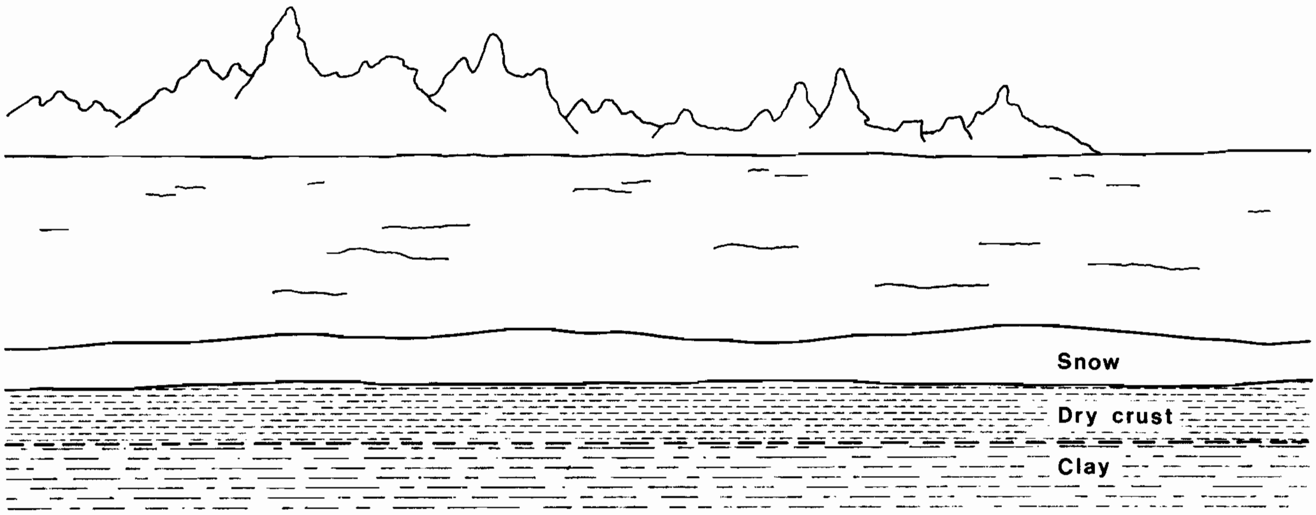
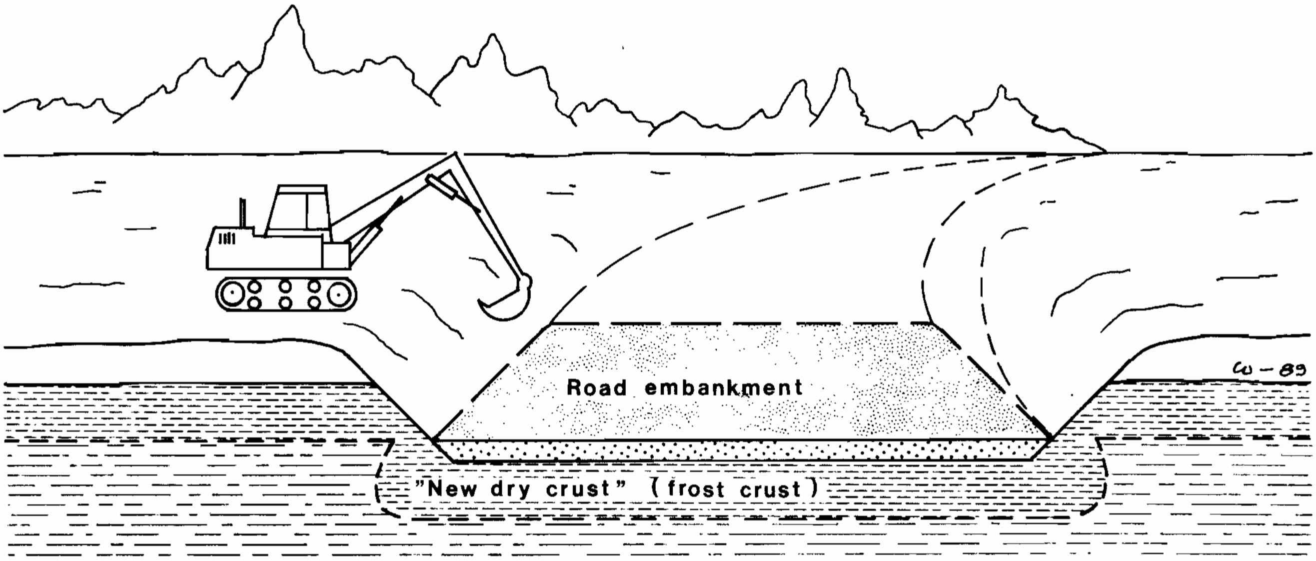
City of Helsinki Real Estate Office
GEOTECHNICAL DEPARTMENT

STEP 1



STEP 2

FROST STABILIZATION
1 - 2 WINTERS + THAWING BEFORE
BUILDING THE ROAD EMBANKMENT



Ilkka Vähäaho

THE EFFECTS OF THAW CONSOLIDATION ON GEOTECHNICAL PROPERTIES OF CLAY

Geotechnical Department Report 51

Ilkka Vähäaho

THE EFFECTS OF THAW CONSOLIDATION ON GEOTECHNICAL PROPERTIES OF CLAY

Report 51/1989
Geotechnical Dept.
City of Helsinki

FOREWORD

An investigation into use of the ground freezing method was begun in 1980 in the Geotechnical Department of Helsinki under the direction of Ilkka Vähäaho. This took place in conjunction with a subway construction project. A report "Use of Ground Freezing"(Geo. no.44/1987) on this work was published. The present report is the English translation of Part I of Report no.50/1989 on Thaw Consolidation in Clay by Ilkka Vähäaho, translated by Seppo Kumar Ph.D. Part I concerns the effects of thaw consolidation on geotechnical properties of clay; Part II by Hannu Ryhänen in the original report concerns thaw consolidation effects on clay structure.

The research revealed new aspects of clay freezing and thawing.Investigations were therefore continued, particularly by closer analysis of the thaw phase. The Geotechnical Department agreed on a research project in engineering geology with the Department of Quaternary Geology at Turku University, to concern the changes in clay structure during the freeze-thaw cycle.

The clay structure was investigated by Hannu Ryhänen M.Sc, under the direction of Professor Veikko Lappalainen. Hannu Ryhänen has previously worked at the geotechnical department and is familiar with the engineering geological conditions of Helsinki.

The geotechnical and engineering geological results and conclusions presented herein are in mutual agreement and lay a new foundation for determining the strength and compressibility of clay as a result of freeze-thawing.

The publication of a joint report is also an indication of successful co-operation between city and university in the area of applied science.

Foundation engineering in Helsinki is executed at an annual cost of about 500 million marks. The results in this report may be significantly used in constructions on clay areas, by renewing and developing winter construction technology. Savings are notable not only in Helsinki but in Finland at large. This concerns a saving of several millions annually.

Helsinki, 20 April 1989

Usko Anttikoski	Veikko Lappalainen
departmental head	professor

ABSTRACT

This project was carried out under the title "EFFECTS OF THAW CONSOLIDATION ON CLAY".

Thaw consolidation has a very significant effect on serttlement properties in relation to geotechnical design. After a freeze-thaw cycle the clay is overconsolidated and thus settlements caused by extra loads decrease to one-third compared to those of unfrozen, normally consolidated clay. The clay sensitivity is also decreased because of the considerably increased remoulded shear strength value. Residual shear strength increases significantly, whereas increase in the undisturbed shear strength is not as large, but nevertheless still notable. So after thaw consolidation the clay is is less compressible, less sensitive and resembles dry crust in its properties.

The structure of clay is changed by the physico-chemical phenomena that occur during freezing and thawing. The change is recognized in the increasing particle size which results from the higher degree of particle aggregation. The freezing process both reduces the slightly alkali pH-value of pore water and increases the ion concentration in the water film surrounding clay particles. The former effect increases attractive forces between clay particles by turning the originally negative charge on particle edges and amorphous clay components into positive. The latter reduces the thickness of the electric double layer, thereby decreasing the repulsive forces between particles and allowing closer mutual approach. The consequence of these effects, along with locally increasing effective stress during the freeze-thaw process, is a considerably dense clay structure where consolidated aggregates are separated by shrinkage cracks.

CONTENTS

SYMBOLS

A = thaw settlement for a constant load (%)

a = compressibility modulus of thawed ground [MPa]

c = cohesion [kPa]

G = unit weight [kN/m^3]

k_1 = thaw settlement factor (=3)

k_2 = factor (=20)

k_3 = factor (=40)

k_4 = factor for compressibility modulus of thawed ground (=2...4)

m_2 = oedometric rebound modulus[MPa] when stress exponent $\beta_2 = 1$

r_t = shear strength change factor

S_f = shear strength by fall-cone test [kPa]

S_{fr} = remoulded shear strength by fall-cone test [kPa]

S_{res} = residual shear strength by vane test [kPa]

$S_{res}(t)$ = residual shear strength by vane test[kPa] during/after thaw consolidation

S_t = sensitivity to remoulding

S_v = shear strength by vane test [kPa]

$S_v(t)$ = shear strength by vane test [kPa] during/after thaw consolidation

S_{vr} = remoulded shear strength by vane test [kPa]

$S_{vr}(t)$ = remoulded shear strength by vane test [kPa] during/after thaw consolidation

w = original water content(%)

w_L = liquid limit (%)

β_2 = stress exponent

$\Delta\epsilon_2$ = settlement after second freeze-thaw cycle (%)

$\Delta\epsilon_3$ = settlement after third freeze-thaw cycle (%)

Φ = friction angle (o)

1. INTRODUCTION

The freezing of clay and its subsequent thaw settlement as a techno-scientific phenomenon has gone unrecognized in our country, even though thaw settlements may extend upto 30...40% of the frozen layer thickness. The observed thaw settlements have been regarded as arising from normal consolidation settlements.

This work reports results of thaw settlement investigations on clay in the Helsinki area. In geological origin these are post-glacial clays deposited in the bay of Finland which, due to elevation of the ground, are no longer influenced by the sea.

The clays investigated are from beneath the frost limit, having a water content in the range 40...120%, unit weight 14.5 ...18.0 kN/m^3 and they shrink strongly on drying. According to Soveri(1956) the mineralogical composition of Finnish clays for components below 0.001 mm. grain size comprises quartz (<10%), feldspar(<10%) and remnants of amphibole minerals. The major part of clay consists of micaceous minerals comprising illite, mixed-layer minerals, vermiculite and chlorite. From the viewpoint of building technology the mineral composition of Finnish clays is to be regarded as "easy and of even quality", since in particular the absence of clay minerals with expandable lattices eliminates many constructional problems.

Towards the end of 1979 plans for construction of a subway were drawn. The concomitant freezing and laboratory tests together with in-situ and laboratory tests conducted over the succeeding 8 years yielded results which are reported herein in condensed form. Results of the freezing test are reported in detail in Report 44 of the Geotechnical Department:"Use of the Freezing Technique." (Vähäaho 1987)

The letter codes appearing in the figures denote experimental method. The code FST denotes tests carried out in the field or upon samples frozen in field conditions. LT denotes results from freezing and testing in the laboratory.

The mode of presentation of the results seeks to serve practical geotechnical planning as far as possible and hopes to innovate the finding of new applications in the field of thaw consolidation.

2. SETTLEMENTS

2.1 Thaw settlements

The theory and results which follow pertain to the situation where frozen clay is thawed for the first time.

Figure 1 shows thaw settlements as a function of water content. The broken line is a regression function calculated from the results of the geotechnical department. The full line is based upon over 1000 experimental results from China on the native thin clay (Tong C.& Chen E.1985).

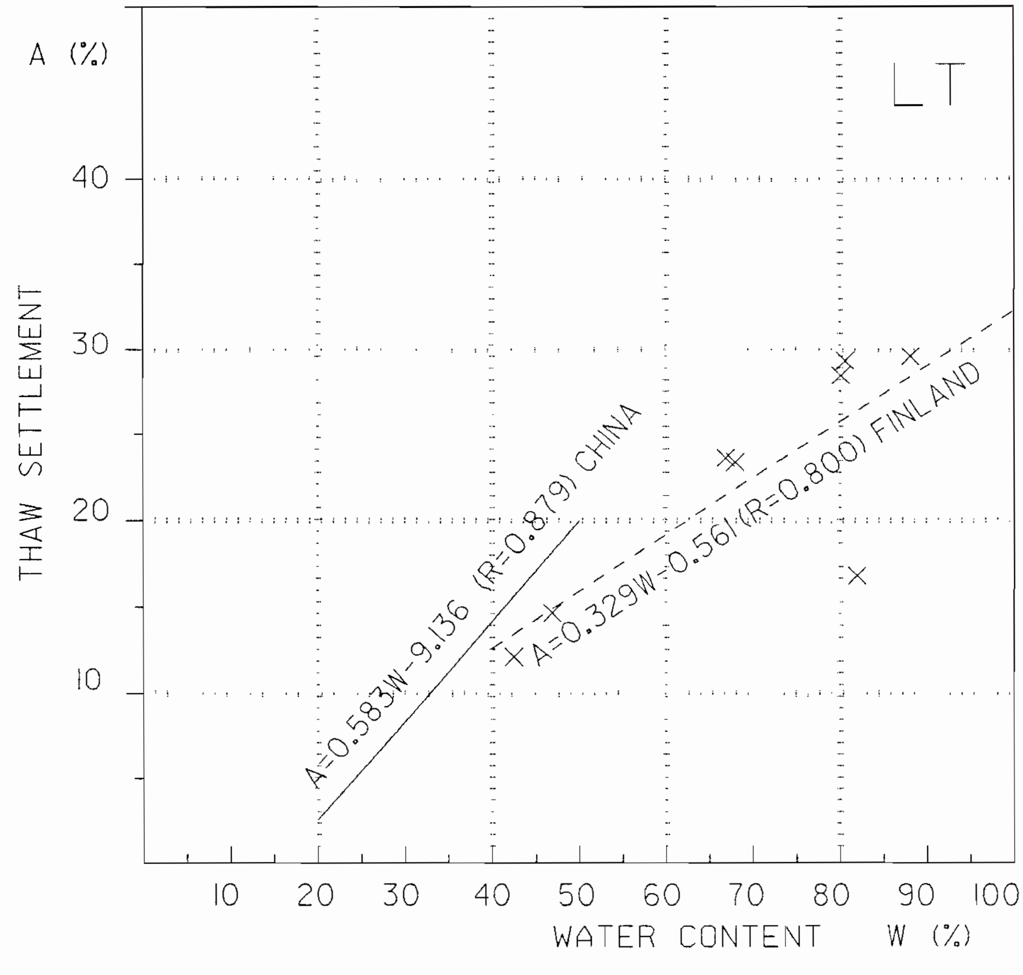


Figure 1. Thaw Settlement as a function of Water Content
In the common region (w = 40...50%) the two different results approach one another, given that the samples come from different parts of the globe.

The following formula for estimating thaw settlements is given by the author (Vähäaho 1988)

$$A = w/k_1 \qquad (1)$$

where A = thaw settlement (%), w = water content(%) and k_1 = thaw settlement factor, the value of which falls in the range 2...6 depending on field conditions. Laboratory tests recommend a value $\cong 3$.

Formula (1) gives a reasonably good estimate of thaw settlement on the basis of water content alone. Other simple thaw settlement formulae have been given by Speer et al.(1973) and Watson et al.(1973). These Canadian results are based on measurements connected with thawing of permafrost.

Figure 2 presents statistical formulae by the Canadians for functions based on unit weight of material,and results from thaw settlement investigations by the Helsinki geotechnical department. The results are in agreement particularly in the case of Speer.

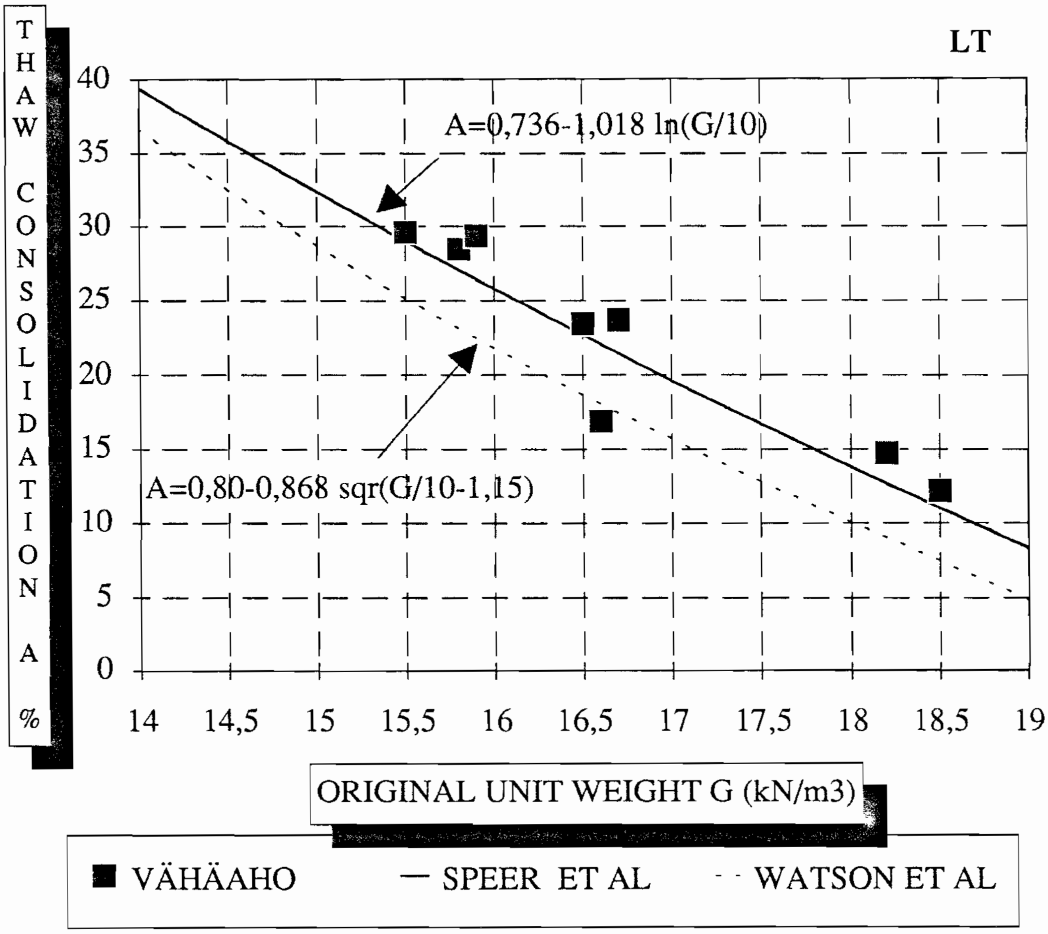


Figure 2. Thaw Settlement as a function of Clay Unit Weight.

Formula (1) is based on tests where the freezing termperature was -10°C and may therefore be applied to estimate thaw settlements caused by seasonal frost. Since the thaw settlement is one third of the water content, the formula is easily remembered. If the original water content is, for example, 100% and the clay has not frozen previously, the thaw following freezing causes a settlement of 33% approximately.

2.2
Further Thaw Settlements

According to laboratory tests the effects of second and third freeze-thaw cycles are significantly smaller than in the case of first thaw (figure 3).

Formula (2) enables estimation to be made of net settlements arising from second and third freeze-thaw cycles.

$$\Delta\epsilon_2 = w/k_2 \text{ and } \Delta\epsilon_3 = w/k_3 \qquad (2)$$

where $k_2 \cong 20$ and $k_3 \cong 40$

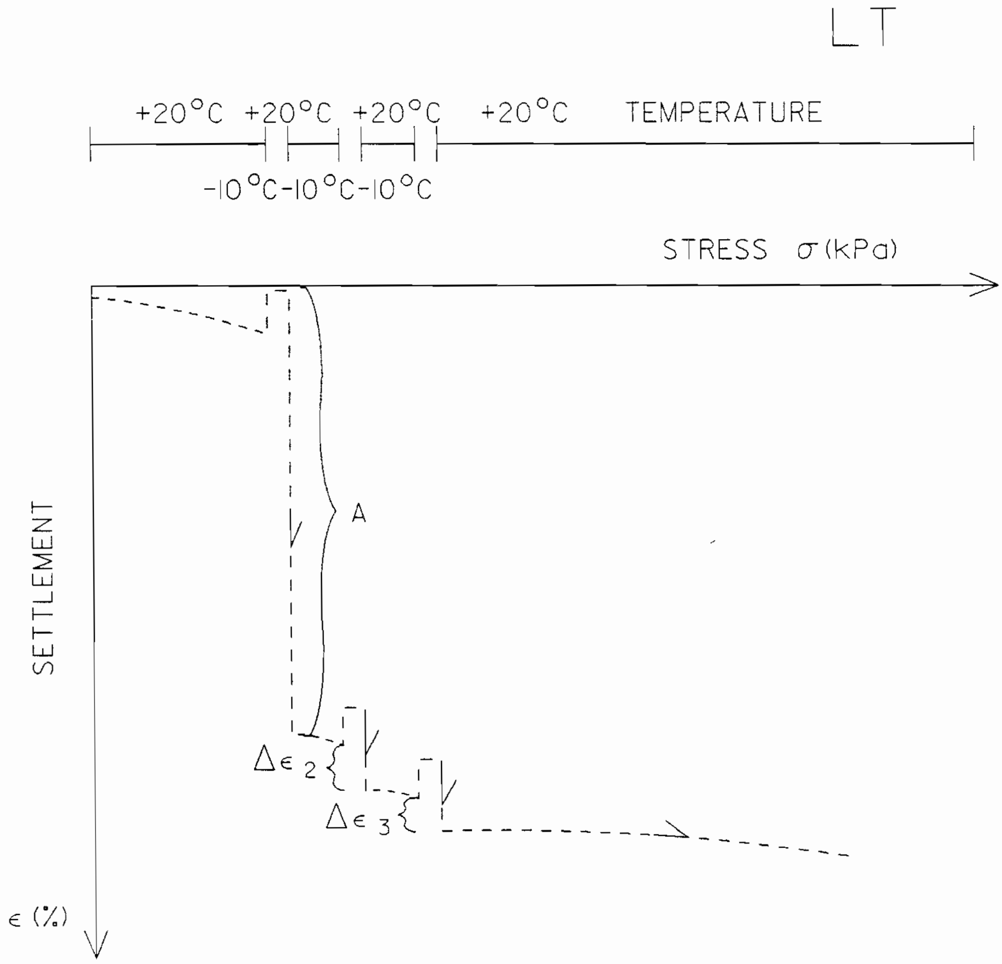


Figure 3. Typical load - settlement function for triply frozen clay.

According to this behaviour a clay layer with 100% original water content would experience an additional depression of 5% and 3% on second and third freezing respectively.

2.3
Post-thaw settlements caused by extra loads

Settlements caused by extra loads subsequent to thawing are relatively small in comparison to normal thaw settlements or settlements due to same extra loads on unfrozen clay.

The settlement curve in the post-thaw loading situation is similar to settlement of overconsolidated clay (figures 4 and 5). A load of 100 kPa causes a settlement of 17% on unfrozen clay (fig.5), whereas after thaw consolidation the same load causes a 6% settlement. Thus, settlements of these clays are reduced to one third by the effects of thaw consolidation.

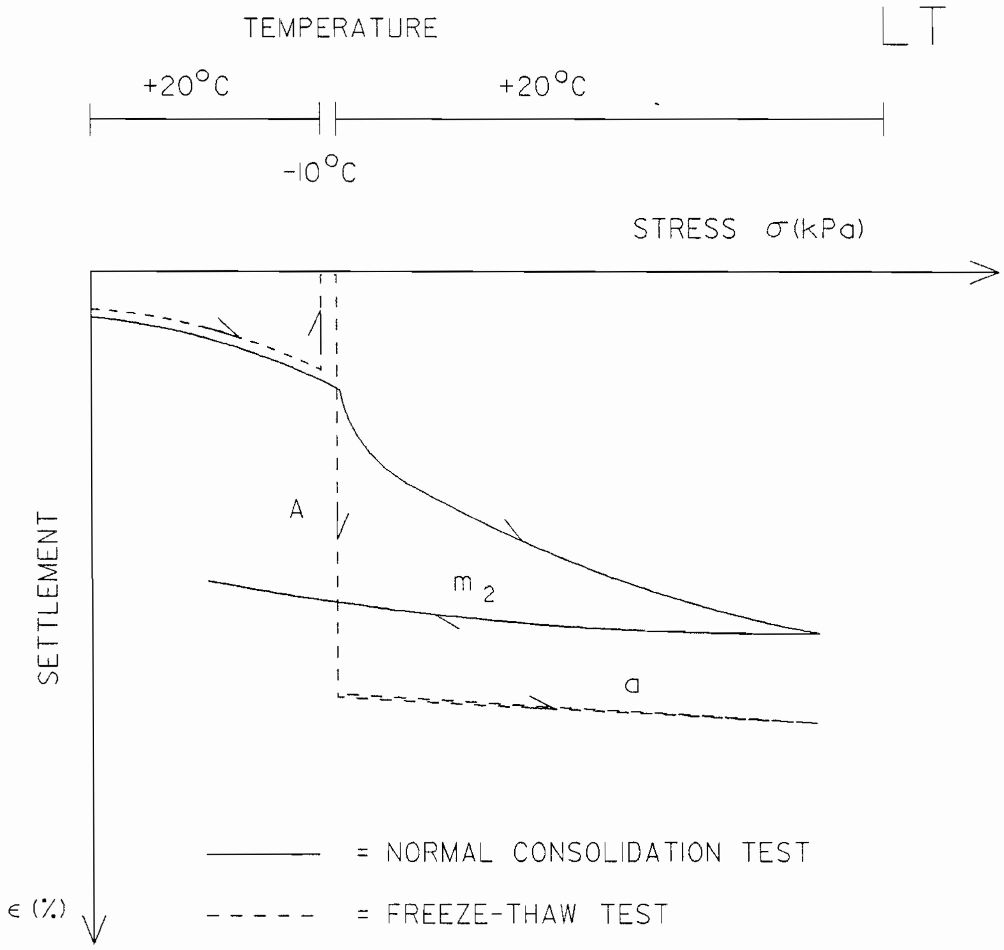


Figure 4. Consolidation curves in ordinary CRS-test and in freeze-thaw test.

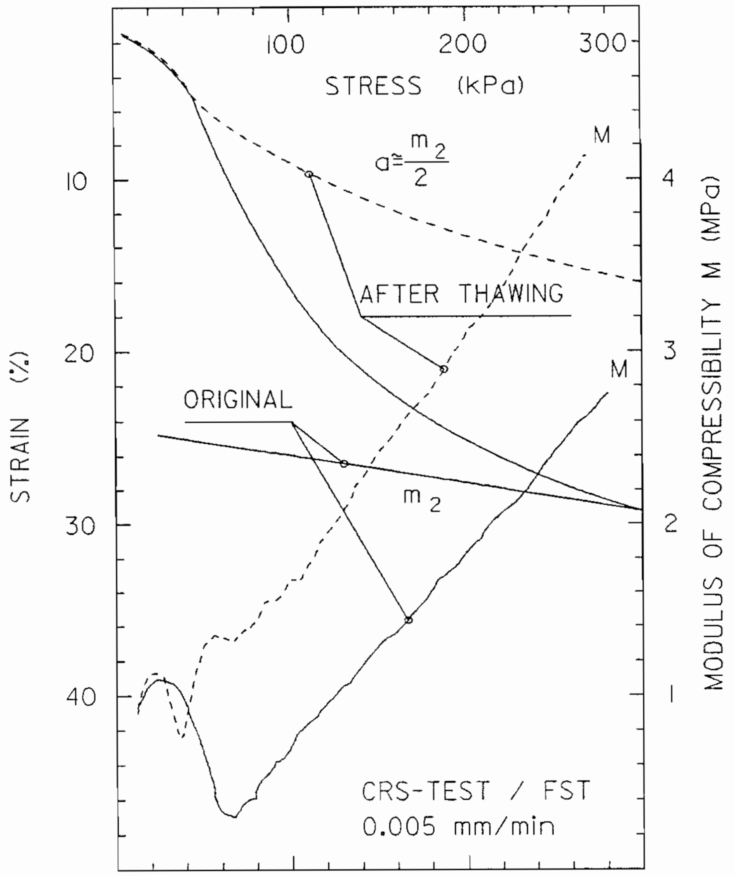


Figure 5. CRS test results on unconditioned and thaw-consolidated clay samples.

The author suggests the following formula for estimating settlements due to extra loads:

$$a = m_2/k_4 \qquad (3)$$

where $k_4 \cong 2...4$

According to eqn.(3) the post-thaw compressibility modulus (a) is 25...50% of the value of the original clay rebound modulus(m_2).

3.
SHEAR STRENGTH CHANGES DUE TO THAW CONSOLIDATION

Vane test measurements in the test freeze area of Oulunkylä gave a shear strength for clay in the range 7...15 kPa, water content 45...110% and a liquid limit 45...90%. The development of shear strength was observed over a 6-year period. Vane tests were also carried out in between the first and second freezing when the lower layers were still frozen.

Shear strength change may be seen from figures 6-8. In particular the increase in remoulded shear strength and the concomitant decrease in sensitivity is clearly visible. The maximum shear strength value decreases initially, but then increases as a function of time to a value clearly greater than the original.

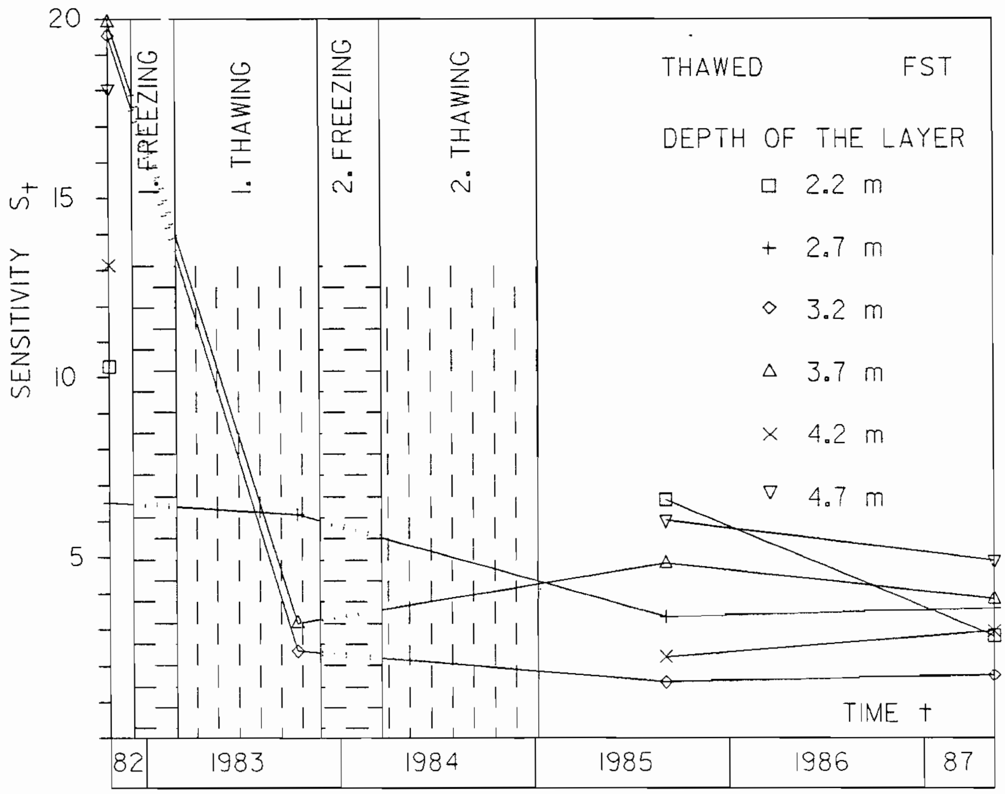


Figure 6. Thaw Consolidation Effects on Sensitivity

The author suggests the following formula for estimating shear strength changes arising from thaw consolidation:

$$S_v(t) = r_t \, . \, S_v \qquad (4)$$

where r_t is a factor which during thaw takes a value of 0.5 and in the final consolidation stages is 1.35...1.9.

A similar formula for estimating changes in remoulded shear strength is:

$$S_{vr}(t) = 4 \, . \, r_t \, . \, S_{vr} \qquad (5)$$

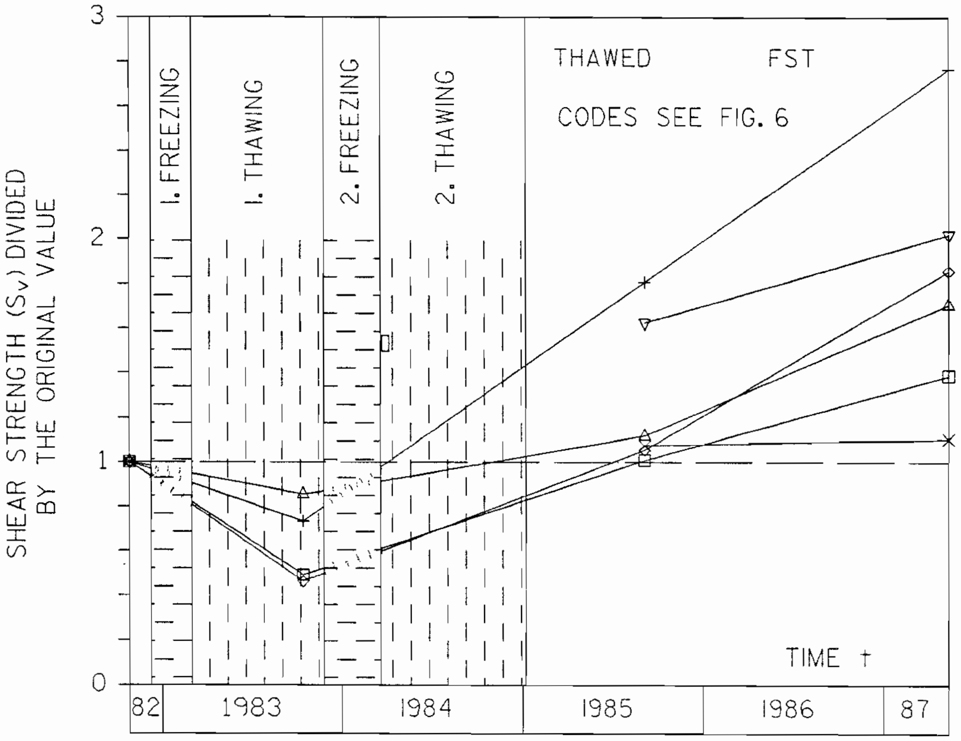


Figure 7. Effect of Thaw Consolidation on Shear Strength.

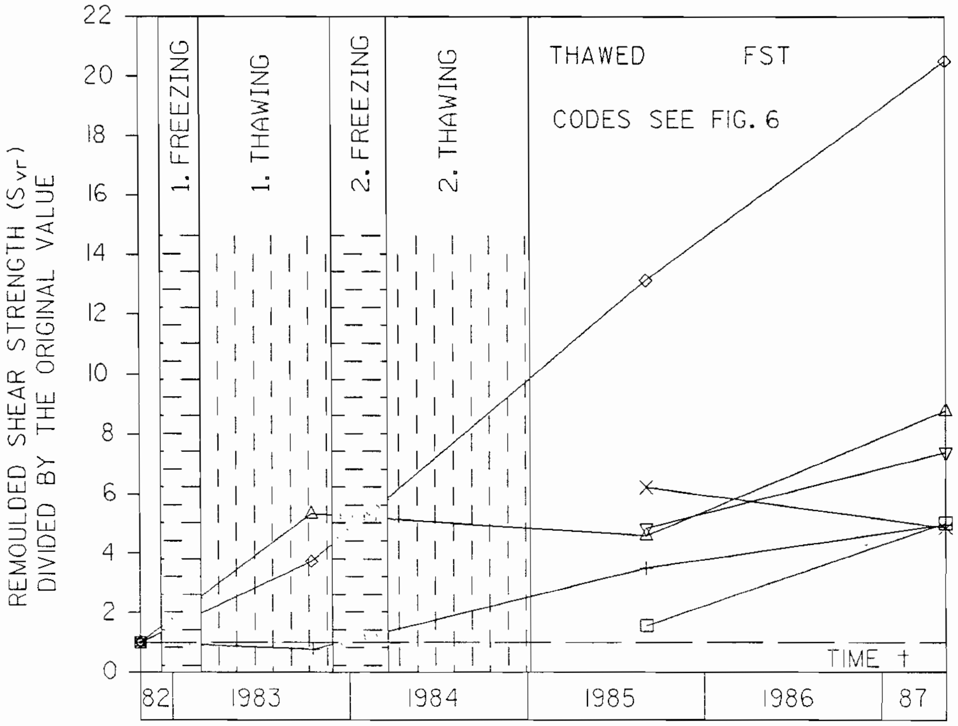


Figure 8. Effect of Thaw Consolidation on Remoulded Shear Strength.

The coefficients in equations (4) and (5) have now been slightly altered with respect to earlier presentations (Vähäaho 1987, 1988, 1989a). These modifications are based on field investigations in October 1988, whence changes in shear strength and remoulded shear strength were determined from 41 analyses. In this connection change in the residual shear strength(S_{res}) was also analysed and the following result obtained:

$$S_{res}(t) = 1.5 \,.\, r_t \,.\, S_{res} \qquad (6)$$

Figure 9 presents the vane test results obtained in October 1988.

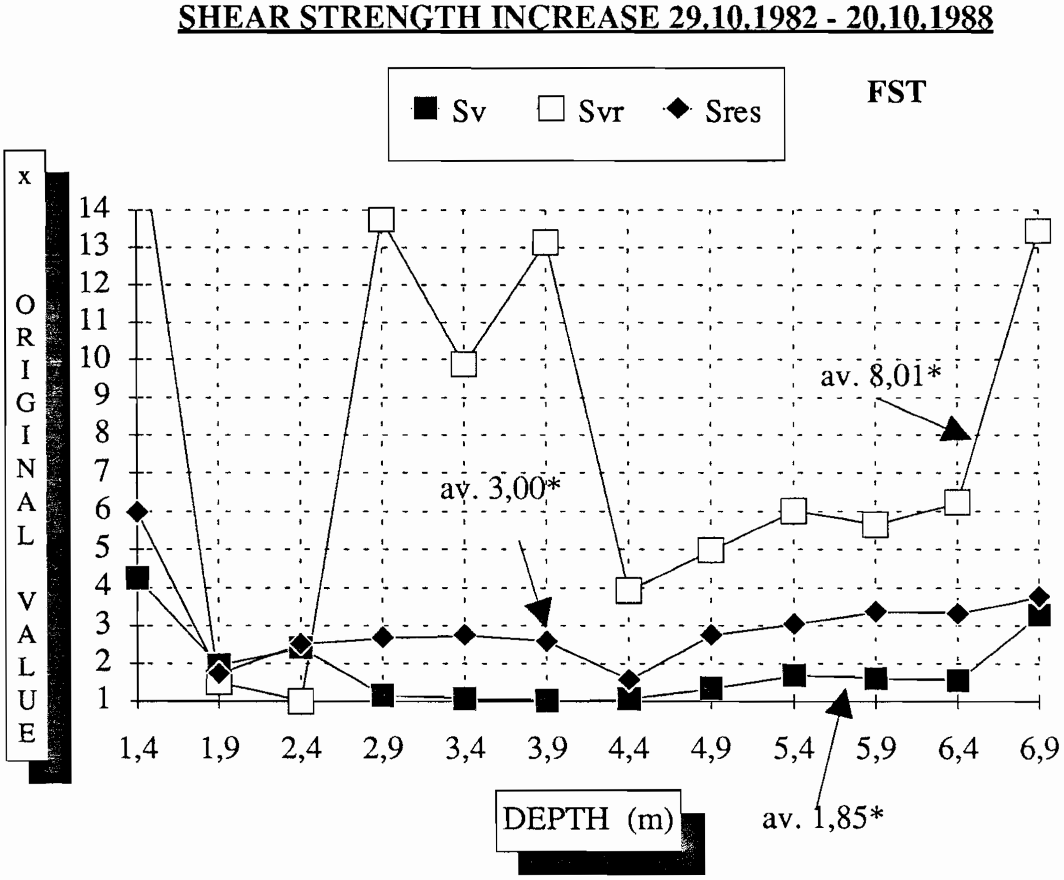


Figure 9. Thaw Consolidation Effects on Shear Strength (S_v), Remoulded Shear Strength (S_{vr}) and Residual Shear Strength (S_{res}) by vane test.

In addition to shear strength the following presents the effect of thaw consolidation on shear strength parameters viz. cohesion and friction angle. These were determined by 73 direct shear experiments, results of which are presented in figure 10.

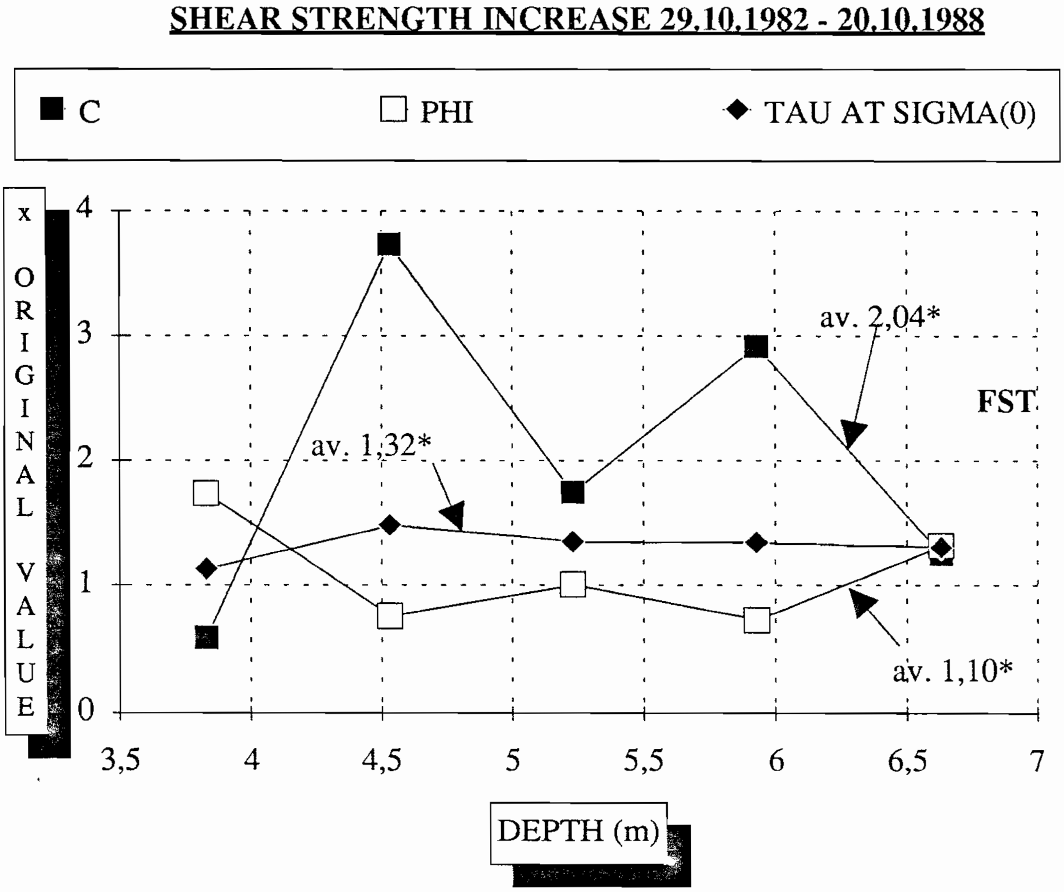


Figure 10. Effect of Thaw Consolidation on Cohesion (c) and Friction Angle (PHI) and on Shear Stress (TAU) value corresponding to the pre-consolidation load.

According to figure 10 cohesion has increased on average by 100%, friction by 10% and the pre-consolidation load shear stress by 30%. These results differ from results published previously by the author (Vähäaho 1988), where increase in strength was considered as arising from increase in friction angle. The present results are based on more extensive investigations where errors arising from local variations are sought to be eliminated by using mean values of several determinations from parallel sampling points.

Shear strength parameter changes as a function of time may be described by the following equations:

$$c(t) = r_t \, . \, c \qquad (7)$$

$$\Phi(t) = \Phi \qquad (8)$$

According to eqns.(7,8) thaw consolidation causes increase in cohesion in the same manner as in shear strength measured by vane test (eqn.4), but there is no change in friction angle. This conclusion is also confirmed from results in Part II (Vähäaho & Ryhänen 1989b), where face to face bonds in clay particles increase in number as a result of thaw consolidation and thereby increase cohesion strength.

Laboratory cone test determinations (fig.11) yield almost the same result for the increase in shear strength and remoulded shear strength in comparison to the vane tests presented in figure 9.

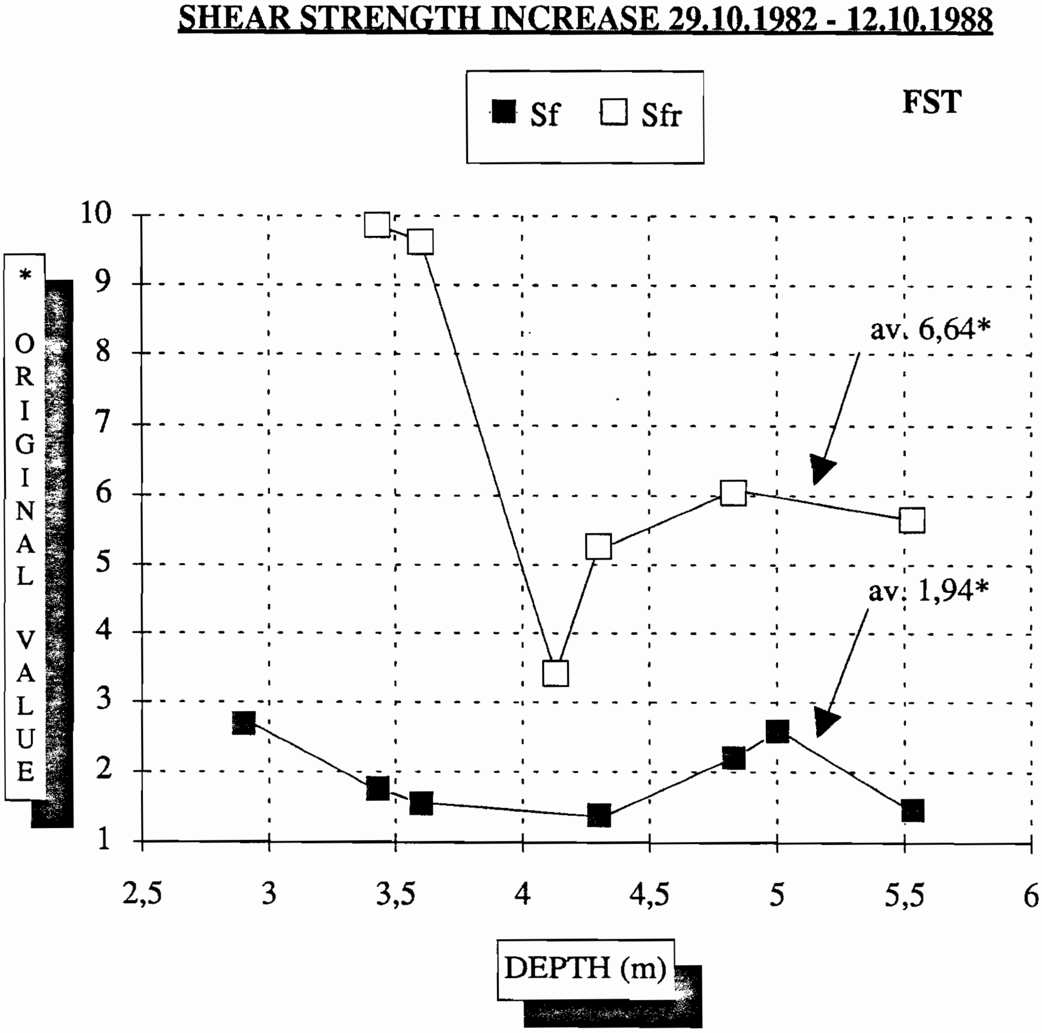


Figure 11. Thaw Consolidation Effects on Shear Strength (S_f) and remoulded Shear Strength (S_{fr}) determined by fall-cone test.

4.
CHANGES IN CLAY MECHANICAL PROPERTIES

On examining both original and thaw-consolidated clay and their test results, it is apparent that great changes in nearly all mechanical properties occur. The immediately visible difference is in material appearance, where change is mostly from clay to a silt or sand texture. The causes of these changes are examined in part II (Vähäaho & Ryhänen 1989b) where changes occuring in the clay microstructure are reported.

Figure 12 presents changes in unit weight, water content and liquid limit observed in the test areas.

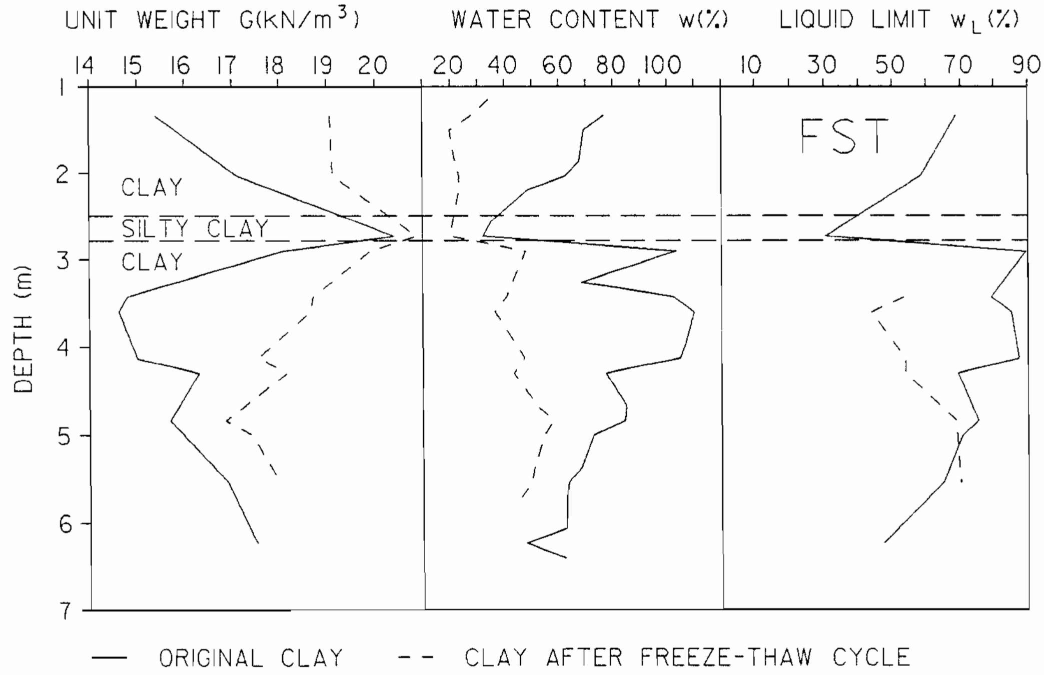


Figure 12. Changes in unit weight (G), water content (w) and liquid limit (w_L) caused by thaw consolidation.

Mean changes in the above properties are:

- increase in unit weight (G)	10...15%
- decrease in water content (w)	33...40%
- decrease in liquid limit (w_L)	15...25%

Observed mean changes in shear strength parameters are according to chapter 3:

- increase in shear strength (S_v and S_f)	33...95%
- increase in residual shear strength (S_{res})	140...200%
- increase in remoulded shear strength(S_{vr} , S_{fr})	250...700%
- decrease in sensitivity (S_t)	60...75%

Mean changes in settlement properties are:
- decrease in settlement arising from 100 kPa overload with respect to consolidation stress 65...71%
- increase in consolidation factor (c_v) 130...410%

Examples of changes in consolidation factor (fig.13) and decrease in settlement (fig.5) are shown.

The maximum values in the above ranges represent the mathematical average, while the minimum values are so-called careful averages which are obtained by subtracting half of the standard deviation from the mathematical average.

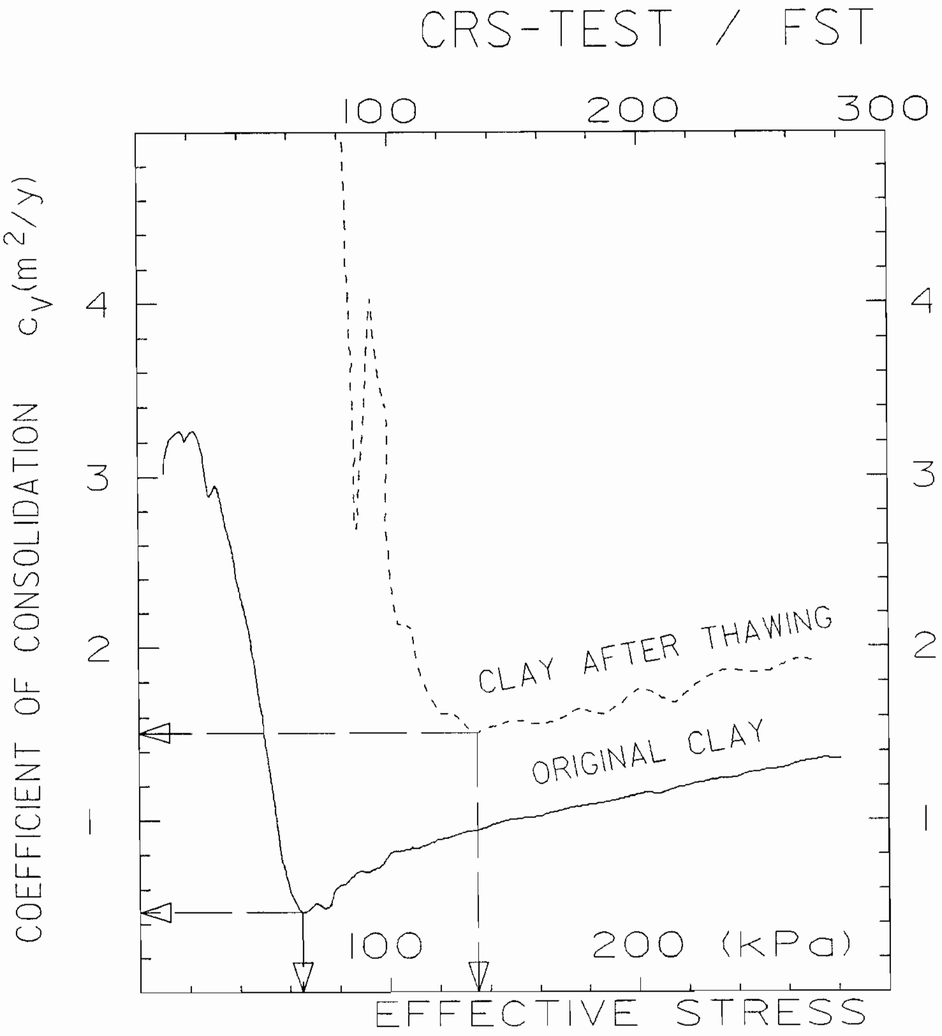


Figure 13. Example of thaw consolidation effects on consolidation factor (c_v) and on stress corresponding to minimum value of consolidation factor.

In summarizing the changes in mechanical properties of clay from the viewpoint of geotechnical planning, it may be noted that thaw consolidation has a decisive significance in settlement properties. On undergoing a freeze-thaw cycle the clay experiences overconsolidation and settlements due to overloads are in magnitude about a third of those in unfrozen, normally consolidated clay layers. In addition,the clay´s sensitivity to remoulding decreases significantly through thaw consolidation, since the shear strength of remoulded clay increases by several factors. The increase in residual shear strength is noteworthy,whereas shear strength of undisturbed clay increases by a lesser amount. **After thaw consolidation the clay is therefore less compressible, less sensitive and similar in property to dry crust.**

5.
FROST STABILIZATION - USE OF THAW CONSOLIDATION

Thaw consolidation may be utilized for many purposes, particularly as a natural and cheap stabilization method. The construction principle of a simple, artificial dry crust ("frost-crust") applicable to Finnish conditions is shown in figure 14. Under normal conditions frost penetrates clay layers to a depth of only 0.5.....1.0 m from ground surface, i.e. approximately the lower surface of dry crust layers. If dry crust is removed from the surface, subsequent foundation and earth constructions are based on poorly carrying layers. This can be avoided by excavating in advance and keeping the surface snow-free over 1-2 winters, as a result of which water is lost from the frozen layer during thawing and it consolidates. Under normal conditions frost is formed to a depth of 1 m. This means that under thawing a clay layer with a water content of, say 90%, is compacted by 30 cm (=100 cm. x 90%/3). Under subsequent loading this layer would be compressed by approximately 1/3 in comparison to an equivalent unstabilized layer. Settlements due to loads in thawed layers occur notably quicker than in unfrozen layers. If the original layer shear strength, residual shear strength and remoulded shear strength were 8 kPa, 3 kPa and 0.8 kPa respectively, then after a freeze-thaw cycle these strengths would respectively assume the values 11-15 kPa, 6-8.5 kPa and 4-6 kPa.

Another interesting application of frost stabilization is in improving the properties of weakly supportive and hard to handle surplus masses (clay/sludge). The use of frost stabilization in compacting dredge masses has been investigated in waterways of large lakes in the USA (Chamberlain & Blouin 1978). Dredge masses are located in such a way that the whole layer has time to freeze during winter. The other possibility is to pump dredge masses as thin lamellae in such a manner that the previous layer freezes before pumping of the succeeding layer. Formation of thick snow layers on the freezing layer weakens the efficiency of frost stabilization. After freezing, the effect of frost stabilization may be boosted by a loading berm. As a result of freezing and thawing dredge masses are compacted and if, in addition, a loading berm is used the actual consolidation settlements are speeded up due to increased values of the consolidation factors.

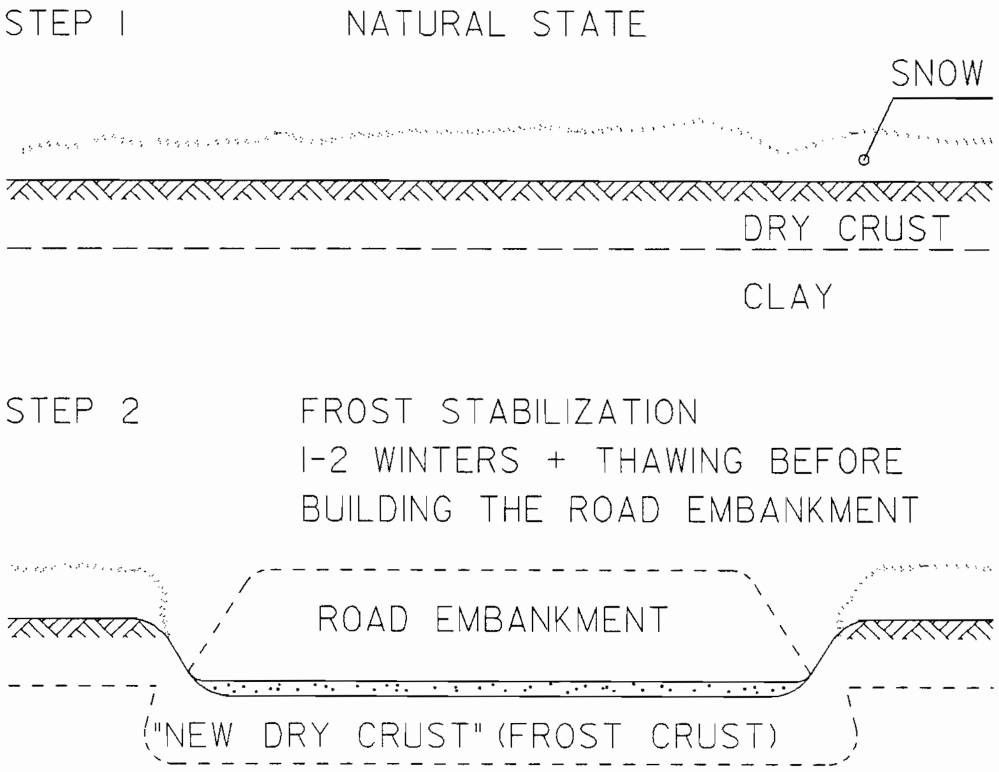


Figure 14. Principle of Frost Stabilization (i.e. frost crust) applied to consolidate foundation of a road embankment.

6.

THAW SETTLEMENTS AND THAW WEAKENING - AVOIDING PERTURBATIONS DUE TO THAW CONSOLIDATION.

Figure 15 shows an example of settlement damage arising from thaw consolidation. This was observed in summer 1987 in the Torpparinmäki area of Helsinki. The base of the road embankment was cut 0.5 m below the natural ground surface. Since the road was kept clear of snow after construction, frost penetrated the clay 0.7 m deeper than previously. This resulted in a 0.25 m settlement. The origin of this settlement was not initially known, and prior to this dangers from thaw settlements in relation to civil construction were not even recognized. Thaw consolidation settlements were assigned to overloads. In this case the load difference between the pipeline and the rest of the road embankment was however too small to account for the almost vertical settlement difference (figure 16).

Figure 15. Thaw Settlements observed in Torpparinmäki area of Helsinki in summer 1987.

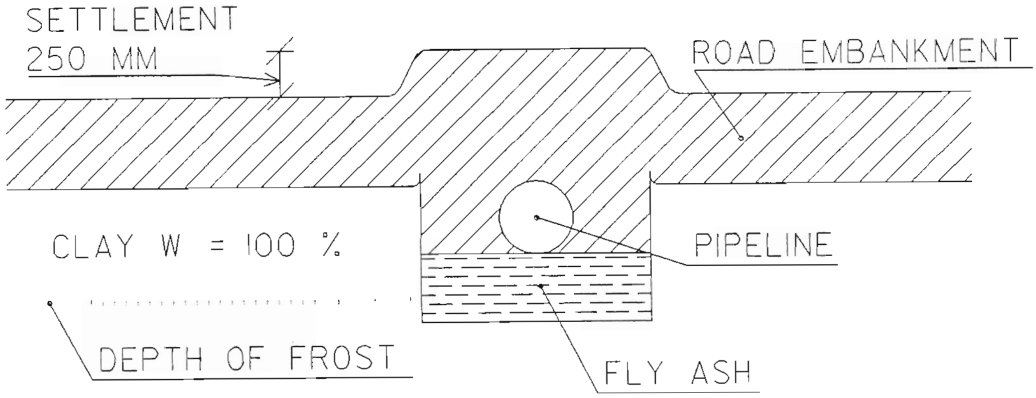


Figure 16. Settlement damage due to freezing of clay layer below road embankment (Helsinki/Torpparinmäki)

The settlement difference arose from the fly-ash bed constructed below the pipeline. As a thermal insulator it prevented freezing of clay below the pipeline. The clay layer below the remaining embankment however froze, thus causing the settlement, the calculated value of which according to eqn.(1) is 233 mm (=100%/3/100x700 mm).

Figure 17 shows an example of stability risk arising from thaw consolidation.The slope in question, in its original state prior to freezing, fulfills the stability condition F = 1.5. If the ground freezes, this further increases the stability, but at the outset of thawing the shear strength drops below its original value, thus causing a stability risk. On thawing of the frozen layer the original shear strength value(10 kPa) drops acc.to eqn.(4) to 5 kPa(= 10 kPa x 0.5), whence the average shear strength calculated for the whole slip surface drops to 7.3 kPa. This gives an overall stability factor of F = 1.1. In this state the slope is in danger of collapsing. This results in at least notable slides. If, however, the slope remains erect during the critical stage, the stability factor finally rises to F = 1.8...2.2, the shear strength attaining (acc.to eqn.4) the value 13.5...19 kPa (= 10 kPa x (1.35..1.9)), whence the average shear strength calculated for the entire slip surface is 11.9...14.9 kPa.

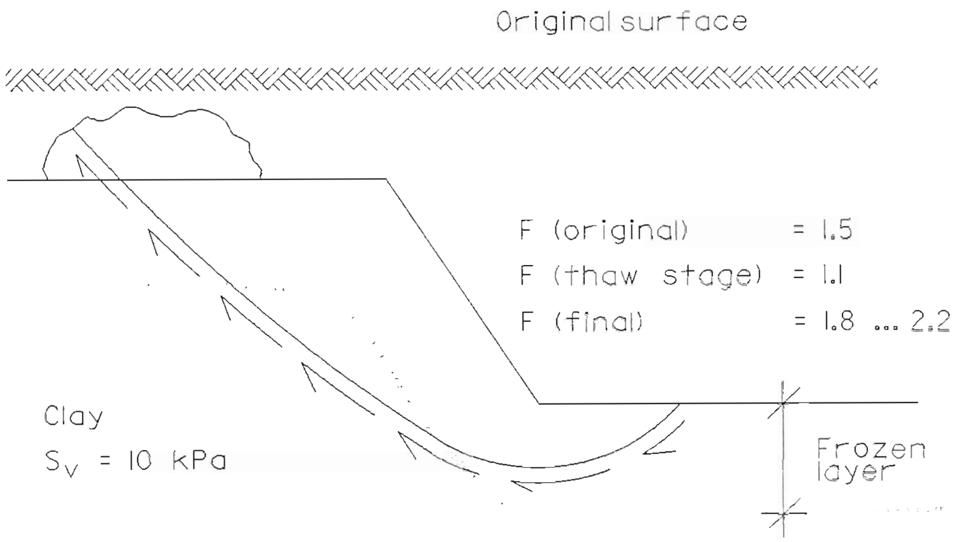


Figure 17. Example of an excavation that originally fulfils the stability requirement F=1.5, but which after freeze-thawing is in danger of collapsing.

The following list sets out other hazardous examples of thaw consolidation in clay:

- decrease in embankment stability due to shear strength decrease arising from thaw consolidation
- decrease in river bank stability for same reasons.
- thaw settlements arising from construction on frozen layers.
- thaw settlements arising from differing frost insulation properties of structures
- use of freezing method causes settlement and stability risks during thawing
- freezing of construction, pipeline, etc. excavations causes decrease in stability as well as settlements and lateral translations during thawing. These movements may continue over several years.

This limited list shows that avoidance of problems due to thaw consolidation belongs to geotechnical planning, just as obviously as the planning of frost protection in avoidance of frostheave.

7.

SUMMARY

The following summarizes the effects of thaw consolidation on the compressibility and strength properties of clay. The most important result is the finding of certain laws.The values of factors shown in the equations need, however, to be refined and their comprehensiveness established. The greater part of the research material presented in this report originates from the Oulunkylä test-freeze area of Helsinki. The range limits for clay properties in the test area are shown in table 1 :

TABLE 1. Range limits for clay properties in Oulunkylä test-freeze area.

Water Content	Liquid Limit	Unit Weight	Shear Strength		
			undisturb.	remould.	residual
w(%)	w_L(%)	G(kN/m^3)	S_v (kPa)	S_{vr}(kPa)	S_{res} (kPa)
45 - 110	45 - 90	14.5 - 18	7 - 15	0.3 - 1.7	3.7-5.2

Thaw settlements may be estimated from the following equation:

$$A = w/k_1$$

where A = thaw settlement(%), w = water content(%) and k_1 = thaw settlement factor whose value varies in range 2...6 depending on field conditions, with a recommended laboratory value of approximately 3.

Additional settlements(net) for second and third freeze-thaw cycles :

$$\Delta\epsilon_2 = w/k_2 \quad \text{and} \quad \Delta\epsilon_3 = w/k_3$$

where $k_2 \cong 20$ and $k_3 \cong 40$

Settlements after thawing caused by extra loads may be estimated from the compressibility modulus with the following equation :

$$a = m_2/k_4$$

where $k_4 \cong 2...4$ and m_2 = rebound modulus of original clay in oedometric test.

Shear Strength changes may be estimated by:

$S_v(t) = r_t . S_v$

where the factor r_t takes on the value 0.5 during thawing and during final consolidation is 1.35...1.9.

The corresponding equation for changes in remoulded shear strength is:

$S_{vr}(t) = 4 . r_t . S_{vr}$

Residual Shear Strength S_r changes may be estimated from:

$S_{res}(t) = 1.5 . r_t . S_{res}$

Thaw consolidation effects on shear strength parameters (cohesion and friction) may be estimated from:

$c(t) = r_t . c$

$\Phi(t) = \Phi$

In addition thaw consolidation increased the clay´s :

- unit weight (G)	10 - 15%
- consolidation factor(c_v)	130 - 410%
- water permeability	

Thaw consolidation decreased the following :

- water content (w)	33 - 40%
- liquid limit (w_L)	15 - 25%
- sensitivity(s_t)	60 - 75%

In conclusion, with regard to changes in clay mechanical properties from the viewpoint of geotechnical planning, it may be stated that thaw consolidation has a very significant effect on settlement properties. After a freeze-thaw cycle the clay in a sense "overconsolidates" and settlements due to overloads are in magnitude only about one-third in comparison to settlements in unfrozen,normally consolidated clay layers. The clay sensitivity (to perturbation) also decreases significantly through thaw consolidation, since the shear strength of remoulded soil increases by several factors. The residual shear strength increase is notable, while the undisturbed shear strength increases by a lesser amount. After thaw consolidation the clay is therefore less compressible, less sensitive, and in its properties is similar to dry-crust clay.

BIBLIOGRAPHY

Chamberlain, E.J., and S.E.Blouin,1978. Densification by Freezing and Thawing of Fine Material Dredged from Waterways. Proc. 3rd. Int.Conf.Permafrost, Edmonton, Alta., pp.623 - 628.

Soveri, U., 1956. On the mineralogical composition of argillaceous sediments of Finland. Ann.Acald.Scient, Fennicae, Ser A, III, 48.

Speer,T.L., G.H.Watson and R.K.Rowley, 1973. Effects of Ground Ice Variability and Resulting Thaw Settlements on Buried Warm Oil Pipelines, North Am. Contrib.Proc.2nd.Int. Permafrost, Yakutsk, U.S.S.R., National Academy of Sciences, Washington, pp.746 - 751.

Tong C., and E.Chen, 1985. Thaw consolidation behaviour of seasonally frozen soils. Proc.Fourth Int.Symp. on Ground Freezing, Sapporo, (ed.S.Kinosita & M.Fukuda, Balkema,Rotterdam, pp.159-163)

Watson,G.H., W.A.Slusarchuk, and R.K.Rowley, 1973. Determination of some Frozen and Thawed Properties of Permafrost Soils, Can.Geotech.J.,10:592-606

Vähäaho,I., 1987. "Jäädytysmenetelmän käyttö" (=The Use of Ground Freezing), Report no. 44, Geotechnical Dept., City of Helsinki (Finnish).

Vähäaho,I., 1988. Soil Freezing and Thaw Consolidation Results for a major project in Helsinki. Proc.5th.Int.Symp. on Ground Freezing,Nottingham (ed.R.H.Jones & J.T.Holden), Balkema,Rotterdam, pp.219-223.

Vähäaho,I., V.Lappalainen and H.Ryhänen, 1989a. Thaw consolidation of frozen clays of post-glacial origin in Helsinki. Proc.Int.Symp.Frost in Geotechnical Engineering, Saariselkä, Finland, Vol.2(ed.H.Rathmayer, Technical Research Centre of Finland VTT), Espoo. pp.583-600.

Vähäaho I. and H.Ryhänen,1989b. "Sulamiskonsolidaation vaikutukset savessa"(=The Effects of Thaw Consolidation on Clay). Report no.50, Geotechnical Dept., City of Helsinki(Finnish)

GEOTECHNICAL DEPARTMENT REPORTS
15.Dec.89

1	*Anttikoski, U.*	Geotechnical Maps And Their Use	Finnish	1973
2	*Anttikoski, U.*	Geotechnical Research and Design in City Planning	Finnish	1973 *
3	*Anttikoski, U.*	Geotechnical Research and Design in Municipal Engineering	Finnish	1974 *
4	*Mäkinen, R.*	Construction of Earth-Fill Mounds in City Areas	Finnish	1974 *
5	*Saarelma , M.*	Survey of Sound-Proof Barriers and their Foundations	Finnish	1974 *
6	*Saarelma, M.*	Load-bearing Capacity of Friction Piles	Finnish	1976
7	*Petäjä, J.*	Dimensioning of Pipeline Foundations	Finnish	1977
8	*Raudasmaa, P.*	Grouting of Metro-Tunnels	Finnish	1977 *
9	*Anttikoski, U.*	Use of Rock Tunnels for Storage	Finnish	1977 *
10	*Tikkanen, H.*	Construction Effects on Groundwater in Central Helsinki	Finnish	1978
11	*Arkima, O.*	Freezing of the Kluuvi Weakness Zone	Finnish	1978 *
12	*Raudasmaa, P.*	Timber Foundation Constructions	Finnish	1979
13	*Havukainen, J.*	Use of Power Station Ash and Incineration Plant Slag in Construction	Finnish	1979
14	*Vähäaho, I.*	Settlement Calculations for Small Houses on Soft Ground	Finnish	1979 *
15	*Raudasmaa, P.*	Groundwater Control -80	Finnish	1980
16	*Anttikoski, U.*	Survey of Current Technique in Tunnel Engineering presented at Atlanta International Tunnel Conference	Finnish	1979 *
17	*Roinisto, J.*	Report on a Visit to Stockholm Multipurpose Tunnels	Finnish	1981
18	*Havukainen, J.*	Use of Power Plant Coal Ash in Earth Works	Finnish	1981 *
19	*Roinisto, J.*	Report on Techno-Economical Aspects in Multipurpose Tunnels	Finnish	1981
20	*Vuola, P.*	Earth Works in Housing Constructions and their Quality Control	Finnish	1981
21	*Havukainen, J.&* *Korhonen, O.*	Earth Works in Plot Areas	Finnish	1981
22	*Havukainen, J.*	Examples of Use of Waste as Raw Material and Energy Source	Finnish	1981
23	*Havukainen, J.*	Survey on Use of Power Plant Coal Ash in Municipal Engineering	Finnish	1982
24	*Latvala, A.*	Utilization of Waste Building Material	Finnish	1982
25	*Havukainen, J. &* *Hämäläinen, A. &* *Sulamäki, A.*	Preliminary Report on Utilization of Incineration Plant Slag in Earth Works	Finnish	1982
26	*Halkola, H.*	Municipal Geotechnical Test - Building Sites in Torpparinmäki	Finnish	1982 *
27	*Paavola , P.*	Report on Excavation Costs of Municipal Engineering Tunnels	Finnish	1982
28	*Vähäaho, I.*	Type Specifications for Earth Works	Finnish	1982 *
29	*Gulin, K.*	Construction Effects on Groundwater Level and Settlement of Buildings in Helsinki Puistola Area	Finnish	1982
30	*Halkola, H.*	Control Methods for Quality and Strength of Deep Stabilization	Finnish	1982
31	*Havukainen, J.*	Utilization of Coal Ash in Earth Works: Technical Guidelines	Finnish	1983
32	*Havukainen, J.*	Utilization of Coal Ash in Earth Works: Technical Guidelines	Swedish	1983
33	*Havukainen, J.*	Utilization of Coal Ash in Earth Works: Technical Guidelines	English	1983
34	*Salmelainen , J.*	On the Geology of the Helsinki Bedrock and Strength Properties of Stone Types from the Standpoint of Drilling	Finnish	1983
35	*Havukainen, J.*	Conference Report on the Environmental Effects of Coal Ashes	Finnish	1983
36	*Hytti, P.*	Pre-Grouting : Execution and Registration in Contract Documents	Finnish	1984
37	*Leinonen, J.*	Rock Mechanical Measurements in Hanasaari Deep-Store Cavern	Finnish	1984
38	*Pirinen, J.*	Construction of a Floating Shore Bank	Finnish	1984 *
39	*Latvala, A.*	Geotechnical Cost-Listing : Geo-kuti	Finnish	1984
40	*Korpela, J. &* *Schuller, M.*	Foundation Structures of Rigid Pipeline Connections (Jäli-Report)	Finnish	1984
41	*Lahtinen, E-R.*	Underground Structures and Municipal Engineering (Marasu Report)	Finnish	1985
42	*Korpi, J.*	In-Situ Loading Test for Determination of Settlements	Finnish	1985
43	*Havukainen, J.*	Development of Pre-Building	Finnish	1985
44	*Vähäaho, I.*	Use of Ground Freezing	Finnish	1987
45	*Havukainen, J. &* *Hämäläinen, A. &* *Latvala, A.*	Experiences in Use of Coal Ash in Municipal Engineering Earth Works	Finnish	1987
46	*Julkunen, A.*	Geophysical Research Methods in Rock Engineering	Finnish	1987
47	*Hutri, K-L.*	Suitability of Vuosaari Stone-Types for Asphalt Surfacing	Finnish	1988
48	*Melander, K.*	The Static-Dynamic Sounding Method	Finnish	1989
49	*Leppänen, M.*	Use of Reinforcing Fabrics in Shore-Area Construction in Vanhakaupunl	Finnish	1989
50	*Vähäaho, I. &* *Ryhänen, H.*	Effects of Thaw Consolidation on Clay	Finnish	1989
51	*Vähäaho, I.*	Effects of Thaw Consolidation on Geotechnical Properties of Clay	English	1989
52	*Koskela, P.*	Effects of Thaw Consolidation on Dredge Masses	Finnish	1989

Sale Prices:

1	Copy	80 mk
2-3	Copies	70 mk
4-6	Copies	60 mk
7-	Copies	55 mk

*) out-of-print