice lens not fully thawed. According to this supposition, the following two tests were carried out as quickly as possible to confirm or invalidate these initial results.

The shear test carried out on the frozen soil was only one, because it was immediately evident that it was too difficult to implement. The values provided by this test show a strong increase in the soil cohesion and a slight increase in the internal friction angle; however, these results should be considered with caution because only one test was performed.

Unfortunately, the results of the shear tests do not show a clear trend; therefore, it seems impossible to establish a correlation of the obtained results and calculate some average values of the shear strength characteristics of the soil. Moreover, during the tests many specimens were destroyed, which considerably reduced the number of results.

Since the results obtained for the post-freezing shear tests are not conclusive and insufficient to draw conclusions, from about 30 to 40 additional tests are planned to be performed in order to obtain more results and be able to calculate a statistically acceptable average value of the soil characteristics c' and φ.

6. CONCLUSIONS

This work aimed to perform a preliminary study of the effects of the phenomenon of freezing / thawing on a silty soil, analysing the possible variations of the shear strength characteristics and compressibility properties of the soil itself.

First, a complete soil characterisation was performed in terms of granulometry, Atterberg limits, optimal water content and Bulk density. Specimens of soil were prepared and shear and oedometric tests were also carried out on the soil before freezing in order to define a reference case.

Then, specimens were subjected to a 3-days freezing phase with following thawing, but no variations of compressibility properties were remarked. Therefore, another group of specimens were subjected to an 18-days freezing phase followed by thawing.

The results provided from the second series of tests suggest, concerning oedometric tests, an increase of the compressibility properties of the soil. On the other hand, the results of shear tests do not provide any recognisable trend and are insufficient to draw any conclusion about the variations of the characteristics of the soil in terms of shear strength. Since the preliminary character of this study and according to these first results, several additional tests are planned to be carried out in order to improve the available data and possibly be able to defined average values of the variations of the soil characteristics.

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