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RESEARCH OF THE BEHAVIOUR OF NON-COHESIVE SOILS WHEN TREATED BY ARTIFICIAL FREEZING.

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ABSTRACT

During the period 1977-1979 a certain number of large scale tests have been performed in the testpit of the State Geotechnical Institute ; the testpit has a diameter of 3 m and a height of 10 m. During these tests a ground volume of 4 till $8m^3$ has been frozen and thawed under different conditions in order to obtain data concerning the ground movements - swellings or settlements - and concerning the variation of the bearing capacity of the soil.
Non cohesive soils with respectively 13%, 20% and 25% particles finer than 60 µm have been tested. Alternatively an overburden soil pressure of about 14 kN/m^2 or about 70 kN/m^2 has been realized and the watertable within the testpit was installed at different levels.
During the execution of the tests a large number of difficulties have been encountered in relation to the installation of the watertable within the testpit and to the measurement of the ground movements. According to the observations and results obtained, the research programme has been modified repeatedly.

Introduction.

In June 1976 an extensive program of large scale tests has been started at the State Geotechnical Institute at Ghent, Belgium, to determine the behaviour of cohesionless soils under conditions of artificial freezing. In a large test pit, with a capacity of 70 m^3, different kinds of soils are submitted to cycles of freezing and thawing, varying several parameters, and informations are gathered about the soil movements, temperature variations and bearing capacity variation.

The research program is performed by the N.V. Foraky, Brussels with the scientific co-operation of the Belgian Geotechnical Institute and is sponsored by the Belgian Governmental Institute for Scientific Research in Industry and Agriculture.

Out of different parameters influencing possibly heave and set, four were chosen

for examination of their influence :
- the composition of the soil,
- the arrangement of the freeze tubes,
- the position of the water table,
- a surcharge on top of the frozen volume.

In the contribution first is given a general description of the normal procedure o: a test ; then a review is given of the assumptions about the various parameters fo: the different tested soils, followed by a description of the measuring installations. Endly the results of the tests are given and tentatively the influences of each of the parameters is defined.

1. General description of a test procedure.

First the test procedure, established before the start of the tests, will be described. During testing this procedure was adapted several times, learning from the tests what was more and what was less important. On discussion of the results, we will indicate the modifications every time some were made.

The tests were carried out in the testpit of the State Geotechnical Institute at Ghent. This test pit consists of a vertical cylindrical shaft in concrete, with the following dimensions : inside diameter 3 m, thickness of the concrete wall 0,40 m, depth about 10 m. The treshold of the test pit is situated two meter above the ground level of the large testing hall of the Institute. This concrete shaft stays in a square cellar, of about 6m x 6m, 8m deep and so can be inspected outside all around, from the ground floor to the bottom through three intermediate storeys (fig 1). On each floor are provided four openings through the pit wall, sealed off with steel doors, permitting the installations of all kind of equipment ; four more smal ler ports can be used as cable passes.
To give a uniformity in the presentation of the results, the level 0,00 was given to the bottom of the test pit.
The soil to be tested can be stored in two underground bunkers, in the vicinity of the test pit, located in the same hall. These bunkers can contain each 35 m^3. A supplementary container for 25 m^3 is placed on the floor of the hall.
To manipulate the soil volumes to be tested, a portal crane is installed in the hall, and can be equipped with a grab or with lifting hooks. The crane's lifting capacity is 50 kN.
With the kind of soil to be tested and which should be submitted to freezing, a tc tal thickness of 2,30 m was realized (fig. 2). Above this volume, a layer of 1 m o 5 m of white fine sand of Mol (Belgium) was placed, without compaction, to act as surcharge on the soil mass to be frozen.
For determining the volume weight of the soil, a densitometer and volumetric rings

were used.
During the filling of the test pit, a structure consisting of nine freeze tubes, each 1 m long and distant of 0,5 m is placed in the soil to be tested. These freeze tubes are made of normal steel pipes of 5/4" diameter, with smaller 3/4" dia tubes inside. Three groups of three in series are connected in parallel in the brine circuit. A sort of a cube with 1 m side and one tube in the middle forms a freezing "module". (fig. 3).
The brine supply and return pipes, connected to the module, are well insulated and fixed against the inside of the pit wall. The brine circuit is completed with a circulating pump, an expansion vessel, and the brine is cooled in the chiller of a refrigeration unit, especially built for these tests.
The refrigeration unit consists of a semi-hermetical tandem compressor, a water cooled condensor serving also as receiver for the refrigerant and a doubled liquid line, consisting each of a humidity- and flow indicator, a filter-dryer, the necessary valves and a thermodynamic regulation valve. The chiller is of the "dry-ex" type, suitable to work with Freon as refrigerant. The compressors have motors of 3,75 kW each. The brine pump has a motor of 0,75 kW. All necessary safety controls are installed, as : pressostats for high, low and oil pressure, electric safety controls, thermostatic controls and a time programmable switch.
To follow the temperature progress in the tested volume, ten thermocouples are installed in the soil to be frozen. The variations of the temperatures in these different points are registered on a multipoint recorder for twelve thermocouples. The two more record the temperature of the in- and outflowing brine of the circuit. The thermocouples are of copper-constantan, and the recorder is directly calibrated in centigrades.
The heave and settlement of the tested volume are measured on a setting-beacon, installed 0,25 m above the freezing module. This beacon consists of a square steel-plate of 0,50 m side, 10 mm thick, connected to a rod in the center. To prevent the friction from the surrounding sand, the rod is protected by a casing. The displacements of the beacon are measured with a dial gauge with an accuracy of 0,01 mm. The dial gauge is fixed on a perforated metal beam, fixed in two opposite portholes near the treshold of the test pit, and the stem of the dial gauge rests on the top of the beacon rods.
In some tests, static cone penetration tests have been made before freezing and after thawing, to check the influence of the freezing and thawing cycles on the bearing capacity of the tested soil. These tests were performed with a penetrometer which could be fixed on the treshold on the test pit.
In the normal test procedure after filling the pit with soil, from the underside, by opening a valve, water gets the possibility to rise into the soil. In order to

control this process, and to get an idea about the degree of saturation obtained, the following equipment is installed : a flow meter, a totalizer indicating at each moment the volume of water already introduced in the test pit, an overflow, adjustable in height, in order to be able to realize and maintain a given water level. During filling the water gradient has to be sufficiently small, in order to prevent the air and afterwards the water bubbling out of the soil. The water head can be read by means of four piezometers, placed one on each floor, and fixed on the walls of the test pit. The rapid distribution of the water entering the test pit is obtained by means of a filter layer of coarse sand and a screen made of fabric and placed at the bottom of the pit.

Assumptions about the different parameters.

In order to check in what manner the swellings and settlements on freezing and thawing are possibly influenced by the grain size distribution, by the position of the freeze tubes, the water table, the surcharge, ... a large number of tests has been performed, while varying these parameters. Fig. 2 gives a synopsis of the different combinations of these parameters, which were considered in the programme.

a) grain size distribution of the soil to be frozen.

The tests were carried out on three different soils : silty to clayey sand, with respectively 13%, 20% and 25% of particles smaller than 60 µm. According to the usual criteria, these soils are to be considered as susceptible for frost. In extensive areas in Belgium they form the upper soil layer.

b) disposition of the freeze tubes.

In view to prospect the influence on the heave of the direction in which the frost front progresses, the freezing tubes were placed either horizontally or vertically. The same freezing module was used, but turned over 90° for the alternative disposition.

c) position of the water table.

In the original programme, two different locations of the water table had been included, one in which the water table was located above the freezing module and the soil mass to be frozen, another in which the water table was located underneath but at a sufficiently short distance in order that the soil mass to be frozen, was still in the capillary fringe. However unexpected difficulties arose for holding the watertable at the intended level with the consequence that some tests were performed with the frozen volume partially above, and partially below the phreatic level.

The first tests were made with a fixed volume of water, i.e. after equilibrium of the water head, all in- or outflow was prevented from the test pit. The last tests were carried out with a fixed water head, hold on level during the complete test. In- and outflow was then made possible by coupling the test pit to a vessel in which a constant waterlevel was maintained. Daily the volume of water absorbed or expelled by the soil in the test pit was measured.

d) surcharges.

The tests were performed for two different values of the surcharge namely 1 m or 5 m of sand of Mol. This means a surcharge of about 14 kN/m^2 or resp. 70 kN/m^2. In the application of the freezing technique often much higher surcharges are existing. However, because of the limited possibilities of the installation, it has not been possible to use a larger overload than 70 kN/m^2.

3. Properties of the tested soil.

The three tested soils are found in the nature, in the neighbourhood of Ghent, and are used as material for masonry mortar. The white sand of Mol is a pure quartzite fine sand, found around the city of Mol, in the northern part of Belgium. Because its purity, it is a sand widely used in the glass industry. It first was planned to mix the soil to be tested in well defined proportions between this rather pure Mol sand and fine clay particles. In this way it should have been possible to vary the silt content and to determine the influence of this content on the soil movement by freezing and thawing. But when considering the mixing necessities of so large a volume, say 20 m^3, this intention was abandoned, and it seemed easier to prospect all the sand pits of the surroundings to find a suitable soil for the tests with the sieve characteristic approaching the requirement.

a) grain size distribution.

The grain size curves of the three soils indicated A, B and C are given in fig. 4. Also the frequency curve for the white sand of Mol is given on the same figure.

b) general soil mechanical classification.

The soil mechanical characteristics of the tested soils are given in table I.

c) thermal properties.

The thermal properties of the soil A were determined in the laboratory on samples with a rather low density (γ_d = 14,32 kN/m^3) and a degree of saturation of respectively 33% and 82%. The obtained values for the thermal conductivity K were respectively of 1,669 and 2,19 W/m.K and for the volumetric specific heat capacity C respectively of 1,68 and 2,52 MJ/m^3K. The measured values of the volumetric specific heat are somewhat lower than the values normally accepted for sands. This may be due to the low density and the silt content of the samples.

4. <u>Synopsis of the test results</u>.

a) Tests on soil A (13% particles smaller than 60 µm).

With the soil A a total of 12 tests were performed (see table II). After thawing, in tests 1 to 6, the soil was each time removed, and reloaded after changing the disposition of the freezers, thermocouples, surcharge, etc... The tests showed that the results obtained with large scale tests are rather different with those obtained with similar small scale laboratory tests. After test n° 6, a program was made allowing to perform several tests without removing the soil, changing only the water level and/or the surcharge. It so became possible to perform tests 7 and 8, and tests 9, 10, 11 and 12 for each group with the same filling.

In the tests 1 to 6 the thawing proceeded in a natural way : this means that at the end of the freezing period, the brine circulation was stopped together with the refrigeration unit ; so the warmth to thaw was only brought in through the concrete wall of the test pit. To accelerate the thawing, the brine circulation was maintained in test n° 7 and 8, without refrigeration. The warmth exchange in the brine circuit brought the temperature of the brine quickly to + 4° and gradually to + 10°C. In order to shorten further the thawing time, from test n° 9 on a brine warmer was installed, warming up the brine electrically to about + 30°C during the thawing period.

In tests n° 1 to 8, some static cone penetration tests were made in the soil under test, to investigate the bearing capacity before freezing and after thawing. The results showed that it was not possible to secure the homogeneity of the compaction, probably because the installation of the freezing module and of the measuring equipment prevents an homogeneous compaction of the soil to be tested. The scatter of the results is too large for a possible interpretation. In a general way the penetration resistance seems not to have been influenced by the freezing and thawing cycles.

In the test n° 3 before and after freezing and thawing, the density and water content was measured with a gamma and neutron ray apparatus. The results indicated that even under the phreatic level the saturation was only about 80%. This low value can be explained by the way the water was introduced in the pit : through the filter at the bottom of the test pit, water could rise through the soil mass. This rising water however did not fill all the pores, leaving a large amount of trapped air in the soil ; the test installation is not provided to put under vacuum.

For the later tests other ways of introducing the water are considered, in order to obtain a nearly perfect saturation, as the heave and settlement phenomena under freezing and thawing cycles are without any doubt, largely influenced by the degree of saturation.

It is not possible to reproduce here all the measurements made during all the tests. In fig. 5 we give the results of test n° 9. One can observe that the displacements of the beacon immediately at the end of the freezing period indicate an important heave. This phenomenon was observed in each test, with variable importance.

From the results given in table II the following deduction can be made :

- the tests made under the same circumstances, but for horizontal or vertical dispositions of the freezing tubes have given the same results. We have to accept that for all the tests, there was no influence by the geometric arrangement of the freeze tubes. However it must be stressed that most of the tests have been performed in unsaturated conditions and that the conditions in the tests still differ from those in reality. Therefore one should be cautious not to generalize these findings for normal field conditions.
- the measured heaves are rather limited. In some tests even a small settlement was observed during the freezing period.
- the absence of systematic data about the water content and the saturation ratio hampers greatly an interpretation of the results.

b) Tests on soil B (20% particles smaller than 60 µm).

On this soil B, in total 9 tests were performed (see table III). All the tests were performed with only one filling of the test pit. The freeze tubes were installed horizontally and the variation of the water table within the test pit, was regularly observed in two piezometers installed near the concrete wall of the test pit.

Before starting test n° 13, one tried to stabilize the water table in the test pit at 0,30 m below the lower grid of the freeze tubes. After an absorption of a certain quantity of water in the test pit, the piezometers indicated very different water levels, which were both above the aimed level. During the following freezing and thawing cycles, large variations of the observed water levels occurred. This indicates that in the test pit, there was no apparent water table, and that we had to deal with a mass of soil with largely variable water saturation.

All these tests were performed with a fixed water volume. During the tests no water was allowed to flow in or out the test pit.

Before starting tests n° 15 and n° 16, a volume of water was pumped in the test pit, so that the water level in both piezometers was standing more than 0,50 m above the upper grid of the freeze tubes. During the tests again large variations of the levels were registered, probably partially in relation with the incomplete saturation of the soil.

To shorten the thawing time as much as possible, the brine then was warmed up to + 30°C and circulated in the freeze module.

The soil density was measured at the end of the test n° 21 and after the withdrawal of the water.

From the results given in table III the following conclusions can be made :
- in all tests during the freezing period a heave of the soil mass was observed.
- immediately after stopping the cold brine circulation, and on starting the warm brine circulation, again an abrupt increase in heave was observed. This only for a couple of hours ; later on a more or less important settlement was registered.
- from the results of similar tests, with a surcharge of 14 kN/m^2 or 70 kN/m^2, it appears that the frost heave is less with the larger surcharge, as also the settlement after thawing.
- from the results of test n° 17, restarted at a moment that the temperature recorder showed 0°C everywhere in the soil under test, it appears that again there was a heave, and again there was that abrupt increase of the heave on the start of the thawing.

c) Tests on soil C (25% particles smaller than 60 µm).

Until the end of 1979, a total of 8 tests were performed on the soil C (see table IV). All the tests were performed with only one filling of the test pit. The freeze tubes were installed in a horizontal position and the water level in the test pit was regularly observed in two piezometers installed near the concrete wall of the test pit.

The tests n° 22 and n° 23 were performed with a fixed water volume. After test n° 23 a fixed water head was installed and hold on during the complete test. For the test n° 24 the waterlevel was installed 0,25 m beneath the lower grid of the freezing module and for the tests n° 25 to 29 ca. 0,50 m above the upper grid of the freezing module.

Until test n° 27, it was necessary to limit the freezing time to ca. 10 days, this is until the frost front could reach the concrete wall of the test pit, because it should be avoided that the frozen ground causes an unacceptable pressure on the concrete wall. In order to have the opportunity to perform some long term tests, circular pipes were installed against the concrete wall of the test pit, through which warmed brine was circulated. In this way it was possible to maintain a distance of ca. 0,30 m between the frost front and the concrete wall of the test pit.

The tests n° 23 and n° 24 and the tests n° 25 and n° 26 were performed under the same circumstances with the only difference that during the tests n° 23 and n° 25 freezing took place continuously and that during the tests n° 24 and n° 26 freezing was interrupted for 12 hours a day (12 hours freezing and 12 hours without brine circulation).

From the results given in table IV the following conclusions can be made :

- in all tests again an abrupt increase in heave was observed immediately after stopping the cold brine circulation, and on starting the warm brine circulation.
- the heaves measured under interrupted freezing are of the same order as the heaves measured under continuous freezing, for a same extension of the frozen volume.

GENERAL CONCLUSIONS.

From the program of large scale tests of freezing and thawing performed in a large test pit, which is still in progress, the following general conclusions can already be drawn :

1°) the results of heave and settlement measurements due to freezing and thawing cycles, obtained on small laboratory samples have to be interpreted with caution, for predicting the real field behaviour. In a less degree this is also true for the large scale tests performed until yet.

2°) with due consideration to conclusion 1, it can be stated that the heave and settlement phenomena increase all other considerations remaining equal with the content on particles smaller than 20 µm.

3°) with due consideration to conclusion 1, it can be stated that the heave and settlement phenomena decrease, all other conditions remaining equal, when the overburden pressure increases.

4°) with due consideration to conclusion 1, it is observed that the heave gradient (increase of heave with time), becomes maximum, when at the end of the freezing period, the input of frigories is abruptly decreased. It is only a certain time after stopping the influx of frigories that the heave reverses to settlement.

TABLE I

Properties of the tested soils.

Tested soil	A	B	C
- Content on particles smaller than 20 µm (%)	5,5	15	11,5
- Plasticity index	0,4	7,6	1,0
- Content on organic materials (%)	0,1	0,1	0,2
- Chalk content (%)	3,4	0,8	0,7
- Maximum unit weight of the dry soil (in kN/m^3)			
. Modified Proctor test (AASHO)	16,87	18,93	18,73
. ASTM 1969	15,28	14,18	15,37
- Minimum unit weight of the dry soil (in kN/m^3)	12,69	11,29	12,08

TABLE II - Tests on soil A

Test n°	1	2	3	4	5	6	7	8	9	10	11	12
Surcharge (in kN/m^2)	14	14	14	14	70	70	70	70	14	70	14	14
Phreatic level *	B	B	A	A	B	I	I	A	A	A	A	A
Arrangement of the freeze tubes **	V	H	V	H	H	V	V	V	H	H	H	H
Freezing time (in hours)	91	116	163	166	96	312	264	144	168	167	167	166
Mean brine temperature (°C)	-23	-20	-22	-23	-20	-21	-20	-20	-28	-29	-29 (-12)	-29
Temperature of thermocouple n° 6 (°C)												
. on start of freezing	+18,5	+18,5	+14	+13,7	+15	+15	+12	+10,5	+11,5	+11	+2	+8
. at the end of freezing	-12,4	-12,2	-16,4	-16	-12	-17,6	-13,9	-13,8	-17,8	-20,7	-7,5	-19,9
Thawing time (in hours)	264	276	493	393	240	528	213	191	48	71	146	144
Brine circulation during thawing ***	no	no	no	no	no	no	yes	yes	W.B.	W.B.	W.B.	W.B.
Temperature of thermocouple n°6(°C)												
. after 24 hours of thawing	-3,4	-4	-5,7	-4,9	-3,6	-8,2	-3,7	-3,8	-2,4	-2,3	-1,2	+1,7
Measured swelling (+) or settlement (-) (in mm)												
. during freezing	-0,18	-0,21	+2,00	+0,70	-0,46	+0,33 -0,06	-0,55	-0,25	+1,35	-1,37	-0,10 +1,00	-1,35
. during thawing	+0,17 -0,04	+0,39 -0,12	+1,44 -1,88	+1,73 -0,93	(+0,16)⊛ -0,33	+0,33 +0,39	+0,40 -1,05	(+0,15)⊛ -0,80	+3,10 -0,80	+0,84 -0,51	+0,92 -1,07	+1,15 -0,98

* B = underneath the freeze tubes
A = above the freeze tubes
I = interjacent

** V = vertical
H = horizontal

⊛ only one measured value

*** no = no brine circulation
yes= brine circulation
W.B.= warmed brine circulation

TABLE III - Tests on soil B

Test n°	13	14	15	16	17	18	19	20	21
Surcharge (in kN/m^2)	14	70	14	14	14	14	70	70	14
Phreatic level *	I	I	I	A	A	A	A	A	A
Arrangement of the freeze tubes **	H	H	H	H	H	H	H	H	H
Freezing time (in hours)	216	190	222	168	140	92	288	168	312
Mean brine temperature (in °C)	-29	-28	-15 (-7)	-29	-28	-25	-24	-29	-30
Temperature of thermocouple n° 6 (°C)									
. on start of freezing	+14,5	+12,7	+8,2	+14,5	-0,7	+0,2	+11,5	+17,5	+17
. at the end of freezing	-20,6	-18,8	-3,0	-18,5	-20,7	-16,9	-15,8	-18,8	-21,9
Thawing time (in hours)	312	168	240	28	76	218	194	290	194
Brine circulation during thawing ***	W.B.	W.B.	W.B.	W.B.	W.B.	W.B.	W.B.	W.B.	W.B.
Temperature of thermocouple n° 6 (°C)									
. after 24 hours of thawing	-1,8	-4,5	+2,5	-0,7	-2,5	-1,7	-1,5	-1,5	-2,1
Measured swelling (+) or settlement (-) (in mm)									
. during freezing	+3,2	+4,0	+9,15	+9,70	+1,45	-0,25 +3,95	+6,00	+5,44	+11,5
. during thawing	+1,5 -8,9	(+1,0)@ -6,65	+0,75 -6,1	+1,50 -0,20	+2,20 -3,95	+1,40 -10,40	(?) -8,10	+0,60 -4,60	+3,30 -12,5

* I = interjacent A = above the freeze tubes ** H = horizontal *** W.B. = warmed brine circulatio

@ only one measured value

<u>TABLE IV</u> - <u>Tests on soil C</u>

Test n°	22	23	24	25	26	27	28	29
Surcharge (in kN/m^2)	14	14	14	14	14	14	14	70
Phreatic level *	I	I	B	A	A	A	A	A
Arrangement of the freeze tubes **	H	H	H	H	H	H	H	H
Freezing time (in hours)	98	72	317	145	237	173	846	336
Freezing regime ***	C	C	I(13)	C	I(9)	C	C	C
Mean brine temperature (°C)	-19	-17	-20	-21	-18	-22	-18 (-9,5)-19	-19
Temperature of thermocouple n° 6 (°C)								
. on start of freezing	+10,5	+13,5	+14,8	+12,5	+16,8	+4	+13,5	+13,5
. at the end of freezing	-18,5	-11,5	-12	-16,5	-7	-15,6	-14,8	-15,3
Thawing time (in hours)	190	96	185	145	145	161	125	123
Brine circulation during thwaing ⊛⊛	W.B.	W.B.	W.B.	W.B.	W.B.	W.B.	W.B.	W.B.
Temperature of thermocouple n° 6 (°C) . after 24 hours of thawing	-1,2	-0,6	-0,5	-0,5	-2,5	-0,5	-0,5	-1,5
Measured swelling (+) or settlement (-) (in mm)								
. during freezing	+4,5	+0,5	-0,6 +1,6	+4,0	-0,3 +2,1	+4,0	+7,0	+3,9
. during thawing	+1,0 -1,3		+0,8 -3,2	+1,5 -4,0	+0,5 -2,4	+1,0 -5,1	+0,5 -9,5	+0,5 -4,8

* see table II

** H = horizontally

*** C = continu freezing
I = interrupted freezing
( )= number of cycles

⊛⊛ W.B. = warmed brine circulation

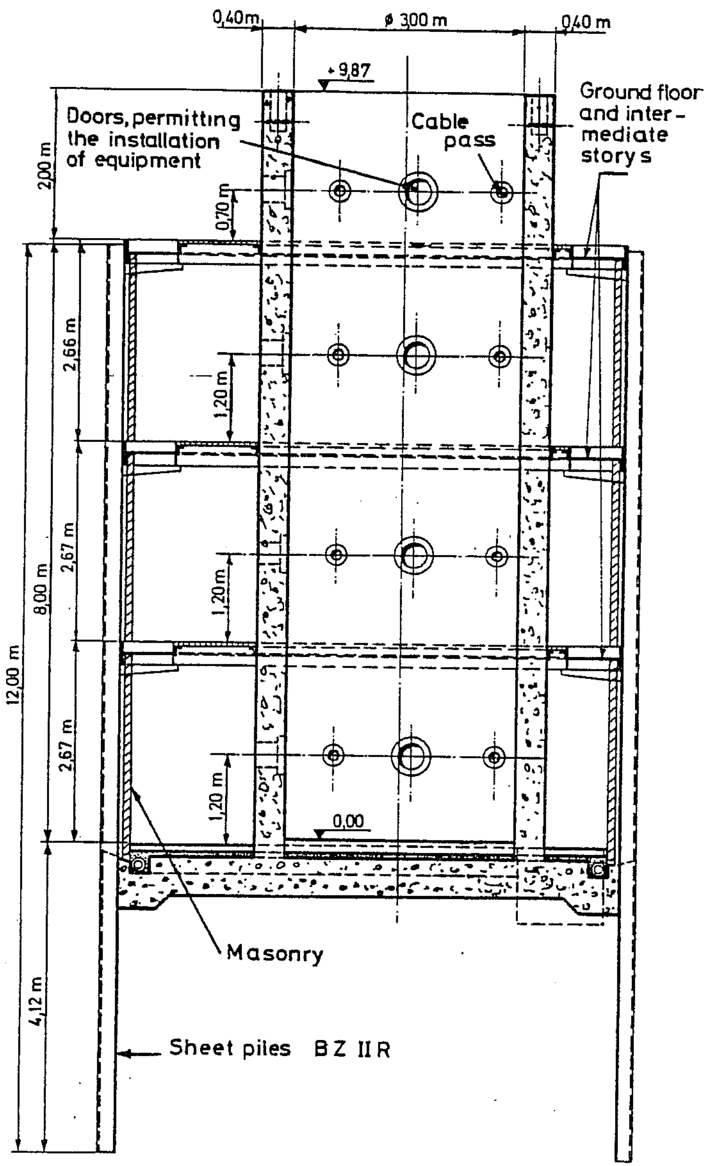

Fig 1: CROSS-SECTION OF THE TEST PIT AT THE STATE GEOTECHNICAL INSTITUTE

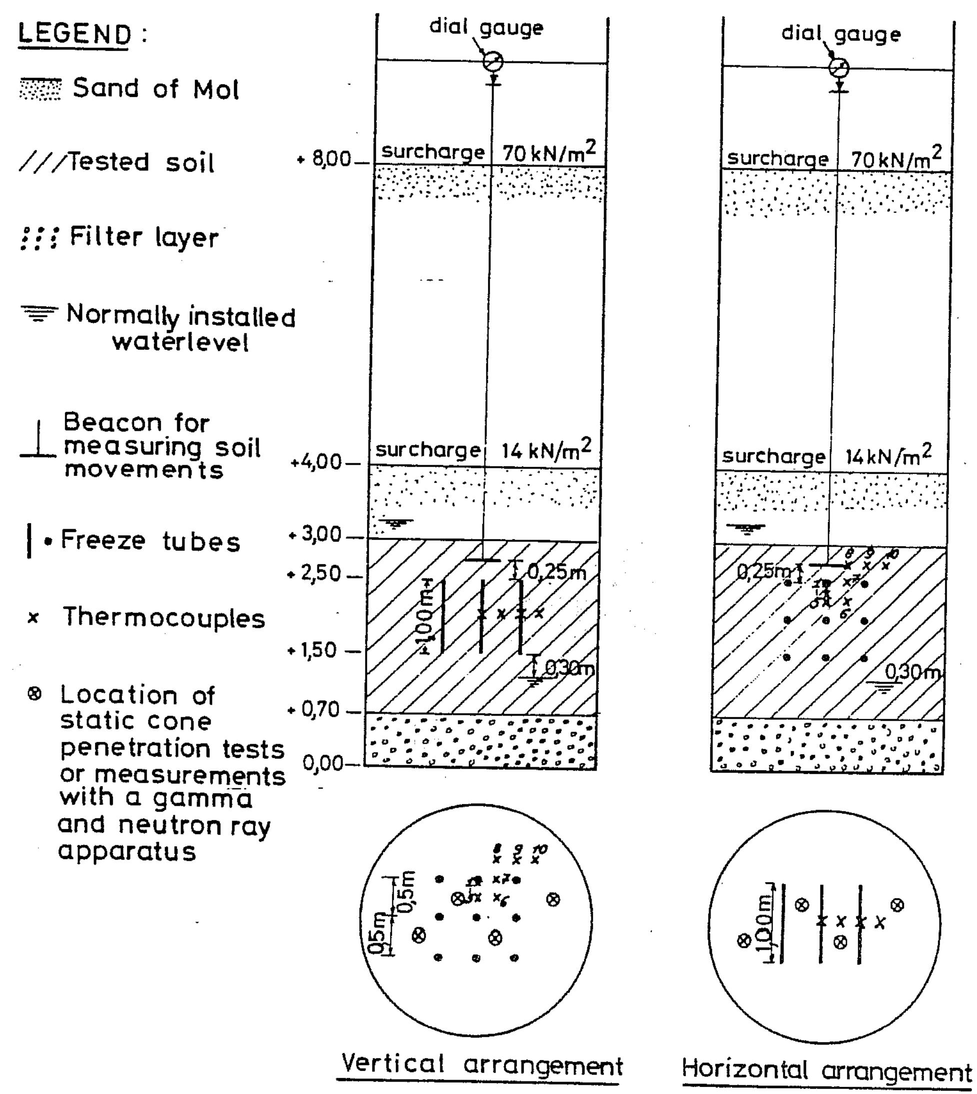

Fig 2: ARRANGEMENTS ADOPTED FOR THE DIFFERENT TESTS

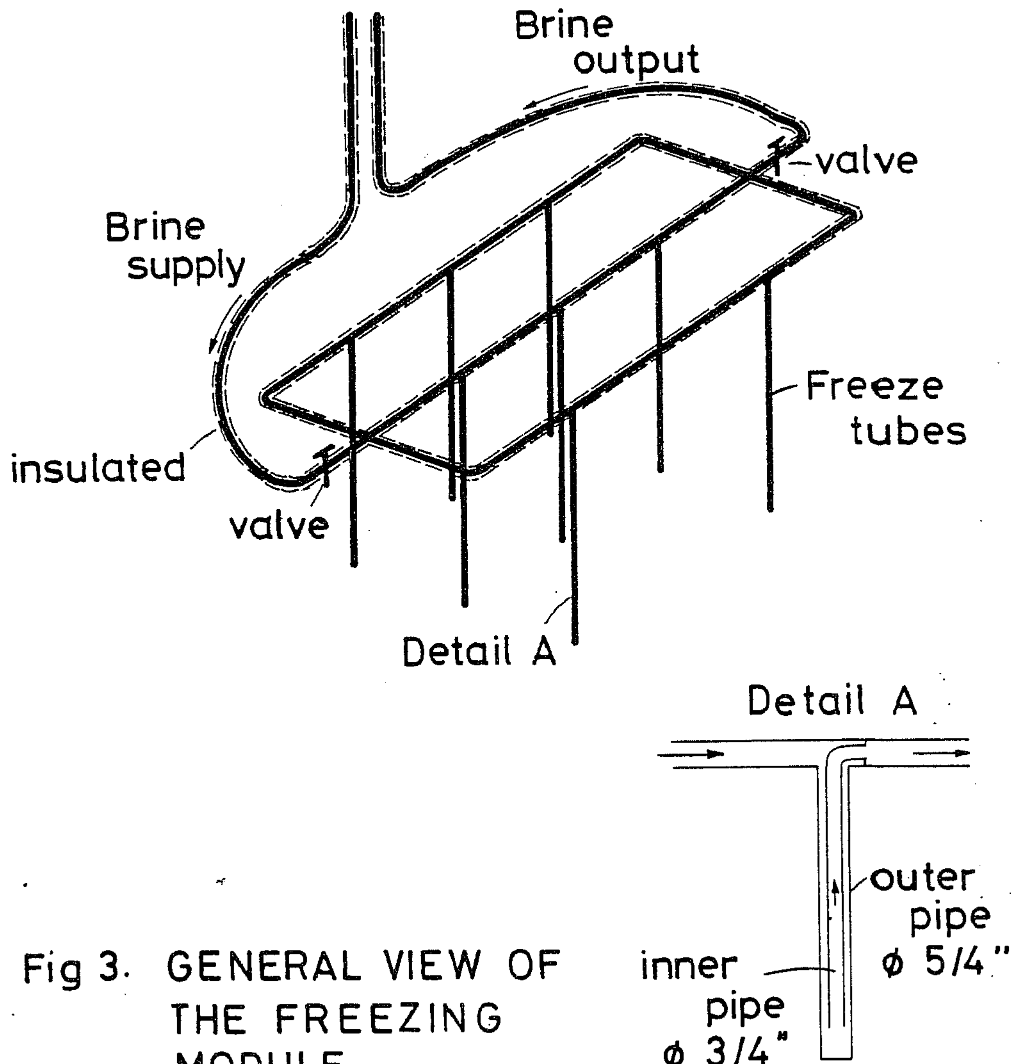

Fig 3. GENERAL VIEW OF THE FREEZING MODULE

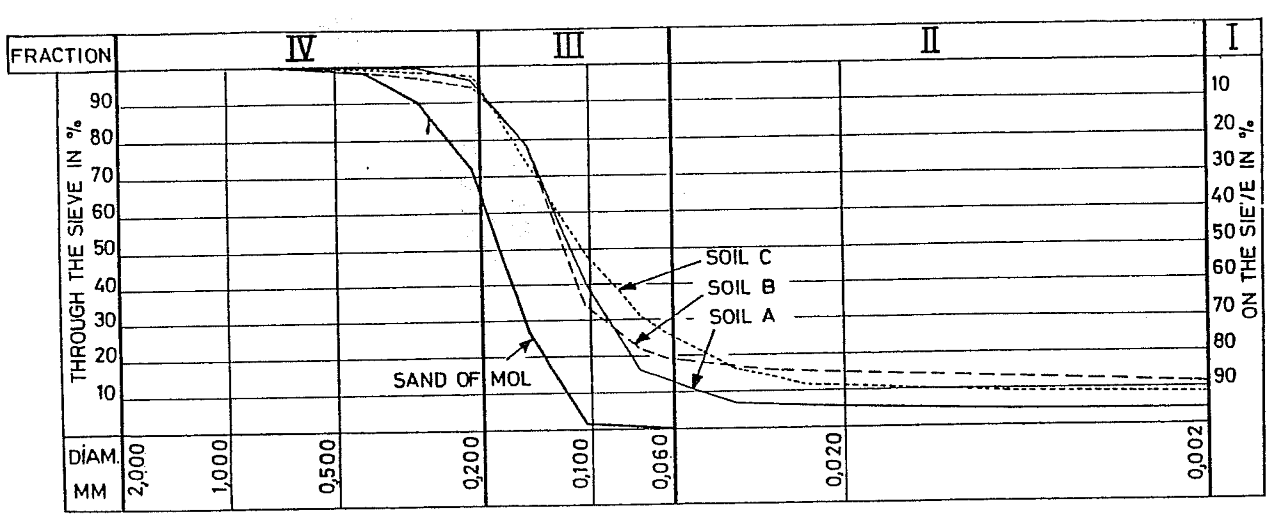

Fig. 4 GRAIN SIZE DISTRIBUTION OF THE TESTED SOILS

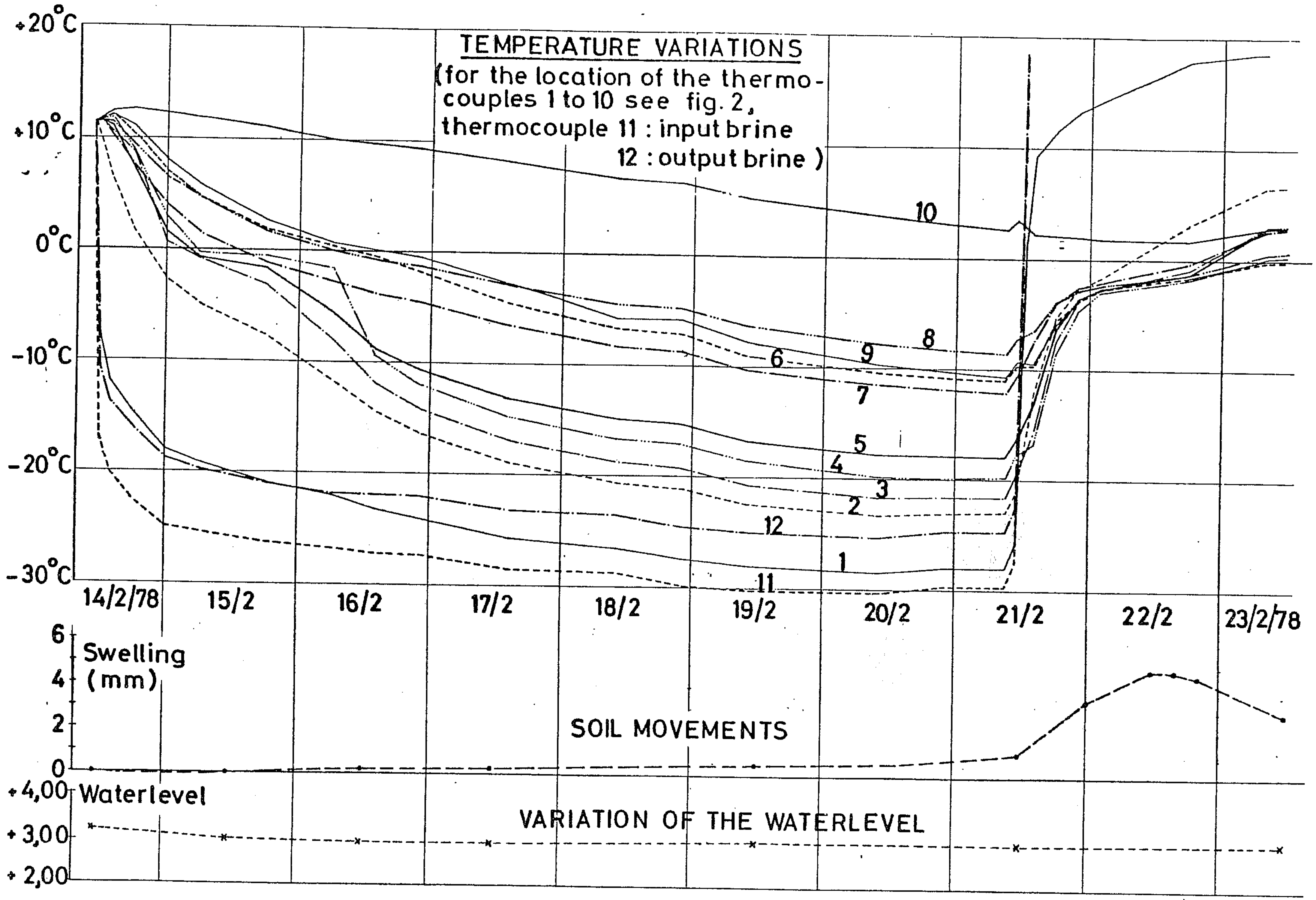

Fig 5 : RESULTS OF TEST nr 9