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Seppo Saarelainen
Road, Traffic and Geotechnical Laboratory

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ABSTRACT

The purpose of this study was to monitor frost heaving and frost penetration at six observation sites in Finland in 1982 - 1984. Frost heaving was also studied in the laboratory with frost-heave tests carried out on undisturbed specimens.

The observed freezing behaviour was compared with the climatic conditions. The frost penetration and frost heave were found to correlate with the freezing index. Relative frost heave was fairly constant at each site, varying between 0.03 and 0.23.

A calculation model based on heat balance at the freezing front was tested for the estimation of frost heave and frost penetration. The spatial description of frost heaving and frost penetration was reasonably good. Estimation of the in-situ segregation potential from the observed frost heaving and frost penetration data was also successful.

Comparison of the back-calculated segregation potentials from site observations with those from laboratory frost-heave tests revealed a good correlation between the average value of frost-heave tests and the in-situ estimate. The laboratory values were, in general, slightly smaller than the in-situ values. This may reflect the influence of side friction on the laboratory test values.

PREFACE

The studies for this report were started in 1982 at the Geotechnical Laboratory (GEO) of the Technical Research Centre of Finland (VTT). Experimental investigations were carried out at VTT, GEO, as part of the project "Geotechnical properties of frozen soils and frost susceptibility" financed by the Finnish Academy in 1982 - 1984. Later the development of the frost heave model was financed mainly by VTT. The work continued in connection with some experimental projects in 1985 - 1990.

The site observations were mainly carried out by the staffs of the road maintenance bases at Alajärvi and Piippola, and the Street Planning Department at Joensuu.

Mr. Juhani Loisalo constructed the sampler for frozen soil and the frost-heave cell. Mrs. Helvi Havukainen and Riitta Seppälä carried out the soil tests, and Mr. Harri Kivikoski most of the frost-heave tests.

The language was controlled by Sen.Res.Scientist K - L. Riipola and Mrs. Gillian Häkli. The text was edited for print by Mrs. A. Asunta.

I express my thanks to Professor Heikki Poijärvi for his active support during this work. I also thank Professor Jorma Hartikainen of Tampere University of Technology for his encouragement and guidance throughout this work.

Finally, I wish to express my appreciation to my late wife Raija, to my son Tuomas and my daughter Eeva for their understanding and patience during this study.

Espoo, March 1992

Seppo Saarelainen

CONTENTS

LIST OF SYMBOLS

a	coefficient [MPa^{-1}]
h	frost heave [mm]
h_o	frost heave due to the freezing of pore water [mm]
h_s	frost heave due to ice segregation [mm]
k	coefficient of frost penetration [$mm/\sqrt{Kh}$]
k_t	hydraulic conductivity of unfrozen soil [m/s]
m	coefficient of frost heaving [$mm/\sqrt{Kh}$]
n	porosity
n_f	porosity of frozen soil
n_t	porosity of unfrozen soil
n_w	porosity occupied by water
p_w	pore water suction in freezing soil [kPa]
q_f	heat flow due to in-situ freezing of soil [W/m^2]
q_s	heat flow due to ice segregation [W/m^2]
q_+	heat flow in unfrozen ground [W/m^2]
q_-	heat flow in frozen ground [W/m^2]
r	equivalent pore radius [m]
r	coefficient of correlation
t	time [s, h]
v_w	specific volume of water [m^3/t]
w	water content
w_f	water content of frozen soil
w_t	water content of unfrozen soil
w_{vf}	volumetric water content in frozen condition
z	depth [m]
z_f	frost penetration [m]
z_o	frost penetration in the unfrozen soil column [m]
z_i	thickness of the frozen layer i [m]
z_t	thaw penetration [m]
z^*	effective depth of frost penetration [m]
A_o	amplitude of temperature variation on the ground surface [K]
A_z	amplitude of temperature variation at depth z [K]
C_f	volumetric heat capacity of frozen soil [J/m^3K]
F	freezing index [Kh]
F_t	thawing index [Kh]
L	volumetric latent heat of fusion of a soil [kJ/m^3, Wh/m^3]
L_{fz}	volumetric latent heat of fusion of a soil at the freezing front [Wh/m^3]
L_w	volumetric latent heat of fusion of water [Wh/m^3]
P	period of cyclic fluctuation [s]

R_f	Thermal resistance of frozen layers [m^2K/W]
S	coefficient of ground heat
S_i	degree of ice saturation
SP	segregation potential under the actual stress [mm^2/Kh]
SP_o	segregation potential, unloaded [mm^2/Kh]
T	temperature [K, °C]
T_f	freezing temperature of soil [°C]
T^*_m	temperature of melting ice at zero curvature [K]
T_p	temperature of ground surface [°C]
T^*	freezing temperature of pore water [K]
T^*_o	freezing temperature of free water [K]
β	frost-heave factor
ε_f	relative frost heave
ε_t	thaw compression
κ	coefficient of temperature diffusion [mm^2/s]
λ_f	thermal conductivity of frozen soil [W/Km]
λ_{fi}	thermal conductivity of frozen layer i [W/Km]
λ_{fz}	thermal conductivity of frozen soil at the freezing front [W/Km]
λ_t	thermal conductivity of unfrozen soil [W/Km]
λ_{tz}	thermal conductivity of unfrozen soil at the freezing front [W/Km]
ρ_d	dry density [t/m^3]
ρ_{df}	dry density of frozen soil [t/m^3]
ρ_{dt}	dry density of unfrozen soil [t/m^3]
ρ_i	specific density of ice [t/m^3]
ρ_s	specific density of soil material [t/m^3]
ρ_w	specific density of water [t/m^3]
σ_{iw}	interfacial energy of ice-water interface [kJ/m^2]
σ_z	vertical overburden stress of freezing soil [MPa]

1 INTRODUCTION

Soils commonly freeze in cold climates. Except for northern Lapland, where discontinuous permafrost up to a few tens of metres thick is found on some fjell plateaus and mountain tops, Finland lies within the zone of seasonal frost (King & Seppälä 1988).

The existence of frost is a factor that has to be taken into consideration in the construction of buildings and roads. To mitigate the risk of damage from frost heave in frost-susceptible ground, foundations must be laid to a frost-free depth. Limited frost heave is usually permissible for earth structures. Displacements due to frost heave must not jeopardize proper use of a structure or cause damage to it.

Estimates of the structural damage caused by frost heave have been published, as have estimates of the effect of unevenness on traffic safety based on driving dynamics (Slunga & Saarelainen 1989).

Concepts of frost-heave mechanisms have been developed and modified in the course of time. The general requirements for frost heaving are (Anderson et al. 1984):

- soil freezes
- the freezing soil is frost-susceptible and
- water is available in the freezing zone.

Soils are classified, in principle, into frost-susceptible and non-frost-susceptible ones. Frost-susceptible soils are soils that show tendency to swell during freezing. Normally these soils contain fine-grained mineral aggregates. The criteria of frost susceptibility vary from one country to another. The most common criterion of classification is grain size distribution (Beskow 1935, Chamberlain 1981, ISSMFE /TC8 1989). Other classification parameters are also used. In general, frost susceptibility is considered to be a characteristic of a soil type. Cases have been reported, however, in which ice segregation was produced in a freezing specimen, even of coarse-grained gravel, under laboratory conditions (Fel'dman 1988).

The quantitative measure of the frost susceptibility of a soil is the increase in soil volume during freezing, which is usually seen as heaving of the frozen ground surface. In design practice, it is seldom estimated. This is partly due to the lack of reliable determination methods, which, in turn, reflects the confusion prevailing about the basic frost-heave mechanism. On the other hand, the magnitude of frost heave depends on the severity of the climate. So it may be a significant design criterion of structures only within a limited region of the seasonal frost zone, and on permafrost.

In a mild climatic zone, other consequences of frost action may be more important than frost heave. Occasionally frost heaving has been so severe in Finland that it has damaged structures and interfered their normal use. Thus, if the quality and performance of a structure is to be controlled, it is necessary to know, at least within an order of magnitude, the amount of the expected frost heave.

The importance of the frost susceptibility of soils in construction is illustrated by the wide reference to this property in research and the literature. The construction codes of countries in cold regions normally require frost susceptibility to be taken into account. Freezing of the ground has been thermophysically modelled since the 19th century. Applications have varied as numerical computing methods and devices have been developed (e.g. Saetersdal 1976, Lunardini 1981, 1988). In these models penetration of the freezing front is determined by the assuming there is no pore water migration owing to freezing. In assessments of the risk of freezing only, this assumption is on the safe side.

This work examined the relations between the observed in-situ frost heave and

- local climatic conditions
- thaw settlement and thaw compression of frozen soil in situ and in the laboratory, and
- the frost heave of soils in laboratory frost-heave tests with a view to studying the applicability of some existing models and to developing new ones to describe the in-situ frost-heave process.

The frost heaving and related factors were studied at Alajärvi, Piippola and Joensuu. At Alajärvi and Piippola, where the ground consisted of glacial till, long-term monitoring of frost penetration, frost heave and the depth to the groundwater table had been carried out by the National Road Administration. At the Joensuu sites the ground consisted mainly of silt and clay, but no findings from previous site observations were available.

This investigation studied the soil properties before and after freezing, the related changes in soil characteristics and the volume increase in the freezing soil due to the frost heave. The applicability of a calculation model based on thermal balance at the freezing front for estimating the rate and magnitude of frost heave was also studied.

2 FROST HEAVING

2.1 CONDITIONS OF FREEZING

The temperature of the ground surface is highly dependent on the exchange of heat between the ground surface and the atmosphere. As heat is transmitted from the ground to the atmosphere, the ground cools. The heat is transmitted to the ground surface by heat transport mechanisms, the most important of which is conduction. When ground temperature falls below the freezing temperature of pore water, the soil begins to freeze. The heat loss to the atmosphere is mainly compensated for by the cooling of the soil and the freezing of the pore water.

2.2 MECHANISM OF FROST HEAVE

The ground freezes as the temperature of the pore water falls below the freezing point of water. Freezing pore water expands about 9 %. The saturated, freezing soil expands in proportion to the volume of the freezing pore water. Excess frost heave is caused by the migration and freezing of the pore water from the unfrozen soil horizon or groundwater.

Frost penetration and frost heave are determined from the balance of heat and pore water flows. Heat flow obeys the Fourier equation, and pore water migration the Laplace equation. In the freezing zone, a thermal balance is achieved that depends partly on the heat flux in frozen and unfrozen soils and partly on the heat released from freezing local pore water and ice segregation due to migrated pore water.

The heat flow through frozen ground is compensated for by

- the flow of heat from the unfrozen ground to the freezing front,
- the heat released due to the increase in frost penetration in unfrozen ground, and
- the forming of excess ice in the freezing zone maintained by the migration of water to the freezing zone.

The compensation due to freezing is shared between the freezing of in-situ pore water and ice segregation due to water migration in proportions determined by the ice segregation efficiency of the freezing soil (Arakawa 1977). As well as by frost susceptibility, which is a soil property, frost heaving is affected by conditions of freezing such as the cooling rate of freezing soil, effective stress in the freezing zone and seepage resistance from the source of the migrating water to the freezing zone (Konrad 1980).

In the physical explanation and modelling of the frost-heave mechanism, pore water flow has been described using different approaches. According to Everett (1961) the suction maintaining the water flow is generated by surface tension at the water-ice interface.

$$\Delta p_w = 2\sigma_{iw}/r \qquad (1)$$

where Δp_w is pore water suction in freezing soil, kPa
σ_{iw} interfacial energy of ice - water interface, kJ/m^2
r equivalent pore radius of the soil, m

The difference in the pressure potential between unfrozen pore water and the growing ice crystal induces a pressure gradient and water flow toward the ice crystal. The suction pressure is proportional to the surface tension and also to the radius of the concave phase interface. The radius is thought to be related to the pore (grain size) dimensions of the freezing soil. The propagation temperature of the ice lensing mechanism has been described by means of the Kelvin equation as a function of pore radius r:

$$T^* - T^*_m = \Delta T = 2T^*_m \sigma_{iw}/(L_w r) \qquad (2)$$

where T^* is temperature of the ice-water interface at radius r, K

T^*_m temperature of melting ice at zero curvature, K
L_w volumetric latent heat of fusion of water, kJ/m^3
r curvature radius of ice-water interface or the pore radius, m

In another approach developed and presented along with the capillary approach the suction is generated by supercooling of water film between the mineral aggregate and ice (Miller 1972, Keinonen 1977). The suction pressure is proportional to the lowering of the freezing temperature according to the Clausius-Clapeyron equation. Laboratory measurements have shown that this "thermodynamic approach" is more realistic than the interpretation based on the capillary concept (Anderson et al. 1984, Williams 1967).

$$p_w = L_w \ln T^*/T_o^* \qquad (3)$$

where p_w is pore water suction in freezing soil, kPa
L_w volumetric latent heat of fusion of water, kJ/m^3
T^* freezing temperature of pore water, K
T_o^* freezing temperature of free water, 273.15 K

The freezing of a frost-susceptible soil does not proceed at one temperature and at one defined freezing plane, but gradually in the freezing zone controlled by the pore water temperature-pore water pressure profile. As shown by Konrad (1980), freezing is initiated in the largest pores in accordance with the Kelvin equation. It continues at lower temperatures with increasing pore water suction and decreasing hydraulic conductivity until a level is reached at which the rate of ice segregation equals to the rate of pore water flow.

This level has been called the level of the final ice lens (Konrad 1980). Miller (1972) referred to this process as the process of secondary heave, and to the freezing zone, up to the final ice lens, as the frozen fringe.

The frozen soil on the cold side of the final ice lens is assumed to be neutral with respect to ice segregation if its temperature is lower than that of the ice segregation.

2.3 MODELLING OF FROST HEAVE

Frost susceptibility was first considered as a classifying characteristic. Frost-heave modelling has been developed in stages. At one time the pore water migration in freezing soil was thought to be maintained by capillary stresses at the ice/water interface (e.g. Taber 1933, Everett 1961). Other physical and mechanical models for pore water suction at the freezing interface have also been presented (e.g. Fel'dman 1988).

Since the 1960s, increasing evidence has been presented of the thermophysical character of ice segregation. Suction in the freezing zone causing pore water migration is controlled by the freezing temperature of pore water in accordance with the Clausius-Clapeyron equation. The freezing temperature depends partly on the characteristics of freezing soil and partly on the conditions of freezing and moisture movement. These hydrodynamic models require the parallel solution of heat and mass flow equations (O'Neill & Miller 1982, Konrad 1980, Duquennoi et al. 1989). An adsorption force concept for interpreting the mechanism of ice segregation and frost heaving has been presented by Takagi (1980). Keinonen (1977) developed a similar mechanistic concept of frost heaving.

Penner & Ueda (1977) and Loch (1979) showed that the rate of water flow to the freezing front is directly proportional to that of heat flow through the frozen layer or the temperature gradient at the freezing front. According to the laboratory experiments of Konrad (Konrad 1980) this ratio is virtually constant for a given soil and given conditions.

According to Williams & Smith (1989), ice segregation in freezing soil has still not been finally and completely explained. Certain fundamental principles have, however, been proposed. The soil starts to freeze in large pores. According to the Kelvin equation (2), freezing proceeds with decreasing temperature into smaller pores. The influence of soil texture and grain size distribution on frost susceptibility has been interpreted with either specific grain size (Casagrande 1931), gradation of the fines (ISSMFE/TC8 1989) or specific surface (Nieminen 1985) as a classifying parameter.

For practical engineering design, frost heave has also been described with approximate models. In these, either the risk of frost heave is estimated or the expected frost heave is approximately evaluated (Slunga & Saarelainen 1989). The models are experimental and based on field observations, and normally apply characteristics describing local ground conditions and local climatic features. Such models have been presented by Ehrola (1973), Orlov et al. (1977) and Saetersdal (1980).

2.4 THE APPLICABILITY OF FROST-HEAVE MODELS

The applicability of models, in general, depends on how well the actual model describes frost-heave mechanisms and the intensity of ice segregation in situ. Most theoretical work has focused on the description of the freezing behaviour of a specimen in laboratory conditions. The theoretical framework has been less applied to the frost heaving of natural ground.

The model parameter describing the intensity of frost heaving is normally presented to depend on soil type, soil state characteristics, plastic properties, the thickness of the frozen, frost-susceptible layer, distance to the groundwater level, the thermal resistance of the ground and so on. As these models often estimate the relative frost heave that is the ratio of frost heave to the thickness of frozen layer, parameters describing the intensity of frost heaving can be compared with each other (Saarelainen 1989).

The practical models are typically statistical. The coefficients are based on determined, indirect correlations between frost heave and local soil parameters and conditional factors. Thus, wide variation in the accuracy can be expected when such models are applied to other soils and conditions.

The increase in volume due to ice segregation is quantitatively evaluated by the parallel solution of equations of heat and moisture flow (e.g. Miller 1972, Konrad 1980, Duquennoi et al. 1989). The detailed freezing soil model, however, requires a considerable number of soil parameters. Some of these (e.g. the permeability of partially frozen soil (see Horiguchi & Miller 1983)) are difficult to determine with laboratory experiments.

Frost heaving is a deterministic, time dependent process that is controlled by environmental factors. These, in turn, may be stochastic. The segregation potential concept seemed to be a simplification for the description of ice segregation in a freezing soil. It may also form a useful link between the laboratory frost heave test and frost heaving in situ.

Soil properties and local factors affecting on frost-heave susceptibility can be applied as spatial classification parameters when a planning area or a road line section is divided into subareas with different frost-heave susceptibilities. The specific frost-heave characteristics determined with laboratory tests or field measurements can be generalised to apply to a limited area. Thus the design task is reduced to a conventional geotechnical engineering design procedure.

3 FROST-HEAVE MODEL SSR

3.1 THERMAL BALANCE AT THE FREEZING FRONT

3.1.1 Thermal balance equation

The thermal balance at the freezing front in homogeneous ground can be stated according to Fig. 1. This balance concept forms the basis of the SSR model.

$$q_- = q_+ + q_f + q_s \tag{4}$$

where q_- is the heat flow through the frozen layer
q_+ heat flow to the freezing front from unfrozen ground
q_f heat flow generated by freezing in-situ pore water
q_s heat flow generated by ice segregation

The contents of heat flow components are dicussed lower.

3.1.2 Thermal conditions at the ground surface

Temperature variations in the ground follow changes in the thermal balance on the ground surface. The main components are the loss of

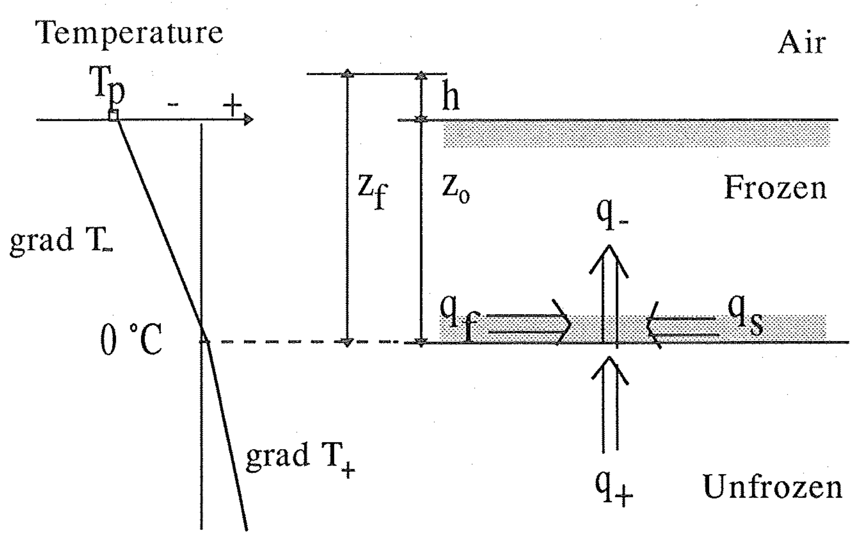

Fig. 1. Thermal balance at the freezing front.

heat stored in the ground, the convective heat exchange between the ground surface and the atmosphere, the radiation balance of the ground surface, and the conduction of heat both in the ground and in the atmosphere. Surface temperature is the decisive factor for frost and thaw penetration in the ground. Under the climatic conditions of Finland, the role of radiation in heat exchange is minimal during the freezing period, and the temperature of the snowless ground surface follows that of the air. During the thaw, solar radiation is intense, and the surface temperature of thawing ground may be significantly higher than the air temperature.

The periodic fluctuation of ground surface temperature causes temperatures to vary with depth in the ground. The amplitude of temperature variation at a depth z depends on the amplitude of the surface temperature variation as follows (e.g. Williams & Smith 1989):

$$A_z = A_o \, e^{-z\sqrt{(\pi/\kappa P)}} \tag{5}$$

where A_z is amplitude of temperature variation at depth z, K
- A_o amplitude of temperature variation on the ground surface, K
- z depth, m
- κ coefficient of the temperature diffusion of the ground λ_f/C_f, m^2/s
- P period of cyclic fluctuation, s
- λ_f thermal conductivity of the frozen soil, W/Km
- C_f volumetric heat capacity of the frozen soil, J/m^3

Thus the variation in temperature is damped with depth. At the freezing front the temperature is constant. Close to the freezing front, the temperature gradient is smoothed to correspond to the long-term mean temperature gradient. The transient heat exchange and temperature variation on the ground surface takes place mainly in the upper part of the frozen horizon. Thus, the fluctuation of temperatures has no essential influence on the frost penetration in general or gradient development at the freezing front. The heat flow through a frozen, homogeneous soil layer obeys the relationship

$$q_- = \lambda_f \, \mathrm{grad}\, T_- = \lambda_f \, T_p / z_f \tag{6}$$

where q_- is heat flow in the frozen layer, W/m^2
λ_f thermal conductivity of the frozen layer, W/Km
grad T_- temperature gradient in the frozen layer, K/m
T_p mean temperature of the ground surface, °C
z_f depth of frost penetration, m

3.1.3 Heat flow to the freezing front from unfrozen ground

Cooling ground releases heat. Some of this heat is transferred from depth by the geothermal gradient (about 3 °C/100 m) and some has been stored in the ground during the preceding summer. In seasonal frost areas, within the zone of annual ground temperature variation, about 5 - 20 metres from the ground surface, the mean temperature of the ground is close to the mean temperature of the ground surface. Thus the heat stored during the preceding warm period, summer, affects on the release of heat from the ground during the freezing period.

The Stefan solution to the frost penetration problem (Stefan 1891) omits the flow of ground heat. This results in over-estimation of frost penetration by 10 - 15% (Apostolopoulos 1981). The effect of unfrozen ground is correctly taken into account in the Neumann solution (Neumann 1860) and other approaches based on it (e.g. modified Berggren solution (Aldrich & Paynter 1953)). An approximate solution used mainly in Scandinavia is that of Watzinger et al.(1938). Skaven-Haug (1971) proposed that ground heat could be considered as a separate factor in the calculation of frost penetration with the aid of a ground temperature gradient, which is related to the freezing index or mean annual air temperature at the site. The relationship is presented in Fig. 2.

Heat flow from unfrozen ground to the freezing front can be solved by numerical analysis considering the initial ground temperature profile at the beginning of the freezing period, the soil profile and properties.

3.1.4 Release of heat from pore water freezing

Pore water will freeze if the rate of heat flow through the frozen layer is higher than that of ground heat flow to the freezing front. The cooling of frozen and unfrozen ground and the freezing of pore water must release enough heat for a heat balance to be maintained.

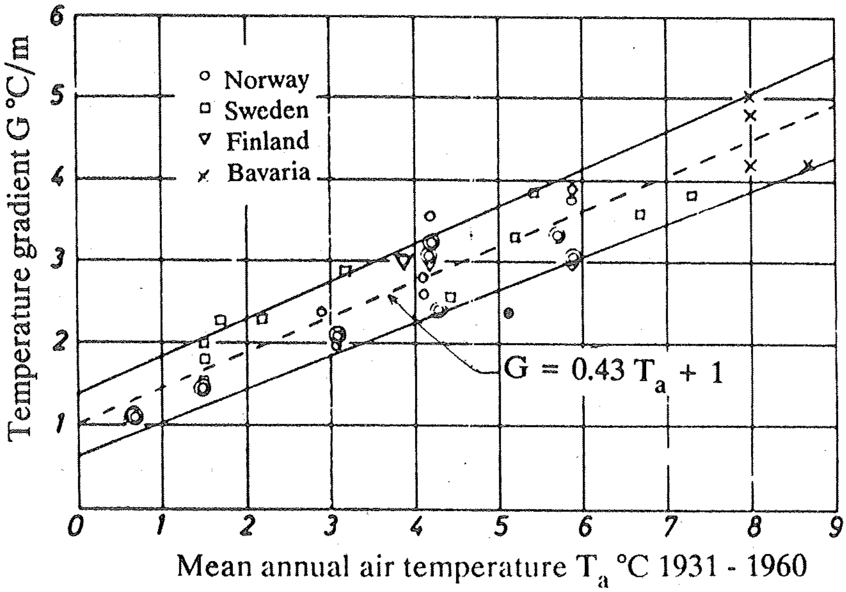

Fig. 2. The variation in the ground temperature gradient early February against the mean annual air temperature (Skaven-Haug 1971).

Pore water freezes gradually as the temperature falls below 0°C. The existence of unfrozen pore water at temperatures below 0°C is partly due to the effect of impurities in the pore water, and partly to the lowering of the freezing point caused by the suction pressure in the pore water. A large portion of the pore water in clay and silt consisting mainly of mineral aggregates freezes at temperatures between 0 and -1°C (see, for instance, Williams & Smith 1989). The volumetric latent heat of fusion of a soil is approximately

$$L = L_w n_w = L_w w_t (\rho_d/\rho_w) \qquad (7)$$

where L_w is the volumetric latent heat of freezing of water, kJ/m³

n_w porosity occupied by water, %/100

w_t water content of the soil, %/100

ρ_d dry density of the soil, t/m³

ρ_w specific density of water, t/m³

3.1.5 Release of heat from ice segregation

Pore water starts to freeze in macropores, in which the ice grows from the cold side. As the temperature falls, pore pressure is lowered in the unfrozen water film between the growing ice body and the mineral grains. This pore water suction causes moisture to migrate from unfrozen soil through the partially frozen ground to the crystallisation zone. There the horizon of pure ice stops the moisture flow (e.g. Konrad 1980, Williams & Smith 1989). Suction is induced by the supercooling of the pore water. If water is available in the unfrozen soil and there is a flow continuum from the unfrozen soil through the freezing soil to the ice lens, ice segregation is maintained. The pore volume grows if the freezing pressure is greater than the soil stress.

According to Konrad (1980), The rate of water flow to the freezing front is directly proportional to the temperature gradient at the level of ice segregation. The coefficient of proportionality is called the segregation potential SP_o

$$dv_w/dt = SP_o \text{ grad } T_- \tag{8}$$

where dv_w/dt is the rate of water flow to the ice segregation, m/h
grad T_- temperature gradient of frozen soil at the level of ice segregation, K/m
SP_o segregation potential, m^2/Kh

The influence of soil stress on frost heaving approximately follows the condition (Konrad & Morgenstern 1982b)

$$SP = SP_o e^{-a\sigma} \tag{9}$$

where σ is overburden stress of the freezing soil, MPa
a coefficient, MPa^{-1}

The description of stress influence on frost-heave rate is based on empirical in-situ observations and laboratory determinations. Physically, the phenomenon has still not been satisfactorily explained. According to Knutsson et al. (1985), the coefficient a is in relation to the clay content of the soil (Fig. 3).

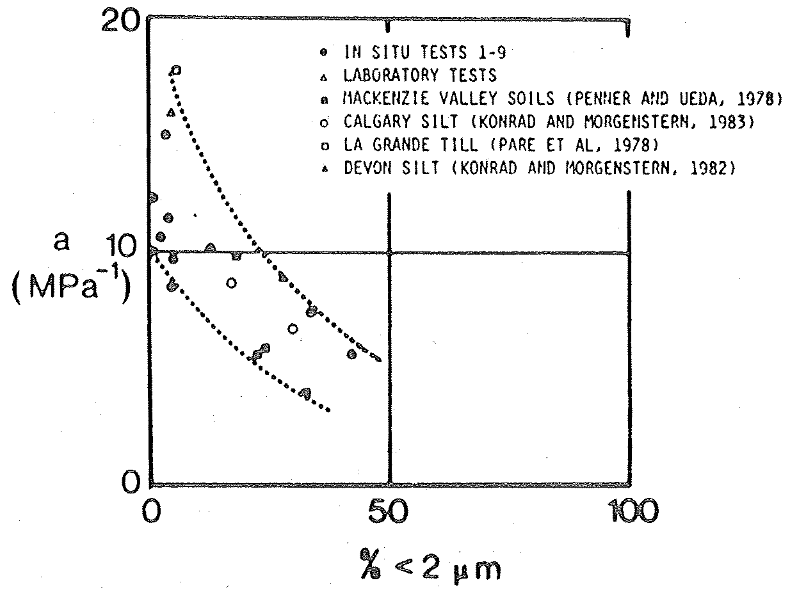

Fig. 3. The coefficient a in equation $SP = SP_0\, e^{-a\,\sigma}$ *vs. the clay content (Knutsson et al. 1985).*

The migrated water freezes, forming pore ice or an ice layer. The one-dimensional rate of volume increase or the rate of frost heaving due to ice segregation in a saturated soil is

$$dh_s/dt = (\rho_w/\rho_i)\, dv_w/dt = 1.09\, dv_w/dt \qquad (10)$$

where dh_s/dt is the rate of frost heave due to ice segregation, m/h
ρ_w density of water, t/m^3
ρ_i density of ice, t/m^3

3.1.6 Release of heat due to the cooling of ground

The periodic heat exchange caused by the fluctuation of surface temperature takes place mainly in the frozen layer. The continuous cooling of the frozen horizon produces heat which slows the rate of freezing. This effect is, however, a minor compared with the cumulative effect of soil moisture freezing, ground heat and ice segregation.

3.1.7 The SSR model

The heat flow components in the balance equation (4) are

$q_- = \lambda_f$ grad T_- heat flow through the frozen layer, W/m^2
$q_+ = \lambda_t$ grad T_+ heat flow from unfrozen ground, W/m^2
$q_f = L\, dz_o/dt$ heat flow produced by freezing pore water, W/m^2
$q_s = L_w\, dv_w/dt$ heat flow produced by ice segregation, W/m^2

where λ_f is the thermal conductivity of the frozen soil, W/Km
grad T_- temperature gradient of the frozen soil, K/m
λ_t thermal conductivity of unfrozen soil at the freezing front, W/Km
grad T_+ temperature gradient of unfrozen soil at the freezing front, K/m
L volumetric latent heat of the freezing soil at the freezing front, Wh/m^3
z_o frost penetration without ice segregation, m

When substituted the balance equation at the freezing front can be written as follows (Eq. (11)):

$$\lambda_f \text{grad}T_- = \lambda_t \text{grad}T_+ + L\Delta z_o/\Delta t + L_w\, SP\, T_p/z^* \qquad (11)$$

where $\text{grad}T_- = (T_f - T_p)/z^*$
$z^* = \lambda_{fz} \sum(z_i/\lambda_{fi}) + 0.5\, \Delta z_o$
λ_{fz} is thermal conductivity of the frozen layer at the freezing front, W/Km
T_p surface temperature, °C
T_f freezing temperature of soil, C

When solved, the increase in frost penetration Δz_o in time increment is:

$$\Delta z_o = (T_f - T_p)\, dt\, (1 - SP\, L_w/\lambda_{fz})/(L_{fz} R_{fz}) - S\, \text{grad}T_+ \lambda_t dt/L_{fz} \qquad (12)$$

where T_p is average surface temperature in the period of time dt, °C
$R_{fz} = \sum(z_i/\lambda_{fi})$ thermal resistance of frozen layers, m^2K/W
z_i thickness of frozen layer i, m
λ_{fi} thermal conductivity of a frozen layer i, W/Km

SP segregation potential of the soil at the freezing front at actual effective stress (eq. (9)), m^2/Kh

L_w volumetric latent heat of fusion of water, Wh/m^3

$L_{fz} = w_t(\rho_d/\rho_w)L_w$ volumetric latent heat of soil at freezing front, Wh/m^3

S coefficient describing the intensity of ground heat (S = 1.0 in November, decreasing to 0.7 in April)

gradT_+ temperature gradient of the unfrozen ground at the freezing front, K/m

λ_{tz} thermal conductivity of the unfrozen soil at freezing front, W/Km

As the quantity Δz_o is included in the thermal resistance R_f, the equation is iterative.

The net increase of frost penetration can be estimated from the model by considering the reducing effect of ice segregation. The increase in frost heave is then determined from the definition of segregation potential

$$dh_s = 1.09\ SP\ grad\ T_-\ dt = 1.09\ SP\ (T_f - T_p)\ dt/(\lambda_{fz}R_{fz}) \qquad (13)$$

If the freezing ground is saturated or the degree of saturation exceeds 85-90% (Orlov et al. 1977), the expansion due to the freezing of initial pore water also causes an increase in pore volume. The maximum relative increase in volume dh_o/dz_o is

$$dh_o/dz_o = 0.09\ w_t\ \rho_d/\rho_w \qquad (14)$$

Thus the increase of frost heave dh and frost penetration dz are

$$dh = (dh_s + dh_o);\ \ h = \sum(dh)$$
$$dz = (dz_o + dh);\ \ z = \sum(dz)$$

The computer program SSR, which was written on the basis of the calculation procedure, is schematically illustrated in Fig. 4.

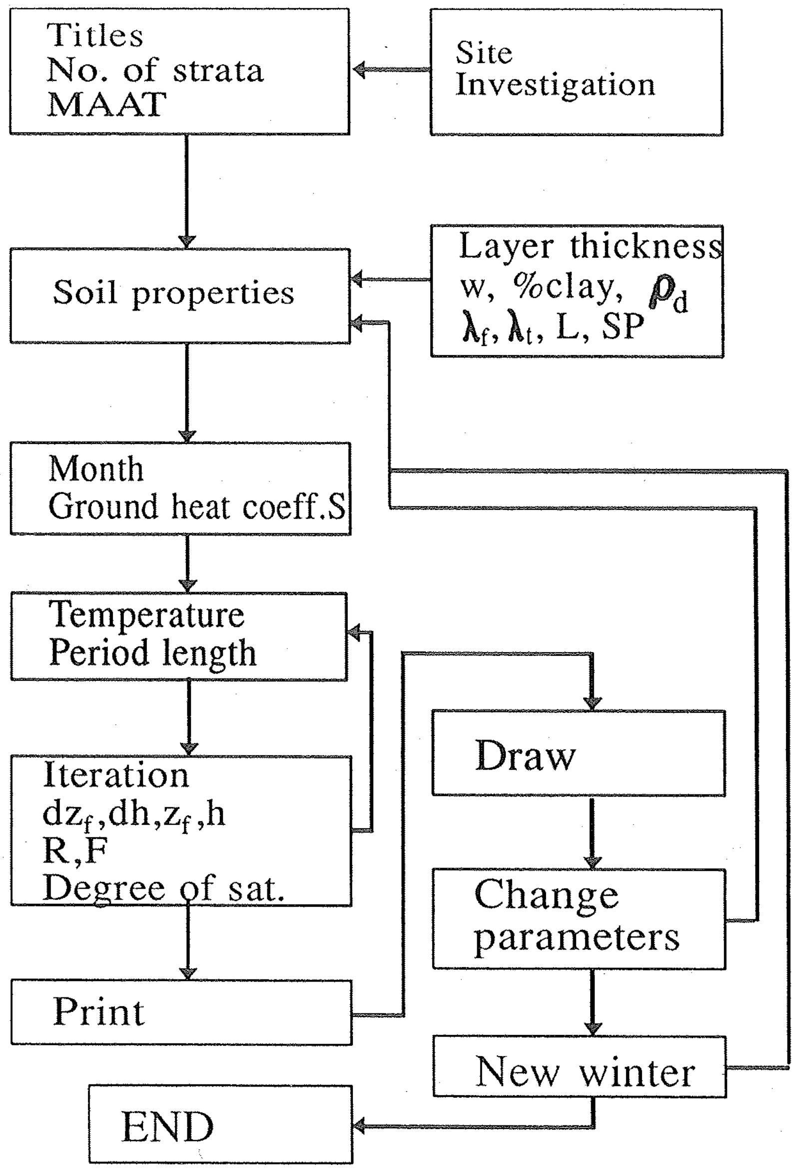

Fig. 4. Structural scheme of the program SSR.

3.2 DETERMINATION OF THERMAL PARAMETERS FOR THE SSR MODEL

The thermal conductivity of unfrozen and frozen soil can be given as characteristic value (measured value etc.). If the soil type, water content and dry density are known, the program determines the thermal conductivity for in-situ soils using Kersten's method (Kersten 1949, Berg et al. 1980, see Appendix). The volumetric latent heat of a soil is proportional to the volumetric water content, which can be determined from the water content and dry density of the soil. The value of the segregation potential is an input parameter. It can be either determined with a frost-heave test in the laboratory or estimated with back-analysis from observed frost heave and frost penetration using the SSR model or formula (16).

The mean temperature of the ground surface is given for each calculation period (for instance, monthly average air temperature). The temperature of the ground surface in the freezing period is assumed to follow the air temperature. However, if there is an insulation layer on the ground (e.g. snow cover), the surface temperature must be corrected for the air temperature (Saetersdal 1976). During the thaw the heating effect of solar radiation on the surface temperature has to be considered in the determination of thaw penetration (e.g. Lunardini 1978). For calculation of the ground heat gradient, the mean annual air temperature of the location is given. This is determined from the climatic statistics (see Chapter 3.1.2).

In frost design it is established practice to consider the local climate assuming that the design value of freezing index occurs at given intervals (for instance, maximum once in 10 years). The local freezing index can be determined from a statistical presentation of design climate (e.g. Talonrakennuksen routasuojausohjeet 1987). Expected monthly mean temperatures for the design winter can be estimated using, for instance, the diagram given in the above source. This diagram was compiled by statistically estimating the cumulative freezing index for successive winter months in Finland.

3.3 DETERMINATION OF FROST HEAVING WITH OTHER MODELS

Frost-heave evaluation should be based on the characteristics that describe the intensity of frost heaving at a given location. These may partly depend on the heave susceptibility of soils in the soil profile and partly on environmental conditions, e.g. the intensity of freezing, the pore water pressure and permeability of the freezing soil, and stress conditions. Because of the complexity of frost-heave conditions, the estimates may be most satisfactory if the characteristics of frost-heave intensity are determined with a back-analysis of local site observations.

The ratio of frost heave to frost penetration in freezing ground consisting of homogeneous mineral soil is approximately

$$h/z_f = \beta \, w_{vf} \qquad (15)$$

where β is the frost-heave factor (Saetersdal 1976)
w_{vf} volumetric water content in frozen condition

Alternatively (Saarelainen 1984),

$$h/z_f = 2SP/k^2 + 0.09 \, n_w \qquad (16)$$
$$\text{or} \quad SP = (h/z_f - 0.09 \, n_w) \, k^2/2$$

where h/z_f is relative frost heave ($= \varepsilon_f$)
n_w porosity occupied by water
SP segregation potential (in situ), mm^2/Kh
k coefficient ($z_f = k\sqrt{F}$), $mm/\sqrt{Kh}$
F freezing index, Kh

which in a saturated soil leads to

$$\beta \approx \varepsilon_f / (n_w + 0.92 \, \varepsilon_f) \qquad (17)$$

According to the above equations, the relative frost heave, segregation potential and frost-heave factor have a common relationship.

Other known experimental characteristics describing frost-heave susceptibility such as the frost-heave rate in the CRREL frost-heave test (Chamberlain & Carbee 1981) or the parameters of frost-heave rate in the VTI frost-heave test (Stenberg 1981) can be compared in a similar manner. In the comparison one must, however, bear in mind that the heave characteristics from the latter tests are also influenced by the experimental arrangement, e.g. the moving freezing front.

Frost-heave susceptibility has also been classified in a qualitative manner (Chamberlain 1981, ISSMFE/TC8 1989).

4 LABORATORY INVESTIGATIONS

4.1 GENERAL PRINCIPLES

Laboratory tests for determining the frost-heave properties of soils are based on three main principles: constant boundary temperature (e.g. Konrad, 1980), constant frost penetration rate (e.g. Chamberlain & Carbee, 1981) or constant heat flow (Stenberg, 1981). Some devices have been developed for modelling or index testing only. Field behaviour has been modelled using the constant boundary temperature test and the constant heat flow test.

The segregation potential of a soil can be evaluated from the results of laboratory frost-heave tests (Konrad & Morgenstern 1982a), and the relevance of the characteristics can be verified under field conditions (Nixon 1982, Jessberger & Jagow 1989, Saarelainen 1990a, 1990b).

Laboratory tests of frost-heave susceptibility are imperative when field observations are not available; they can also be used to support the field determinations. The specimen can be either undisturbed or reconstituted. In the modelling of natural conditions, though, the use of undisturbed specimens is preferred.

It has been suggested that the segregation potential can be indirectly assessed from the factor of fines (e.g. Jessberger & Jagow 1989). However, the validity of the correlation is not clear for all frost-susceptible soils, notably not for clayey materials.

At VTT, GEO a sampling drill for frozen soils was constructed (Fig. 5) on the basis of the CRREL ice drill. The shearing teeth of the drill were fixed to a circular drilling shoe ø 80 mm at the lower end of the drill. The drill cut a circular hole in the frozen soil, and the cylindrical sample stood freely inside the sample tube. The sample was cut by pushing the drill aside, and it was lifted up in the sampler. The length of the intact sample was about 200 - 300 mm in frozen, stoneless silt and clay. The sample was placed in a plastic tube of the same diameter, and the ends were closed with rubber caps. The sample was stored and transported to the laboratory in a frozen state inside a cooled container. In the laboratory the sample was stored in a freezer at a temperature of about -20°C.

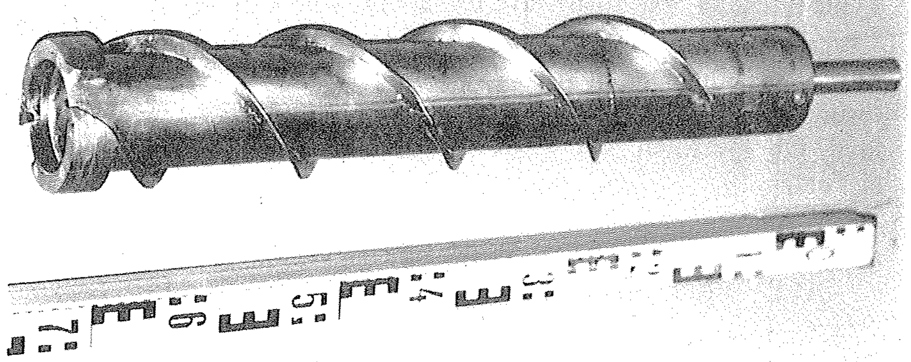

Fig. 5. Sampler drill.

4.2 FROST-HEAVE TEST

For the laboratory determination of frost-heave susceptibility a test cell was constructed by applying concepts presented in the literature (e.g. Roggensack 1977, Konrad 1980). The test cell was designed for samples drilled from frozen ground and for reconstituted specimens prepared in the laboratory. The structure of the cell is shown in Fig. 6 and the lay-out of measurements and control is illustrated in Fig. 7.

The frozen soil sample was shortened to 100 - 150 mm, and its ends were sawn perpendicular to the long axis. The specimen was placed in the frost-heave cell to thaw under an external load of 20 kPa, which corresponds to an average overburden pressure at the sampling depth. After thawing, the specimen was saturated with water by connecting it to an external reservoir through a filter plate at its lower end. The water level in the external reservoir was kept at the level of the specimen top.

In the frost-heave test the top surface of the specimen was cooled by allowing a cold liquid at a constant temperature to circulate in the top plate. The temperature of the warm end was likewise controlled with a liquid circulating at constant temperature. The water flowed into the warm end of the specimen from another external reservoir, in which the water table was at the level of the specimen's lower end. The room temperature and the external reservoir temperature were kept at close to 0°C. The heave of the top plate was measured with a displacement transducer. The temperatures along the side and at the top of the specimen were measured with thermocouples.

Typical results of a frost-heave test are presented in Fig. 8.

The segregation potential was determined at each load step from the results of the test as a function of time. Before the increase in the load, the specimen was thawed, reconsolidated and saturated in the test cell.

4.3 OTHER LABORATORY INVESTIGATIONS OF SEASONALLY FROZEN SOILS

The change in the physical properties of soils due to freezing was studied with a limited set of laboratory investigations.

The structure of the frozen samples was inspected visually. The bulk density, specific density, water content and grain size distribution were determined in the laboratory with standard procedures. The thaw compressibility of frozen samples was determined as was the hydraulic conductivity of thawed samples.

For the thaw compression test an oedometer ring (h = 20 mm, D = 50 mm) was pushed through a cylindrical sheet sawn from the frozen sample in a cold chamber. The specimen was placed in an oedometer apparatus in a laboratory room at a temperature +22°C and under a vertical pressure of 20 kPa, which corresponded approximately to the in-situ stress. The compression was measured from the top of the specimen with an electrical displacement transducer, and it was complete 3 - 5 minutes after the start of the test.

The permeability test was carried out on a subspecimen that was cut from the specimen used for the frost-heave test. Hydraulic conductivity was determined by applying a small hydraulic pressure difference (max. 2 kPa) between the ends of the subspecimen, and then measuring the lowering in the pressure head with time.

The results are discussed in detail in chapter 5.

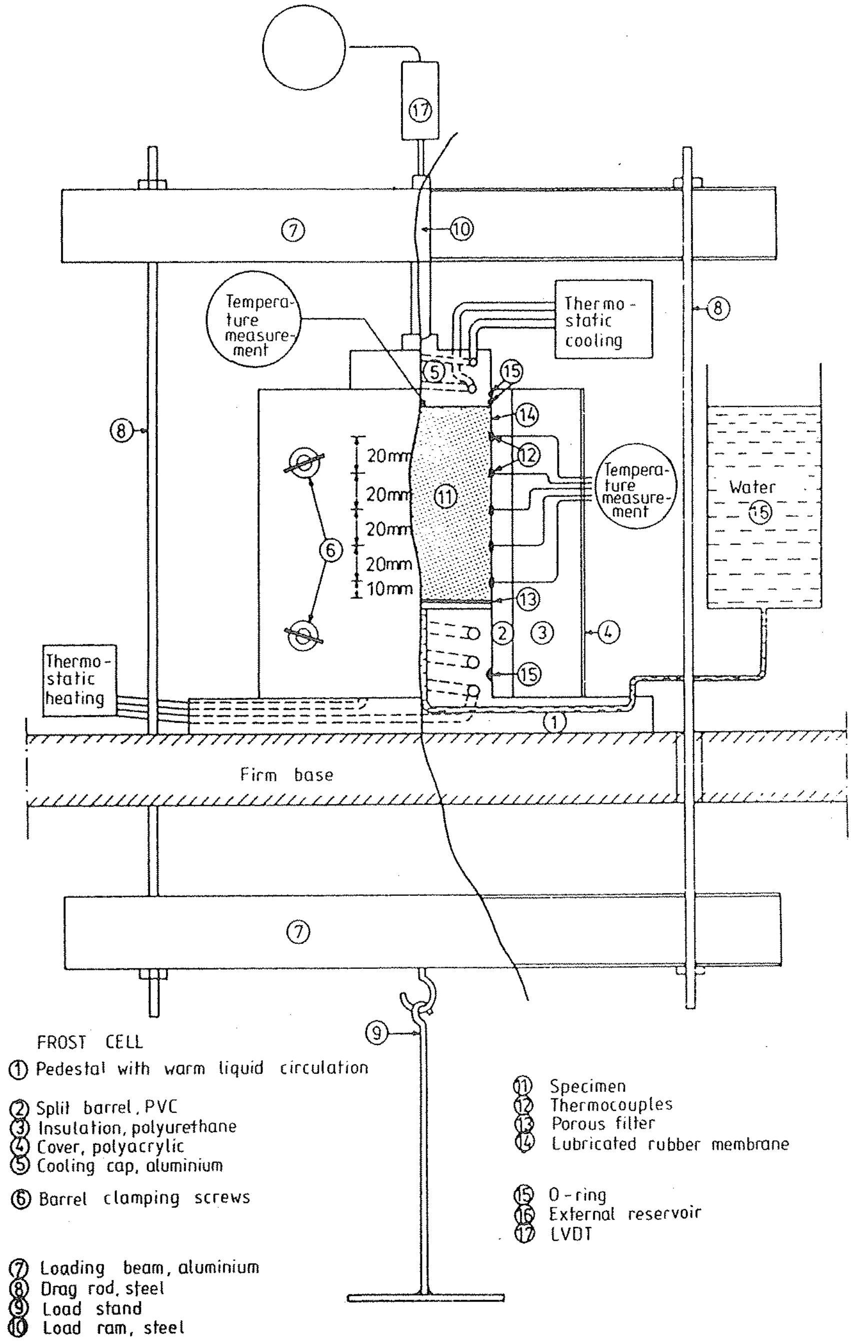

Fig. 6. Set up of the frost-heave cell.

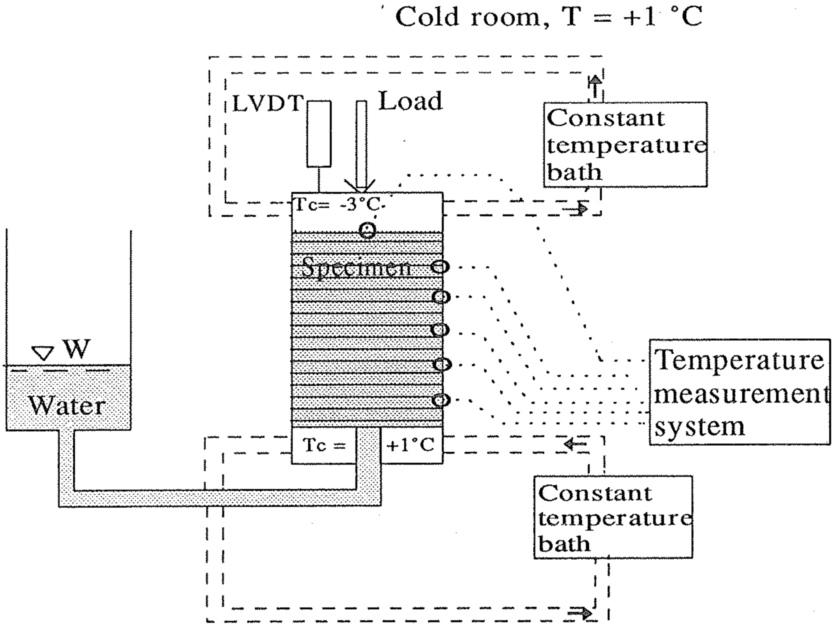

Fig. 7. Data acquisition and control of the frost-heave test.

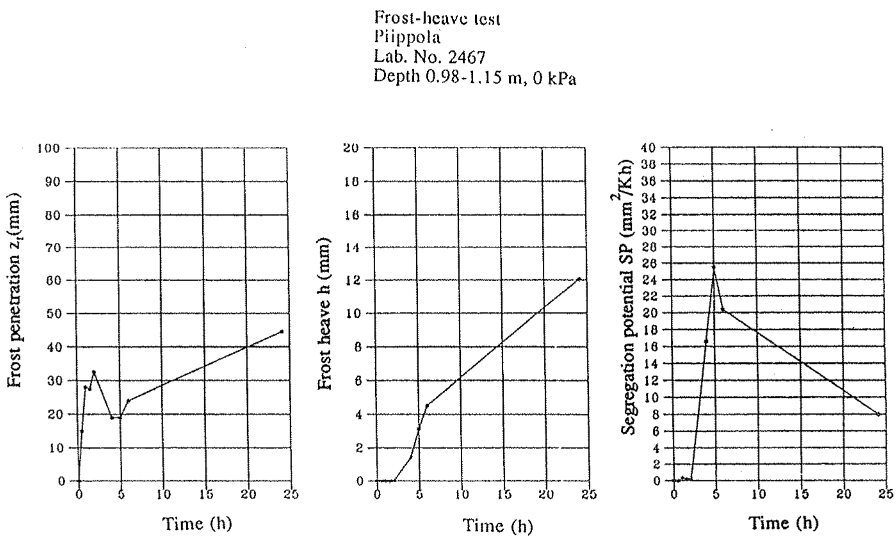

Fig. 8. Presentation of the results of a frost-heave test.

5 OBSERVATION SITES

5.1 ALAJÄRVI

5.1.1 Site location and ground conditions

The site was located at Alajärvi, Vaasa Province, about 60 km ENE of Seinäjoki, at 63°N and 23°50'E. The observation point was situated in the yard of the local road maintenance base, where the ground surface was at +107.3 metres above sea level (Fig. 9).

The terrain was, in general, flat, reasonably well drained forest land. In the north the forest was bounded by the creek Kurejoki and in the south the forest gave way to wetland.

At the observation point the unfrozen surface soil was silty sandy till to the depth of 0.5 metres, changing with depth into silty sand and further into sandy silt. The moisture content was in the range of 14 - 21% and the clay content 2 - 6% (Kivikoski 1983). From the determined water content the dry density of the ground was estimated to be 1.7 - 1.8 t/m^3, assuming the ground was saturated. The soil profile and properties are illustrated in Fig. 10.

Fig. 9. Alajärvi. Site location.

Frozen samples were taken in April 1983 from a depth interval of 0.4 - 1.46 m. According to the frost tube, frost penetration at the sampling point was 1.45 m.

Visual inspection of the frozen samples showed that, below a thin surface humus layer, the ground was silty to a depth of about one metre, changing with depth into till. No distinct ice lenses or ice layers were visible.

The determined grain size distributions of unfrozen and frozen samples are presented in Fig. 11.

The water content of the frozen ground was at a depth of 0.4 metres was about 31%, at a depth of 0.8 - 1.2 metres 15 - 17%, and at a depth of 1.2 metres about 11%. The bulk density of frozen samples varied between 1.6 and 2 t/m^3 and the dry density between 1.27 and 1.78 t/m^3 (Fig. 10). On the basis of the determined parameters the degree of ice saturation of samples varied between 65 and 89% (Fig. 12).

The thaw compression of a sample taken from a depth of 0.7 metres was 2.6%. During the preparation of samples for the frost-heave test

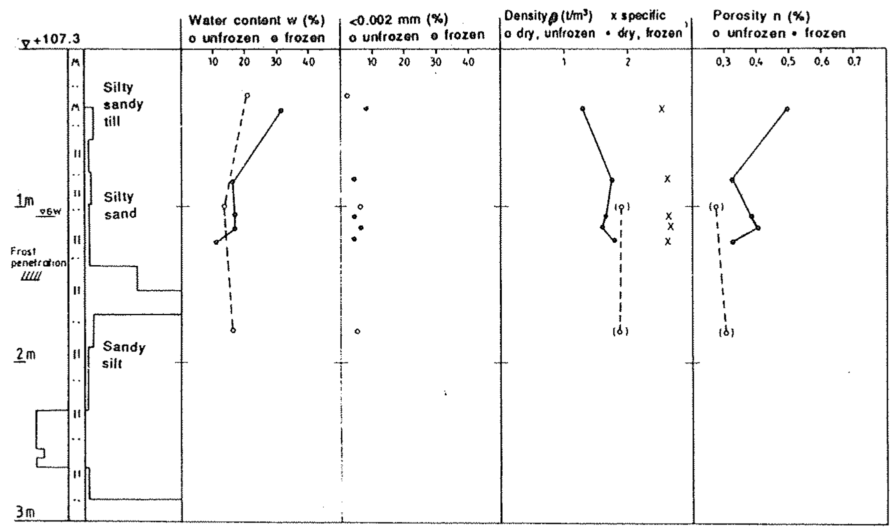

Fig. 10. Alajärvi. The soil profile and soil properties at the observation point measured from unfrozen samples (Kivikoski 1983) and frozen samples.

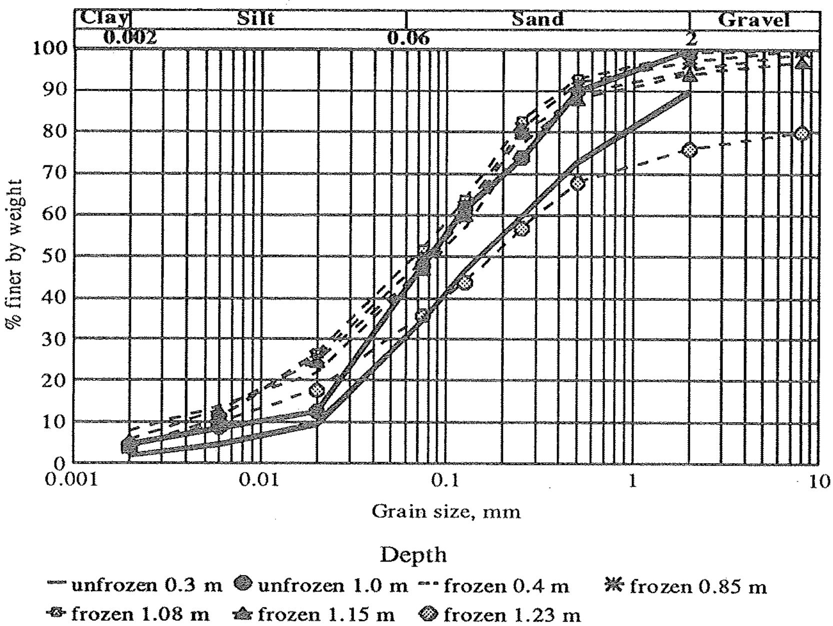

Fig. 11. Alajärvi. Grain size distribution of unfrozen and frozen samples.

in the frost-heave cell (ϕ 80 mm, h 100 mm) the thaw compression was 8 - 21% (Fig. 12).

The coefficient of permeability was about 10^{-6} m/s for a thawed sample from the depth of 1 meter.

Frost-heave tests were carried out on samples taken from the depths of 0.81 - 1.08 m, 0.97 - 1.2 m and 1.23 - 1.46 m. The segregation potentials are shown in Fig. 12.

5.1.2 Frost observations

Observations in the winters of 1959 - 1982

The staff of the road maintenance base had carried out frost monitoring every winter since 1959 except in 1960 - 1963. The number of seasons monitored was 19.

At the end of the freezing season the frost penetration varied in the range 0.85 - 2.11 metres and frost heave in the range 70 - 270 mm.

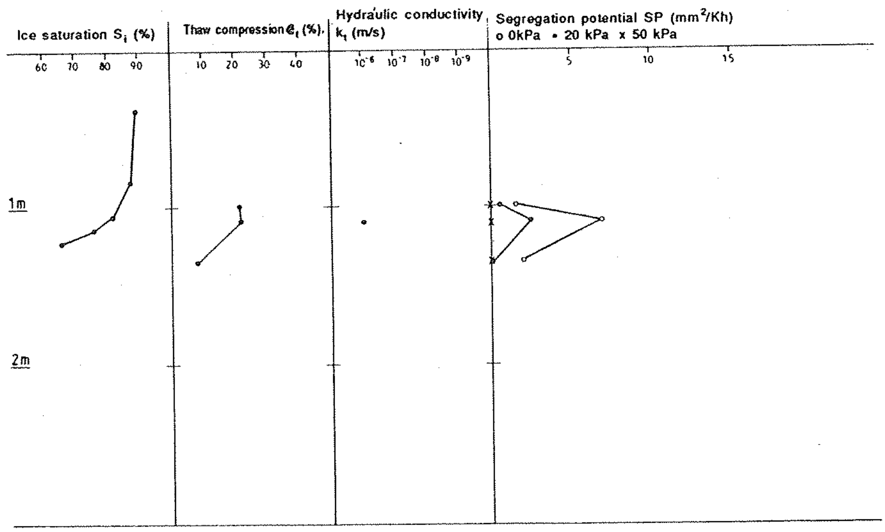

Fig. 12. Alajärvi. Thaw compression of a thawing sample, hydraulic conductivity of a thawed sample and the segregation potential of a freezing sample.

The depth to the groundwater table varied between 0.6 and 3.3 metres, the average depth being at about 1.6 metres below the ground surface or about 1 metre below the freezing front (Kivikoski 1983). The frost heave and frost penetration against the square root of the freezing index is illustrated in Fig. 13 and frost heave vs. frost penetration in Fig. 14.

Observations in the winter of 1982 - 1983

The temperature profile was measured with aseries of temperature transducers installed at 0.2 metre intervals at depths of 0.6 to 3.0 metres. The observation data are ploted in Fig. 15.

In the autumn of 1982 the temperature gradient of the frozen ground was about 7 °C/m and in midwinter about 6.5 °C/m. In the late autumn of 1982 the temperature gradient of the unfrozen ground was about 2.5 °C/m and in midwinter about 2 °C/m.

The observed frost penetration and frost heave, and the corresponding climatic data from the climate observation station of the Finnish

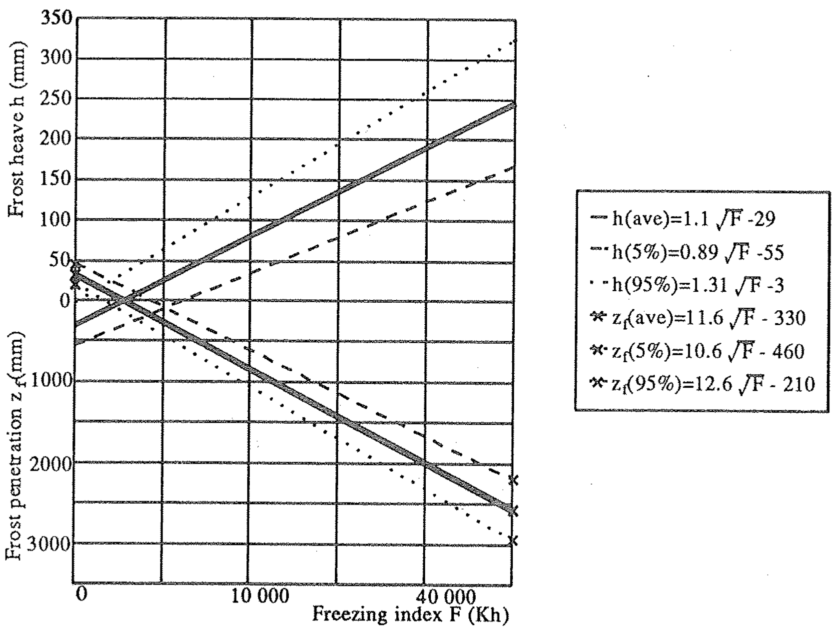

Fig. 13. Alajärvi. Frost heave and frost penetration vs. freezing index in the winters of 1959 - 1982 (Kivikoski 1983).

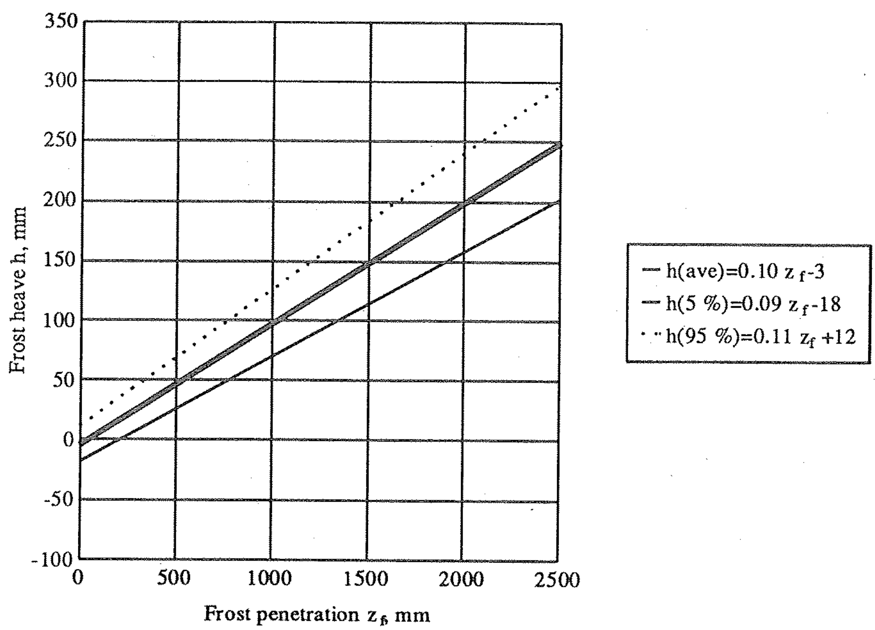

Fig. 14. Alajärvi. Frost heave vs. frost penetration in the winters of 1959 - 1982 (Kivikoski 1983).

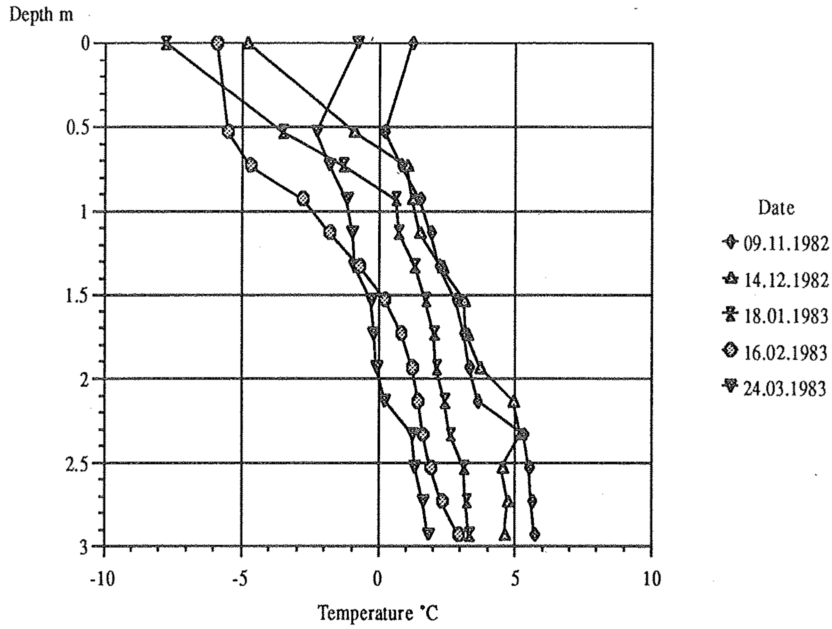

Fig. 15. Alajärvi. Temperature data from the winter of 1982 - 1983.

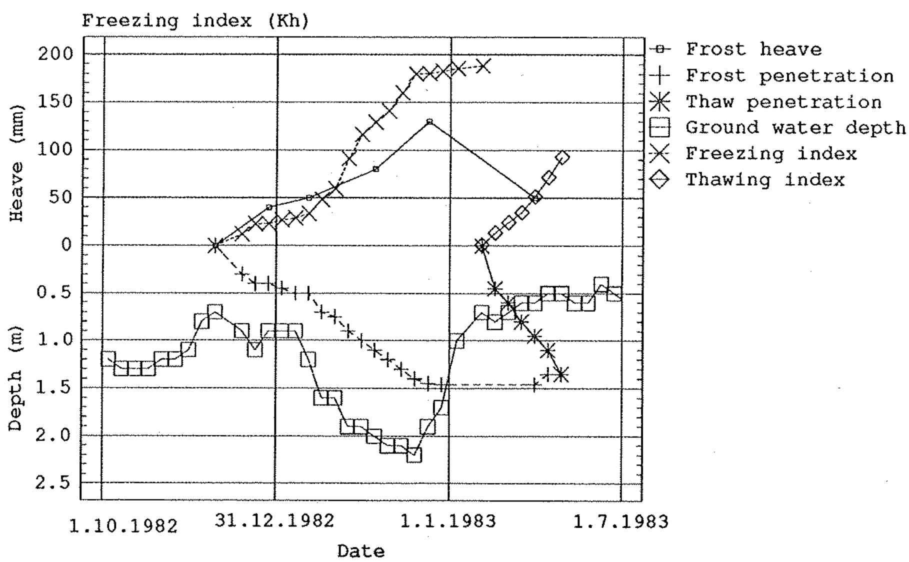

Fig. 16. Alajärvi. Frost heave and frost penetration in the winter of 1982 - 1983.

Meteorological Survey at Alajärvi, Möksy, are presented in Fig. 16. The maximum frost penetration, 1 460 mm, and frost heave, 130 mm, were observed at the end of March 1983. At the beginning of the freezing season the groundwater table was at the depth of about 0.7 metres. During the freezing season it sank to about 0.5 - 1 metres below the freezing front. After the start of the thaw, the groundwater table rose to a depth of 0.5 m below the ground surface.

The frost penetration and frost heave in relation to the freezing index were consistent with those of average long-term observations ($F = 18\ 000$ Kh, $h = 130$ mm, $z_f = 1\ 450$ mm, see Fig. 13).

5.1.3 Modelling of frost heave and frost penetration

Frost heave, frost penetration and freezing index

Kivikoski (1983) demonstrated a linear, significant correlation between the observed frost penetration and frost heave, and the square root of the freezing index for the winters of 1959 - 1982. The estimated ratios of frost penetration to the freezing index and of frost heave to the freezing index were (Figs. 13 - 14):

$$z_f = 11.6\sqrt{F} - 33 \quad r = 0.93 \tag{18}$$

$$h = 1.01\sqrt{F} - 3 \quad r = 0.86 \tag{19}$$

where z_f is frost penetration, mm
- h frost heave, mm
- F freezing index, Kh
- r coefficient of correlation

Frost heave, frost penetration and the depth of the ground-water table against the freezing index in the winter of 1982 - 1983 are plotted in Fig. 17. The distance between the freezing front and the groundwater table during the freezing season was about 0.7 metres.

Relative frost heave h/z_f, frost-heave factor β and average in-situ segregation potential SP

The relative frost heave in the winter of 1982 - 1983 is plotted in Fig. 18. The average ratio of frost heave to frost penetration was then 0.10. The frost-heave factor β was about 0.41. Assuming that the freezing

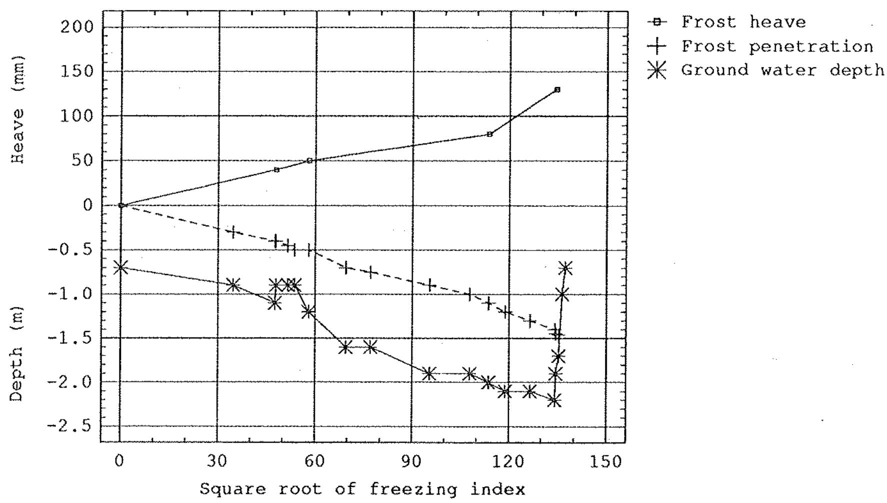

Fig. 17. Alajärvi. Frost heave and frost penetration vs. freezing index in the winter of 1982 - 1983.

ground was saturated, and that the average relative frost heave was about 0.1, the average segregation potential of the site was (equation (16)):

$h/z_f = 0.1$; $n_w = (\rho_d/\rho_w)w_t = 1.75*0.15 = 0.26$;
$k = 11.6\ mm/\sqrt{Kh}$

$SP = (h/z_f - 0.09\ n_w)\ k^2/2 = (0.1 - 0.09*0.26)\ 11.6^2/2 =$
$= 5.2\ mm^2/Kh$

Thaw penetration and thawing index

The measured thaw penetration against the corresponding thawing index calculated from the mean daily air temperatures are presented in Fig. 19. The relationship between thaw penetration and the thawing index was

$$z_t = 15\sqrt{F_t} + 136 \quad r = 0.998 \qquad (20)$$

where z_t is thaw penetration, mm
F_t thawing index, Kh

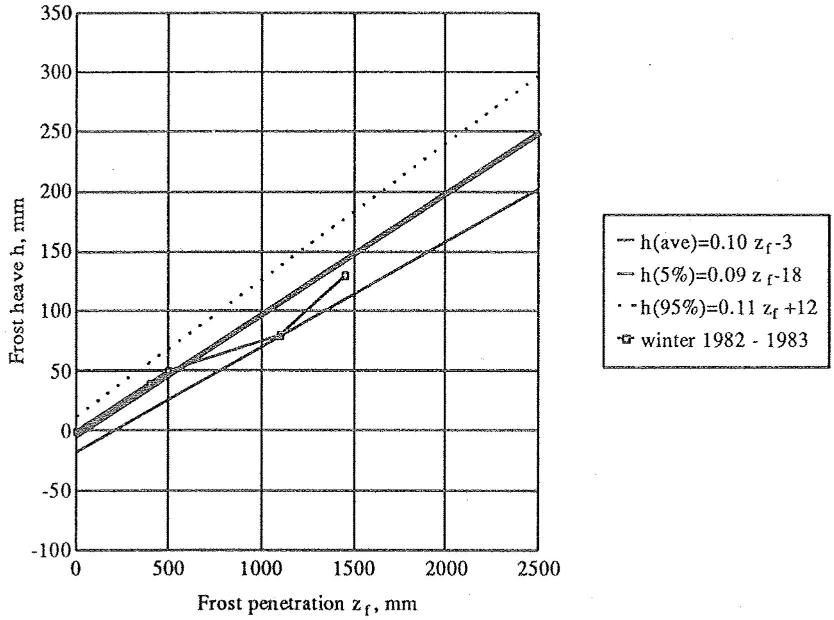

Fig. 18. Alajärvi. Frost heave vs. frost penetration in the winter of 1982 - 1983.

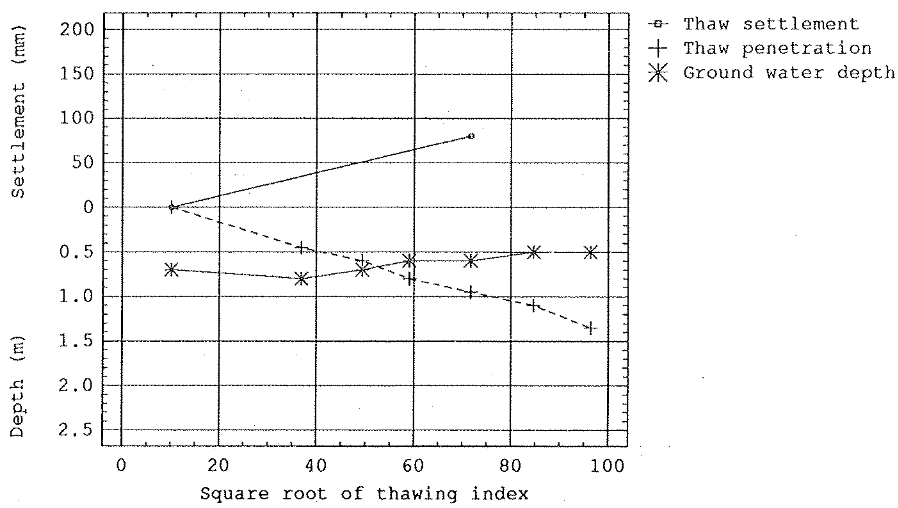

Fig. 19. Alajärvi. Thaw penetration and thaw settlement vs. thawing index in the spring of 1983.

Evaluation of frost penetration and frost heave with the SSR model

The frost heave and frost penetration were calculated using the SSR model. The soil layers and properties were evaluated from soil investigation data. In the analysis, the values of the segregation potential were back-calculated to correspond to the frost heave and frost penetration data for the winter of 1982 - 1983. The soil layers and their properties used in the calculation are listed in Table 1. The corresponding segregation potential in the layers varied between 3 and 8 mm^2/Kh.

Table 1. Alajärvi. The soil layers and properties used in SSR model, and the calculated frost penetration and frost heave in the winter of 1982 - 1983. Mean annual air temperature +2.8 °C.

Layer	Thickness dz, m	Volumetric latent heat L, Wh/m^3	Thermal conductivity Frozen λ_f, W/Km	Unfrozen λ_t, W/Km	Segregation potential SP_o, mm^2/Kh
1	0.5	37 479	2.3	1.3	5.0
2	0.3	24 412	3.0	2.2	3.0
3	0.5	37 200	2.2	1.7	5.0
4	1.0	37 200	2.2	1.7	8.0

Layer	Water content w_t, %	Clay content <0.002 mm, %	Dry density ρ_d, t/m^3
1	31	8	1.3
2	15	2	1.75
3	25	5	1.6
4	25	5	1.6

Month	Freezing index F, Kh	Frost penetration z_f, mm	Frost heave h, mm
12	2 455	483	46
1	6 026	858	62
2	14 157	1 294	111
3	18 026	1 422	128

The observed and calculated frost heave and frost penetration for the winter of 1982 - 1983 are presented in Fig. 20.

5.1.4 Discussion on results at Alajärvi

Frost heave and frost penetration proved to have a linear relationship with the square root of the freezing index, in both long-term observations and the observations made in the winter of 1982 - 1983. Relative frost heave, or the ratio of frost heave to frost penetration, was found to be constant.

Likewise, thaw penetration was linearized with the square root of the thawing index. Thaw compression, or the ratio of thaw settlement to thaw penetration, was comparable to the relative frost heave.

There was one observation of thaw settlement in the spring of 1983. According to this, the ratio of thaw settlement to thaw penetration was about 0.09. This value corresponds to the relative, measured frost heave (0.10).

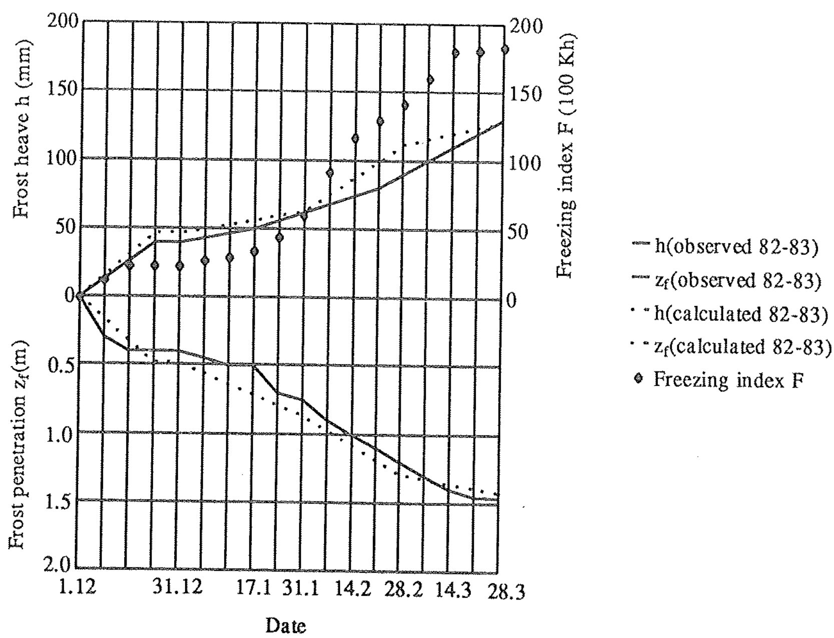

Fig. 20. Alajärvi. Observed and calculated frost heave and frost penetration for the winter of 1982 - 1983.

The thaw compression of the frozen samples was significantly greater (7 - 20%) than the observed relative frost heave (10%). Considering the relatively coarse-grained soil and the low degree of ice saturation of the samples (65 - 90%) thaw compression could not be accurately determined in the laboratory.

When the segregation potentials determined from the frost-heave tests were compared with the values back-calculated from the site observations, it was found that the laboratory values were smaller but that the order of magnitude was correct (average in-situ segregation potential about 5.2 mm^2/Kh, unloaded segregation potential estimated with the SSR model 3 - 8 mm^2/Kh, and the average value determined with unloaded laboratory tests about 3.5 mm^2/Kh).

The spatial estimation of frost heave and frost penetration using the SSR model was reasonably accurate.

5.2 PIIPPOLA

5.2.1 Site location and ground conditions

The site was located at Piippola, Oulu Province, about 80 km south-east of Oulu, 64°11'N and 25°55'E. The ground level at the point was +104 m (Fig. 21).

The observation point was located on a level ground in the partly paved yard of the road maintenance base. At the observation point the ground was covered with a layer of sandy gravel about 0.25 metres thick. The slope was very slight. The surrounding terrain was moist, ditched, cultivated lowland.

The gravel layer was underlain by graded, silty sandy till. At a depth of 0.7 - 1 metres, the clay content of the till was 5 - 10% and deeper 10 - 15%. The natural water content of the unfrozen till was 14 - 20% (Kivikoski 1983). The soil profile and properties at the observation point are illustrated in Fig. 22.

Fig. 21. Piippola. Site location.

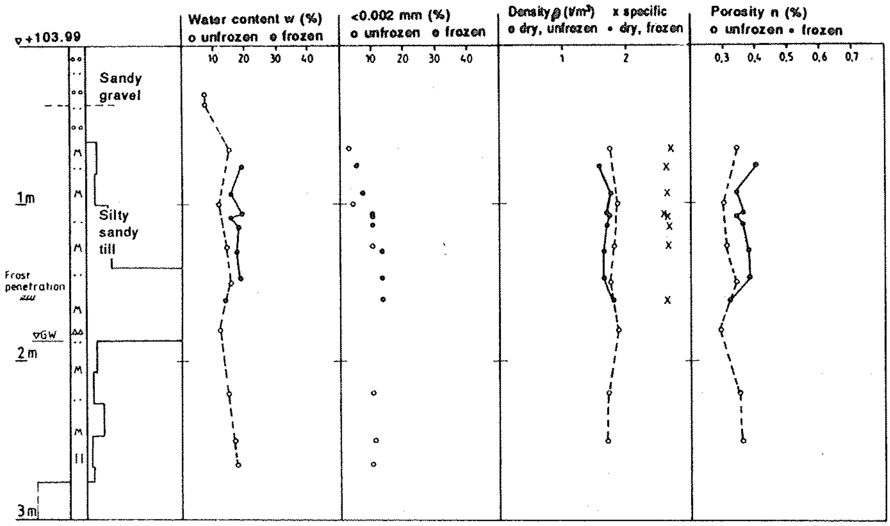

Fig. 22. Piippola. The soil profile and soil properties at the observation point measured from unfrozen samples (Kivikoski 1983, Friberg & Slunga 1989) and frozen samples.

According to field measurements (Friberg & Slunga 1989) and water content data the dry density of the till was 1.7 - 1.8 t/m^3. The degree of saturation of the unfrozen till was 80 - 87%. The capillary rise of the sandy till in the top layer (depth 0.5 - 0.7 m) was about 2.7 metres, and deeper (1.2 - 1.35 m) about 8 metres.

Frozen samples were taken with a drill from a depth of 0.68 - 1.65 metres in late April. Measured with a frost tube, frost penetration during sampling was 1.61 m.

At the ground surface the soil was coarse-grained, and thus undisturbed sampling was not possible with the method used. Visual examination of the frozen core showed that below a depth of 0.7 metres the soil changed to a more fine-grained, grey and silty type. It contained some visible ice, including a layer about 10 mm thick, of segregated ice at a depth of 0.9 metres. Below one-metre depth the soil changed into a coarser-grained, brown silty sandy till. No ice segregation was seen.

According to the grain size distribution, the soil was silty sandy till; the content of fines was 38 - 50%, the content of material ϕ<0.02 mm 17 - 27%, and the clay content 5 - 13%. The soil was coarsest at the top of the investigated profile, becoming finer down to a depth of 1 metre. Deeper than that the soil was fairly homogeneous (Fig. 23).

The total water content of the frozen samples varied in the range 13.7 - 19.3% (Fig. 22).

The bulk density of the frozen soil varied in the range 1.88 - 2.04 t/m^3, the dry density was 1.59 - 1.8 t/m^3, and the specific density 2.61 - 2.68 t/m^3 (Fig. 22). The degree of ice saturation of the samples was 81 - 100%, the average being about 87% (see Fig. 24).

The thaw compression of the samples was 12 - 16% except for the deepest sample, in which it was 6% (see Fig. 24).

At a depth interval of 0.7 - 0.85 metres the hydraulic conductivity of thawed sample was 1.4 - 1.6 10^{-6} m/s, at a depth of 0.98 - 1.15 metres 1.1 - 1.4 10^{-9} m/s, and at a depth of 1.4 metres about 3 10^{-8} m/s (Fig. 24).

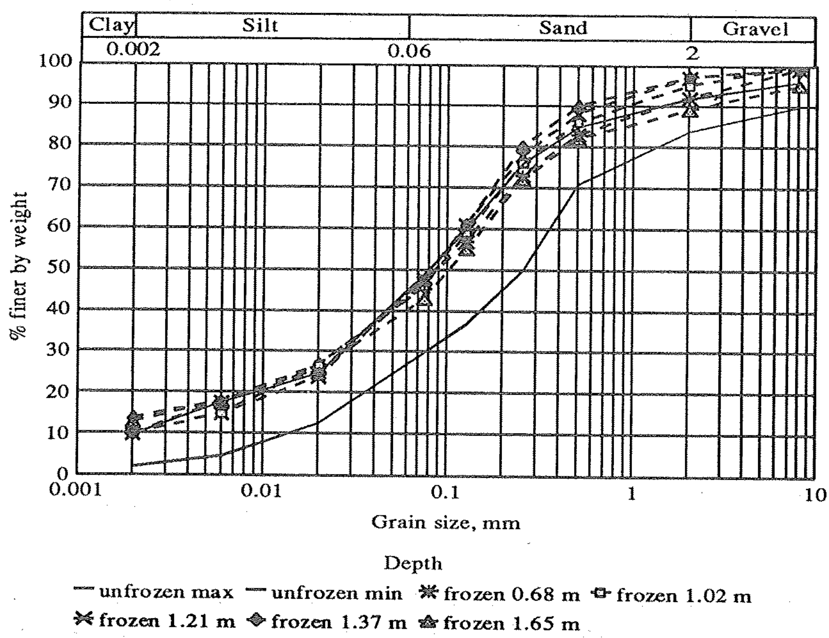

Fig. 23. Piippola. Grain size distribution of unfrozen and frozen samples from the observation point.

The results of the frost-heave tests are summarised in Fig. 24. The segregation potential of unloaded specimens varied between 4 and 9.4 mm^2/Kh, and with the applied load of 20 kPa, between 0.3 and 2.3 mm^2/Kh. When the applied temperature of the cold plate at the top of the specimen was -5°C (normally -3°C), the resulting segregation potential value in unloaded tests was about half of that at -3°C. When a pressure of 20 kPa was applied to the specimen, the segregation potentials were of the same order of magnitude.

5.2.2 Frost observations

Observations in the winters of 1959 - 1982

Frost heave, frost penetration and the depth to the ground-water table had been observed every winter from 1959 except in 1961 - 1963 and 1965 - 1967 by the technical staff of the road maintenance base. The maximum, seasonal frost penetration varied between 1 150 and 2 080 mm, and the maximum frost heave between 88 and 185 mm. The depth to the groundwater table was 700 - 3 690 mm (Kivikoski 1983).

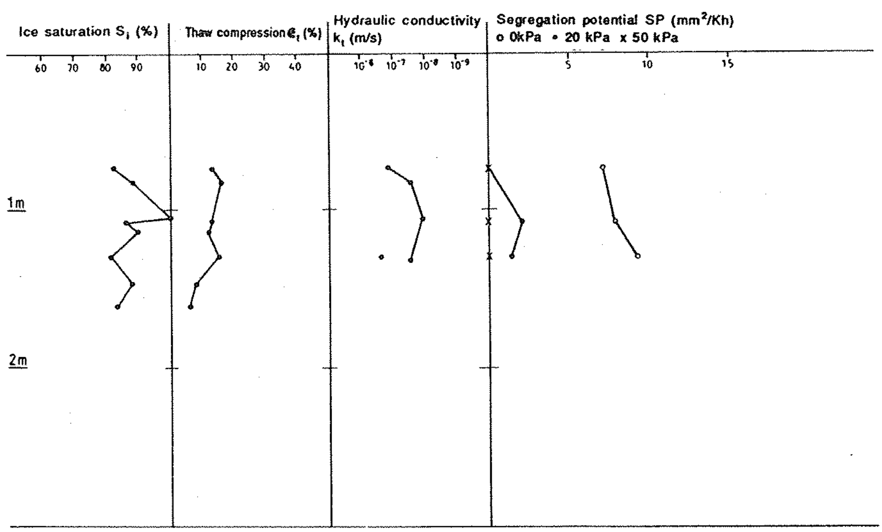

Fig. 24. Piippola. Ice saturation and thaw compression of the thawing sample, hydraulic conductivity of the thawed sample and the segregation potential of the freezing samples.

The relationships between frost penetration and the freezing index, and frost heave and the freezing index are illustrated in Fig. 25. The ratio of frost heave to frost penetration is plotted in Fig. 26. The observation data are discussed in detail in the study of Kivikoski (1983).

Observations in the winters of 1982 - 1986

In the autumn of 1982 a series of temperature transducers was installed at the observation point to monitor the temperature profile during the frost season. The transducers were Cu-K thermocouples located at 0.2 metre intervals from the ground surface down to 2.5 metres. The results for the winter of 1982 - 1983 are presented in Fig. 27.

At the beginning of the freezing period of 1982 - 1983 the temperature gradient of the frozen ground was about 7 °C/m and in January - February about 4.5 °C/m. The temperature gradient of the unfrozen ground at the freezing front was 2 - 3 °C/m.

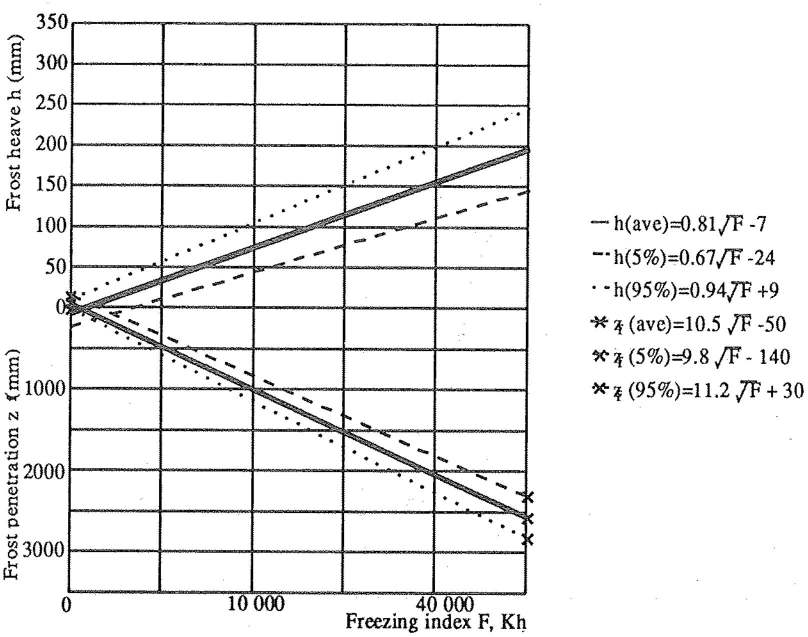

Fig. 25. Piippola. Frost heave and frost penetration vs. freezing index in the winters of 1959 - 1982 (Kivikoski 1983).

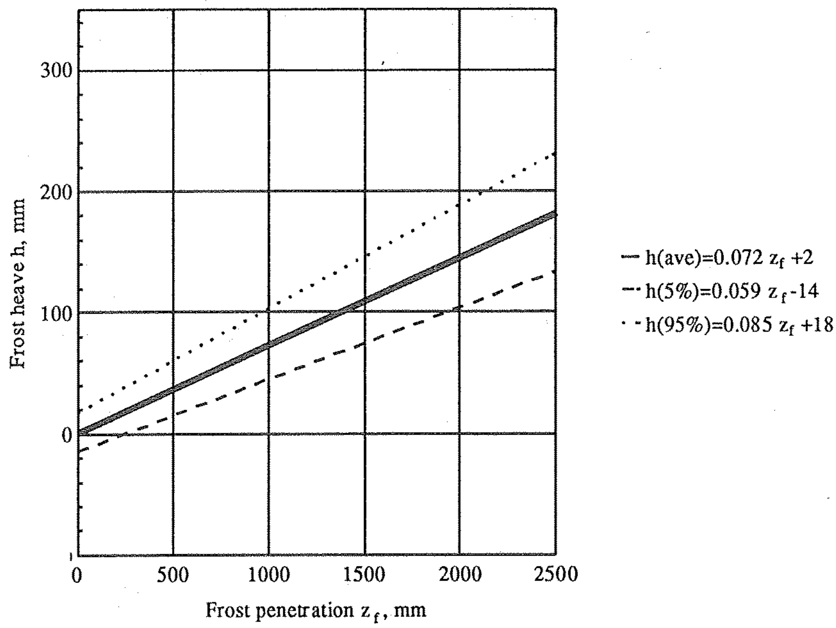

Fig. 26. Piippola. Frost heave vs. frost penetration in the winters of 1959 - 1982 (Kivikoski 1983).

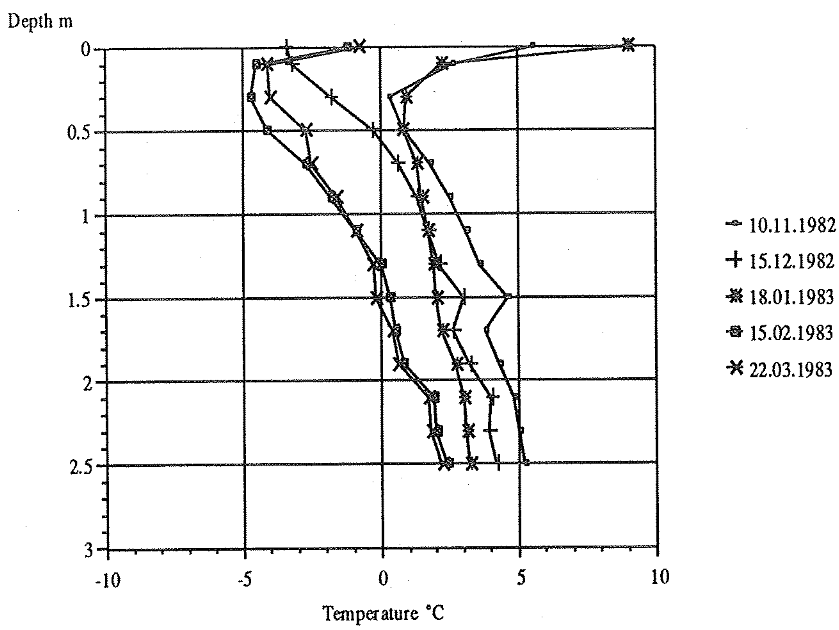

Fig. 27. Piippola. Temperature data from the winter of 1982 - 1983.

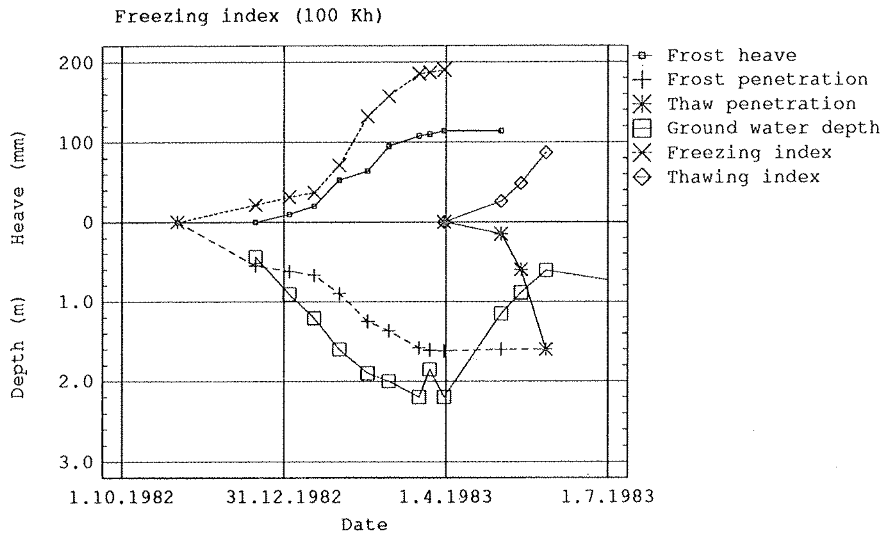

Fig. 28. Piippola. Frost penetration and frost heave in the winter of 1982 - 1983.

The data on frost heave and frost penetration, and the corresponding local climatic data from the climatic observation station at Nivala, are shown in Fig. 28. The maximum frost heave, 124 mm, and frost penetration, 1639 mm, were observed in early April 1983. The groundwater table sank 0.6 - 0.7 metres below the advancing freezing front.

The ratios of frost heave to the freezing index and of frost penetration to the freezing index for the winters of 1982 - 1986 are illustrated in Fig. 29. Frost heave vs. frost penetration in the winters of 1982 - 1986 and the average long -term relationship are presented in Fig. 30. The observed relative frost heave was slightly lower than the earlier long-term average values.

5.2.3 Modelling of frost heave and frost penetration

Frost heave and frost penetration vs. freezing index

In the statistical study of the data from the winters of 1959 - 1982, frost penetration and frost heave showed linear correlations with the square root of the freezing index (Kivikoski 1983). The relationships, which are illustrated in Figs. 25 - 26, have the form:

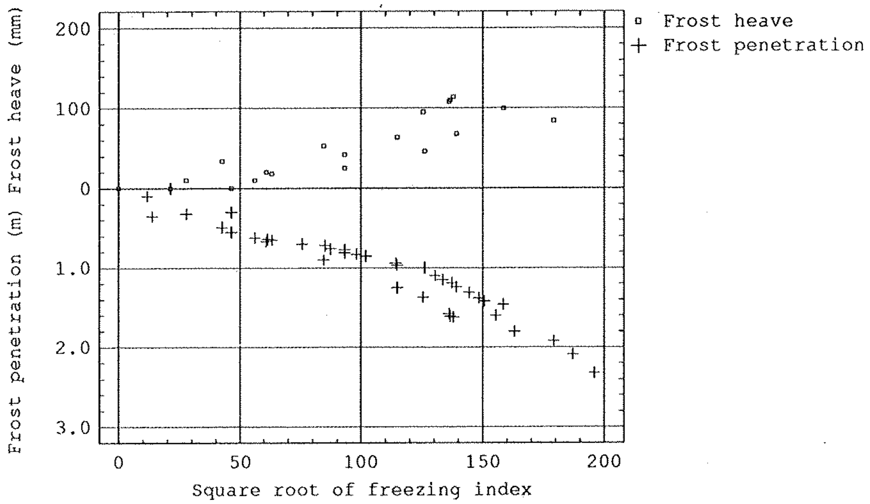

Fig. 29. Piippola. Frost heave and frost penetration vs. freezing index in the winters of 1982 - 1986.

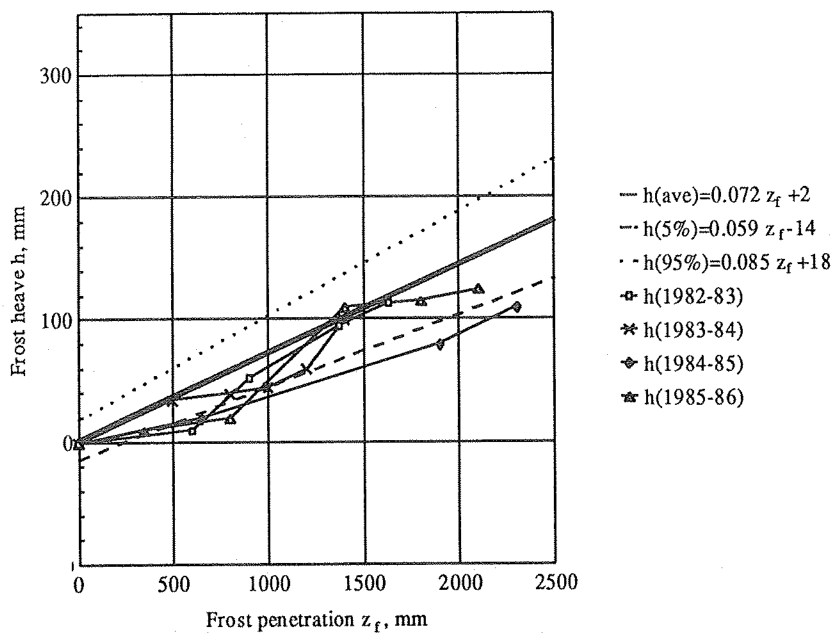

Fig. 30. Piippola. Frost heave vs. frost penetration in the winters of 1982 - 1986.

$$z_f = 10.5 \sqrt{F} - 50 \quad r = 0.964 \tag{21}$$

$$h = 0.81 \sqrt{F} - 7 \quad r = 0.824 \tag{22}$$

where z_f is frost penetration, mm
h frost heave, mm
r coefficient of correlation
F freezing index, Kh

Frost heave and frost penetration in the winters of 1982 - 1986 followed in principle the earlier long-term relationships.

Relative frost heave h/z_f, frost-heave factor β and segregation potential in situ SP

The average ratio between frost heave and frost penetration was in long term observations 0.072. The frost-heave factor β describing the frost heaving susceptibility of the ground was at Piippola β = 0.21, respectively. Considering average properties of the ground (relative frost heave $h/z_f = 0.072$; unfrozen dry density $\rho_d = 1.8$ t/m^3; unfrozen water content of unfrozen soil $w_t = 0.14$, and the coefficient of frost penetration $k = 10.5$ mm/$\sqrt{\text{Kh}}$), the average segregation potential in situ SP was 2.7 mm^2/Kh.

Thaw penetration and thawing index

Thaw penetration and thaw settlement vs. thawing index in the springs of 1983, 1985 and 1986 are presented in Fig. 31. Thaw penetration was found to be related to the thawing index as follows:

$$z_t = 26.5 \sqrt{F_t} - 690 \quad r = 0.89, n = 55 \tag{23}$$

$$h_t = 1.5 \sqrt{F_t} - 38 \quad r = 0.88, n = 6 \tag{24}$$

$$h_t = 0.047 z_t + 14 \quad r = 0.92, n = 6 \tag{25}$$

where z_t is thaw penetration, mm
h_t thaw settlement, mm
F_t thawing index, Kh

The development of thaw compression in the springs of 1983 and 1984 is illustrated in Fig. 32.

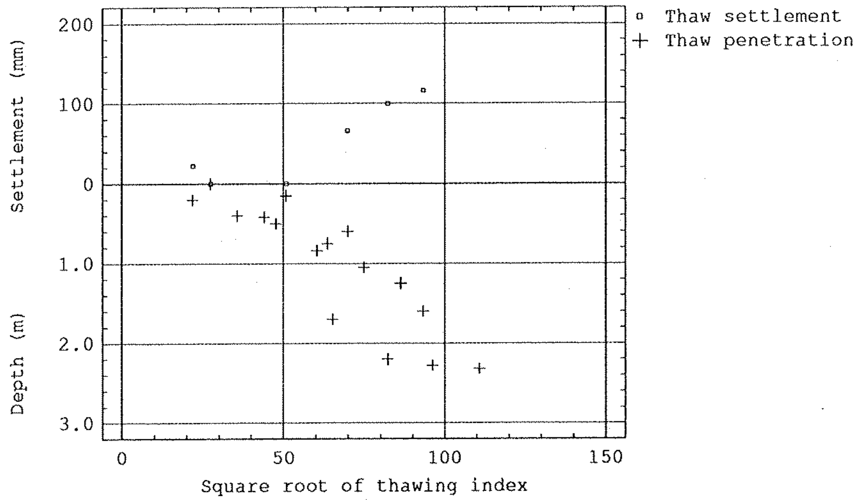

Fig. 31. Piippola. Thaw penetration and thaw settlement vs. thawing index in the springs of 1983, 1985 and 1986.

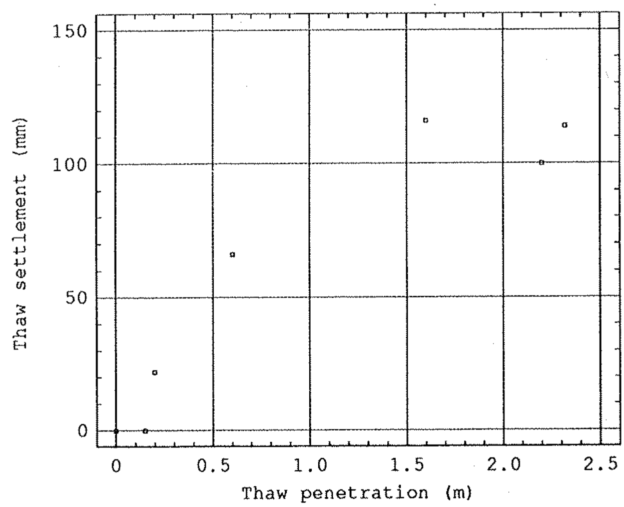

Fig. 32. Piippola. Thaw settlement vs. thaw penetration in the springs of 1983 and 1984.

Evaluation of frost heave and frost penetration using the SSR-model

Frost heave and frost penetration at the observation point of Piippola were evaluated using the soil profile and properties determined in soil investigations as initial soil data. The SSR model was used to backcalculate a value of the segregation potential was back-calculated, with which the calculated frost heave and frost penetration values corresponded to the values measured in the winter of 1982 - 1983.

The soil layers and properties, and the calculated frost heave and frost penetration vs. freezing index are presented in Table 2. The segregation potential corresponding to the best fit was 7 - 9 mm^2/Kh.

Observed and calculated frost heave and frost penetration in the winter of 1982 - 1983, and corresponding values according to long term observations are presented in Fig. 33.

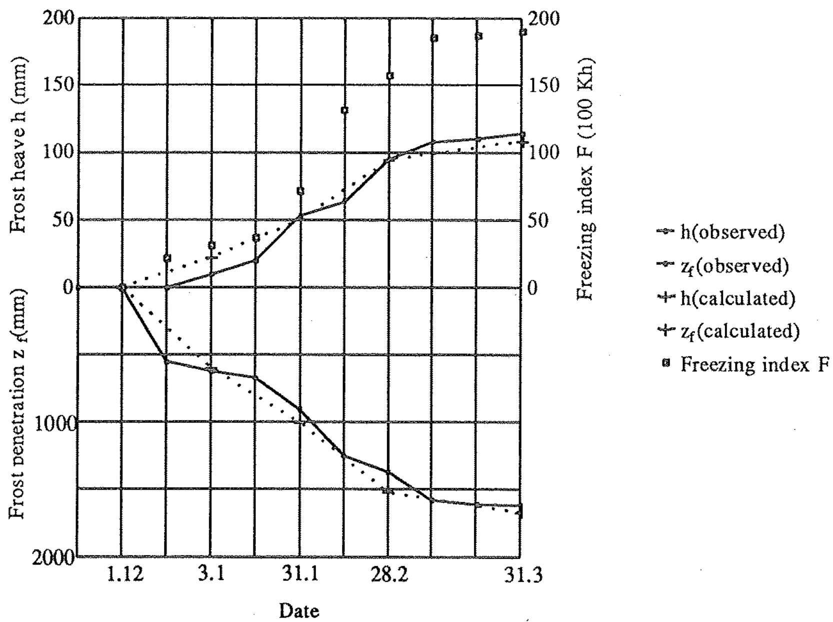

Fig. 33. Piippola. Observed and calculated frost heave and frost penetration for the winter of 1982 - 1983.

Table 2. Piippola. The soil layers and properties used in SSR model, and calculated frost penetration and frost heave in the winter of 1982 - 1983. Mean annual air temperature 2.2 °C.

Layer	Thickness dz, m	Volumetric latent heat L, Wh/m^3	Thermal conductivity Frozen λ_f, W/Km	Unfrozen λ_t, W/Km	Segregation potential SP_o, mm^2/Kh
1	0.3	15 810	1.89	1.83	0
2	0.6	24 552	3.05	2.21	7
3	0.3	25 389	3.46	2.41	8
4	0.3	25 389	3.46	2.41	9
5	0.3	26 040	3.17	2.22	6
6	0.3	20 869	3.14	2.45	1

Layer	Water content w_t, %	Clay content <0.002 mm, %	Dry density ρ_d, t/m^3
1	10	0	1.7
2	15	3	1.76
3	15	4	1.82
4	15	10	1.82
5	16	10	1.75

Month	Freezing index F, Kh	Frost penetration z_f, mm	Frost heave h, mm
12	2 827	600	22
1	7 514	1 000	50
2	15 242	1 519	94
3	18 888	1 667	108

5.2.4 Discussion on results from Piippola

Frost heave and frost penetration showed linear correlations with the square root of the freezing index both in long-term and actual observations. Relative frost heave was fairly constant. The variation in relative frost heave did not significantly depend on the corresponding variation in the groundwater table. Thaw penetration had a linear relationship with the square roof thawing index calculated from air temperatures during the thaw period.

The observed thaw settlement and thaw compression corresponded to the frost heave and relative frost heave in actual observations. The observed frost heave within the 0.67 - 1.58 - metre depth interval was about 88 mm, corresponding to a relative frost heave of about 10%. Relative frost heave measured in the field and thaw compression determined on representative samples in the laboratory corresponded approximately to each other. Further, thaw compression was comparable to the average relative frost heave, 7.2%, in long-term observations (Kivikoski 1983).

The average in-situ segregation potential calculated from the approximate formula (16) was about 2.7 mm^2/Kh. The mean stress level of the frost-susceptible ground was about 17 kPa (depth 1 metre). The average unloaded segregation potential producing the frost heave observed with use of the SSR model was about 7.8 mm^2/Kh. The average unloaded value in laboratory tests was about 8 mm^2/Kh, and under a loading of 20 kPa about 2 mm^2/Kh. The segregation potential determined with laboratory tests at an in-situ stress 17 kPa was about 2.5 mm^2/Kh.

The spatial development of frost heave and frost penetration estimated with the SSR model corresponded fairly well to the observed field behaviour.

5.3 JOENSUU, LEHMIPORTINTIE, POINT 14

5.3.1 Site location and ground conditions

The site was located in east Joensuu, eastern Finland, 62°35'N and 29°48'E. The ground surface in the area varied between +87 and +103 metres above sea level (Fig. 34).

The observation point was located on an asphalt-paved street in a silt area. The elevation of the original, natural ground surface had been about +87.6 m, and the level of the paved surface was about 87.8 m. According to the weight sounding, the silt was about 4 metres thick (Fig. 35).

Preliminary soil investigations showed that the surface soil consisted of silt underlain by till wherever the ground surface was at a level lower than +90 metres. At higher levels the till was exposed. The till bed was usually more than 2 metres thick. The till was silty and it was frost-susceptible owing to its grain size distribution. In areas of lower elevation the silt layer was 5-7 metres thick. The silt was clayey, with a clay content of 20 - 30%.

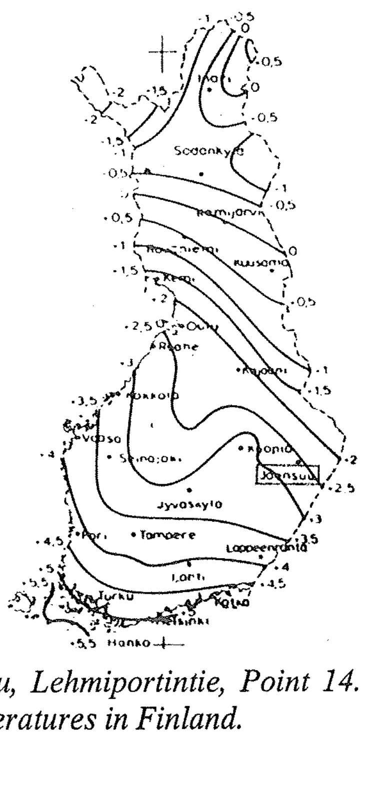

Fig. 34. Joensuu, Lehmiportintie, Point 14. Site location and mean annual air temperatures in Finland.

According to the test pit investigation and to sampling conducted before the frost season the pavement was underlain by non-frost-susceptible, gravelly sand to a depth of about 0.7 metres. This represented the base and sub-base layers of the street embankment. A layer of non-frost-susceptible sand 0.2 metres thick, i.e. the filter layer, occurred between the sub-base and the frost-susceptible, silty subgrade (Fig. 35). The groundwater table was not reached during the test pit investigation.

The water content of the unfrozen sub-base layer at a depth of 0.4 metres was about 2.1%, and that of the unfrozen filter layer at a depth of 0.8 metres about 15.4%. The water content of unfrozen silt was 21.5 - 24.4% (Fig. 35).

If the silt was saturated, the corresponding unfrozen dry density was 1.63 - 1.71 t/m^3. The soil profile at observation point 14 is illustrated in Fig. 35. The grain size distribution of the frost-susceptible silt is shown in Fig. 36.

Frozen samples were taken from the observation point 14 in early March 1983. According to the frost tube, frost penetration was then about 1.33 metres. The frozen samples were taken from the frozen subgrade with a test pit through the street embankment. The observed thickness of the street structure was about 0.9 metres. The frozen core was obtained from a depth of 0.92 - 1.36 metres.

According to the visual examination the soil at a depth interval of 0.92 - 1.15 metres was brownish grey silt with no detectable inclusions of segregated ice. At a depth interval of 1.15 - 1.2 metres, five to ten ice layers less than 5 mm thick were detected. Another zone of ice segregation was found at a depth of 1.3 metres. Here the thickness of the ice layer was about 2 mm.

The clay content of the soil at 0.92 - 1.36 metre depth was about 28 - 30%, and the content of the <0.02 mm fraction 68 - 83%. As shown by the grain size distribution the subgrade was homogeneous (Fig. 36). The water content of the frozen silt increased from 26.6% at the subgrade surface to 43% at the depth of frost penetration, about 1.36 metres. The increase in water content due to freezing was 5 - 20% (Fig. 35). The bulk density of frozen samples was 1.61 - 1.81 t/m^3, the specific density 2.64 - 2.71 t/m^3, and the dry density 1.13 - 1.43 t/m^3 (Fig. 35). The estimated ice saturation was 89 - 100% (Fig. 37).

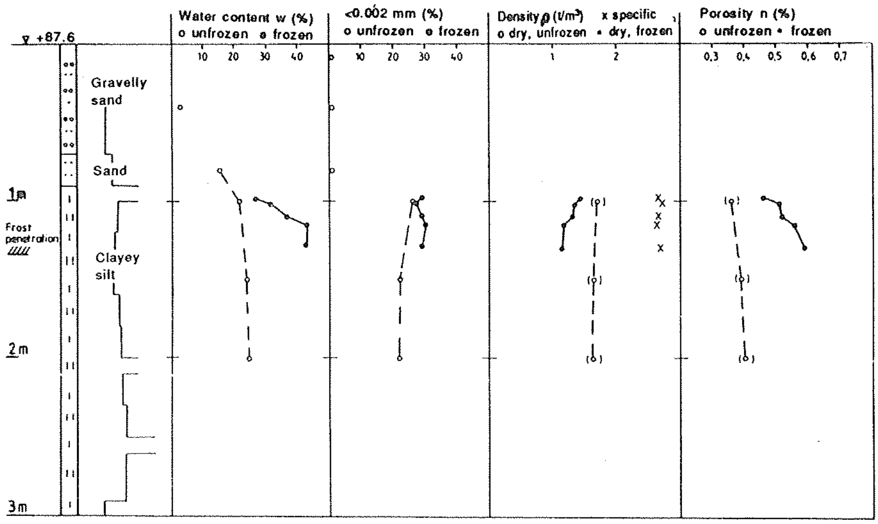

Fig. 35. Joensuu, Lehmiportintie, Point 14. Soil profile and properties unfrozen and frozen specimens.

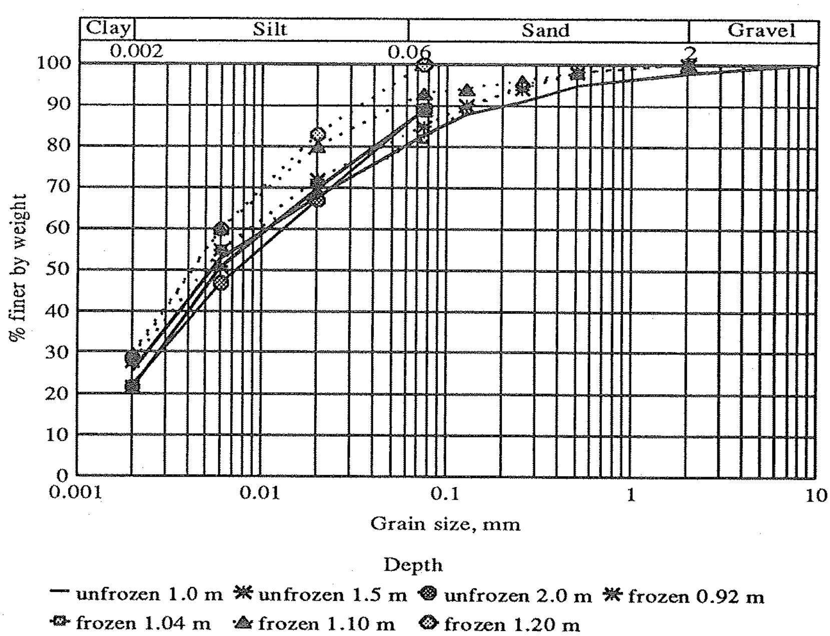

Fig. 36. Joensuu, Lehmiportintie, Point 14. Grain size distributions of unfrozen and frozen specimens.

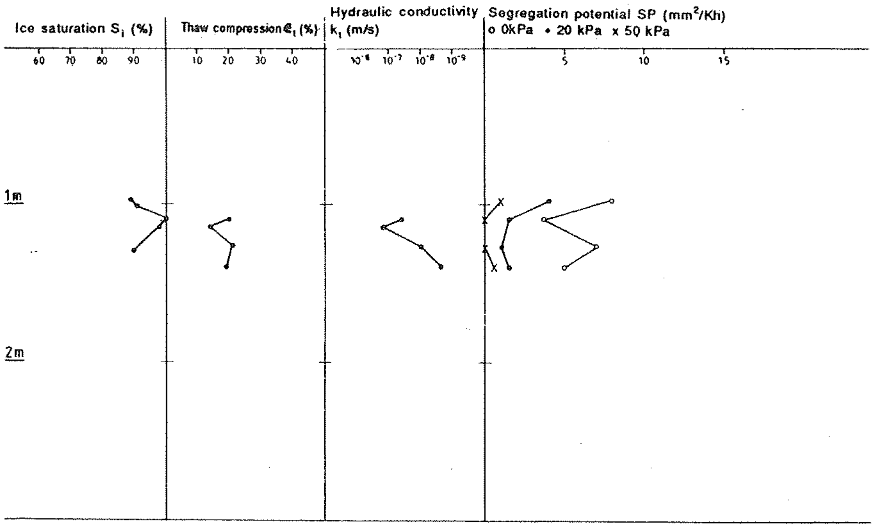

Fig. 37. Joensuu, Lehmiportintie, Point 14. Thaw compression of thawing soil, hydraulic conductivity of thawed soil and segregation potential of freezing soil in frost-heave test.

The thaw compression of samples was 14 - 20% of frozen height during preparation for the frost-heave test (Fig. 37). The hydraulic conductivity of thawed samples was 1.4 10^{-7} - 2.2 10^{-9} m/s. Hydraulic conductivity decreased with increasing depth (Fig. 37).

The unloaded segregation potential in the frost-heave test was 4 - 8 mm^2/Kh. Under an axial load of 20 kPa the segregation potential was 0.5 - 4 mm^2/Kh, and under a load of 50 kPa 0 - 1 mm^2/Kh (Fig. 37).

5.3.2 Frost observations

The temperature data from the winter of 1982 - 1983 are illustrated in Fig. 38. At the beginning of the frost season, in December 1982, the temperature gradient of unfrozen ground at the freezing front was about 3 °C/m. At the end of the frost season, in April 1983, the temperature gradient of the unfrozen ground was about 2.7 °C/m.

According to temperature measurements 0°C isotherm reached its maximum depth in April 1983, when it was about 1.5 metres.

Data on frost heave and frost penetration at point 14 in the winter of 1982 - 1983 are given in Fig. 39 together with the climatic data from the observation station of the Finnish Meteorological Survey at Joensuu airport. The deepest frost penetration, 1.6 metres, and the maximum frost heave, 135 mm, were measured in mid-March 1983. Frost heave started to develop after the frost penetration exceeded about 0.7 metres.

The thaw began in mid-April and was completed at the end of May 1983. The total thaw settlement at the end of thaw was about 110 mm. In the autumn of 1983, before the new freezing period started, the ground surface had settled to the initial level of autumn 1982.

Temperature data recorded during the period October 1983 - March 1984 are illustrated in Fig. 40. The temperature gradient of unfrozen ground at the freezing front in December 1983 was about 4 °C/m and in March 1984 about 2.5 °C/m.

The values for frost heave and frost penetration in winter 1983 - 1984 is plotted in Fig. 41. Frost penetration in early April 1984 was about 1.7 metres, and frost heave about 150 mm. The groundwater table was

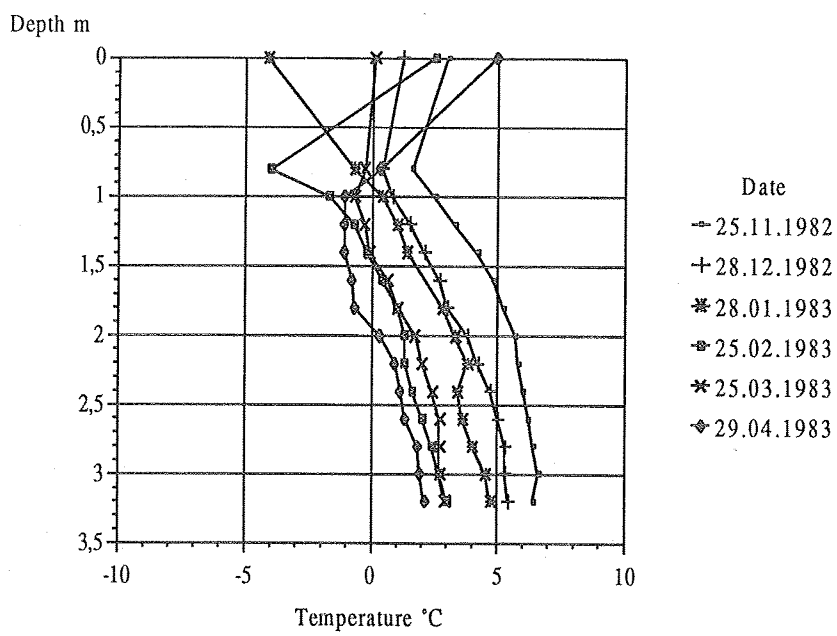

Fig. 38. Joensuu, Lehmiportintie, Point 14. Temperature data from the winter of 1982 - 1983.

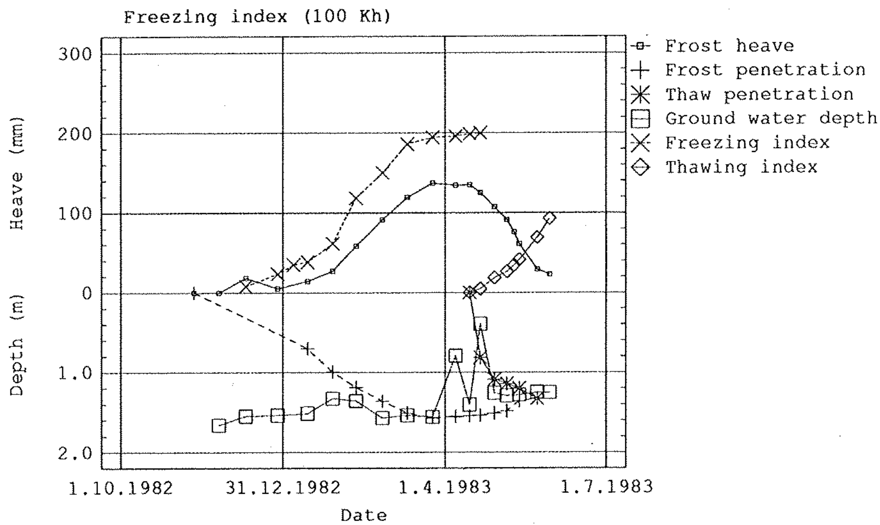

Fig. 39. Joensuu, Lehmiportintie, Point 14. Frost heave and frost penetration in the winter of 1982 - 1983.

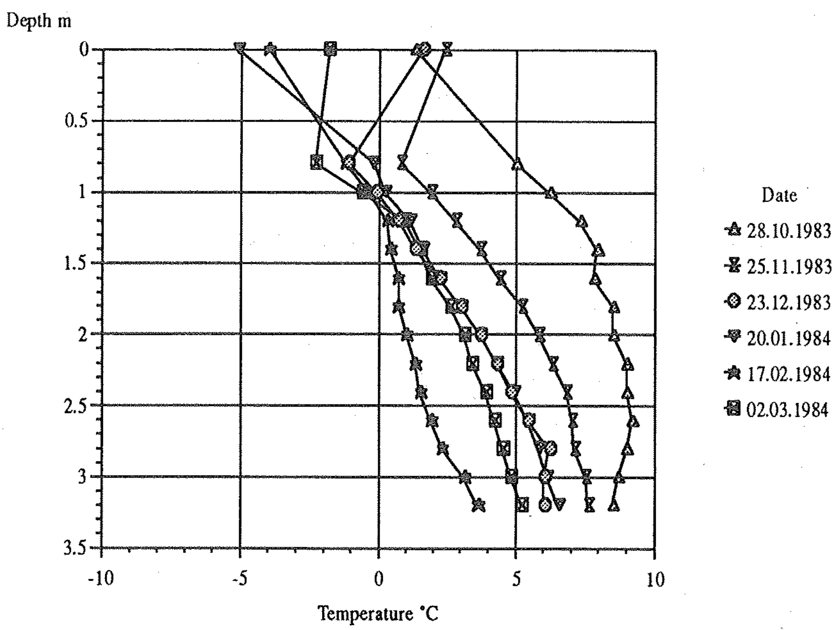

Fig. 40. Joensuu, Lehmiportintie, Point 14. Temperature data from the winter of 1983 - 1984.

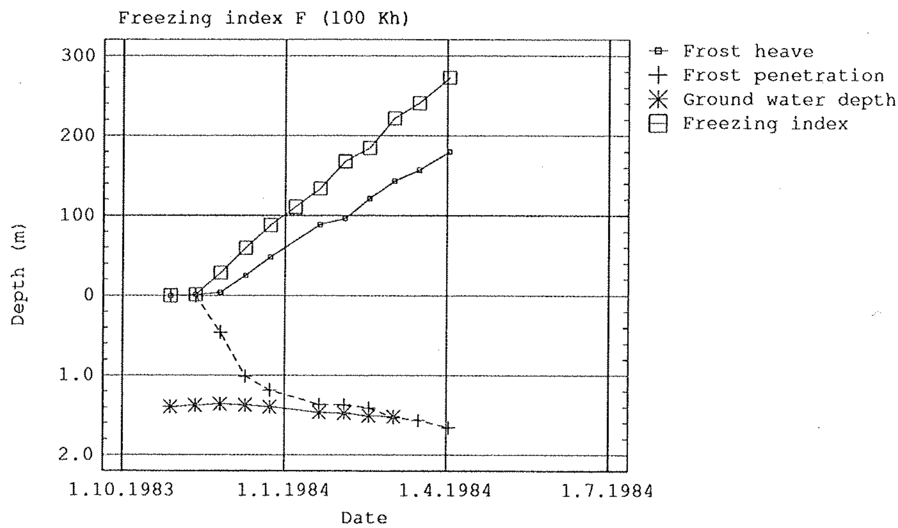

Fig. 41. Joensuu, Lehmiportintie, Point 14. Frost observations in the winter of 1983 - 1984.

at a depth of about 1.5 metres from the ground surface as it had been during the preceding winter. A significant heaving was observed after the frost penetration exceeded about 0.5 metres.

5.3.3 Modelling of frost heave and frost penetration

Frost heave and frost penetration vs. freezing index

The values for frost penetration and frost heave in relation to the square root of the freezing index in the winters of 1982 - 1983 and 1983 - 1984 are plotted in Fig. 42. The following linear equations describe frost heaving and frost penetration with the increasing freezing index:

$$z_f = 10.7\sqrt{F} \qquad (26)$$

$$h = 1.8\sqrt{F} - 120 \qquad (27)$$

where z_f is frost penetration, mm
h frost heave, mm
F freezing index, Kh

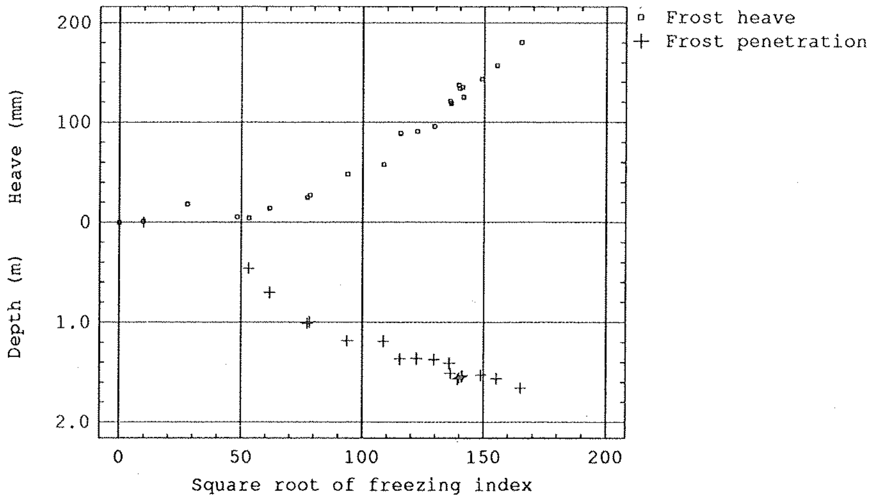

Fig. 42. Joensuu, Lehmiportintie, Point 14. Frost heave and frost penetration vs. freezing index in the winters of 1982 - 1983 and 1983 - 1984.

Relative frost-heave h/z_f, frost-heave factor β and segregation potential in situ SP

The frost heave vs. frost penetration in the winters of 1982 - 1983 and 1983 - 1984 is illustrated in Fig. 43. The ratio of the frost heave to frost penetration in the frost-susceptible subgrade was about 0.17. The frost-heave factor β was 0.36, when the volumetric water content of the soil was about 0.45. For the properties of the ground ($h/z_f = 0.17$, the average unfrozen dry density $\rho_d = 1.65$ t/m^3, the average water content of the unfrozen soil $w_t = 0.23$, and the coefficient of frost penetration $k = 10.7$ mm/$\sqrt{Kh}$) the average in-situ segregation potential was SP = 7.8 mm^2/Kh.

Thaw penetration vs. thawing index

The relation between thaw penetration and thawing index in spring 1983 was as follows (Fig. 44):

$$z_t = 14.8 \sqrt{F_t} + 278 \qquad (28)$$

where z_t is thaw penetration, mm
F_t thawing index (air temperatures), Kh

The observed thaw settlement vs. thaw penetration is illustrated in Fig. 45. Thaw settlement started once the thaw penetration exceeded about 0.7 - 1 metres.

Evaluation of frost heave and frost penetration with the SSR model

The soil layers and properties used in the analysis, the freezing index, and the calculated frost heave and frost penetration at the end of each winter month of 1982 - 1983 are presented in Table 3. The estimated, average, unloaded segregation potential was 8 mm^2/Kh.

The observed and calculated frost heave and frost penetration are illustrated in Fig. 46. The corresponding estimates of thaw penetration and thaw settlement for spring 1983 were established by multiplying the air temperatures measured during the spring thaw of 1983 by the coefficient 1.5 (asphalt pavement, see e.g. Lunardini 1978), and using the same soil profile as above. The results are presented with the corresponding observed data in Fig. 46.

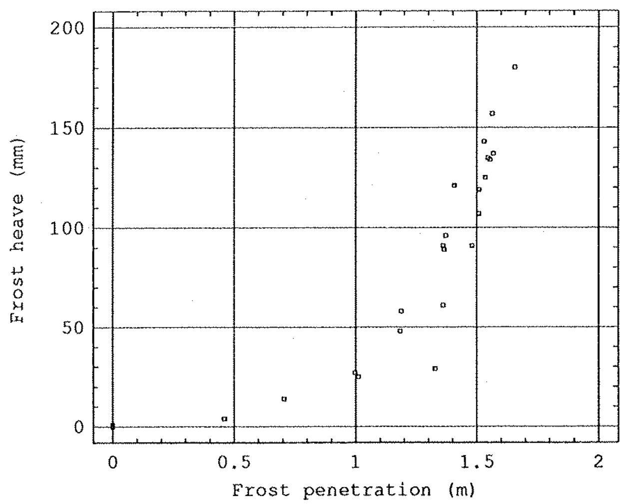

Fig. 43. Joensuu, Lehmiportintie, Point 14. Frost heave vs. frost penetration in the winters of 1982 - 1983 and 1983 - 1984.

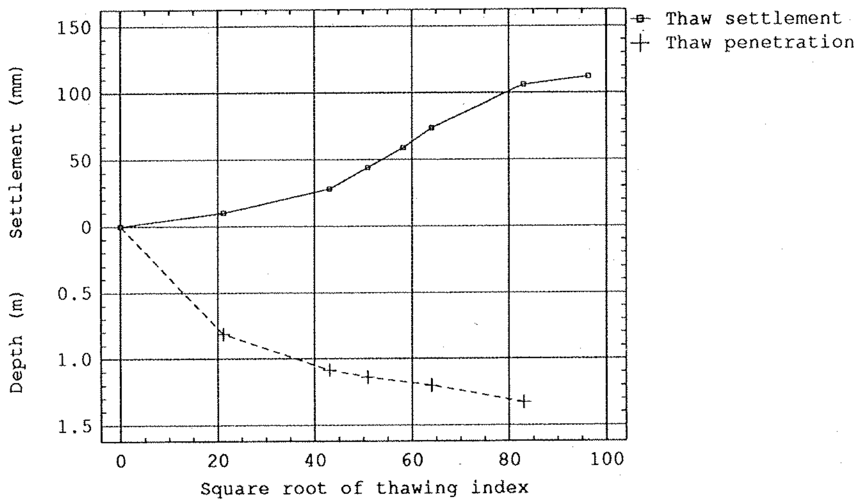

Fig. 44. Joensuu, Lehmiportintie, Point 14. Thaw penetration vs. thawing index in the spring of 1983.

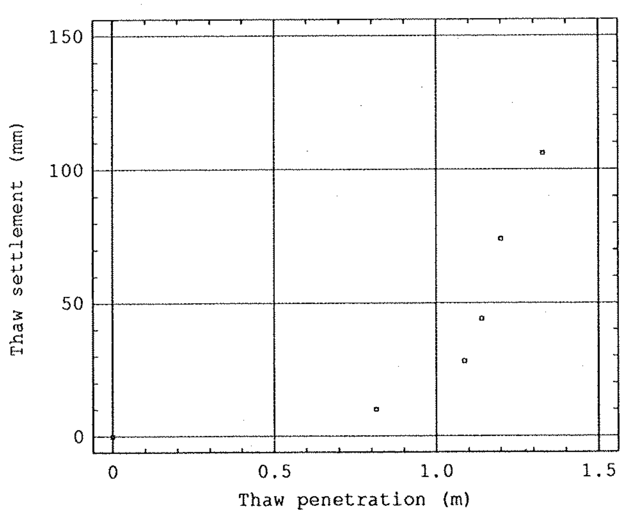

Fig. 45. Joensuu, Lehmiportintie, Point 14. Thaw settlement vs. thaw penetration in the spring of 1983.

Table 3. Joensuu, Lehmiportintie, Point 14. Soil layers and properties, the development of freezing index and calculated frost heave and frost penetration in the winter of 1982 - 1983. Mean annual air temperature 2.5 °C.

Layer	Thickness	Volumetric latent heat	Thermal conductivity Frozen	Unfrozen	Segregation potential
	dz, m	L, Wh/m^3	λ_f, W/Km	λ_t, W/Km	SP_o, mm^2/Kh
1	0.7	14 136	2.36	2.28	0
2	0.1	25 779	3.40	2.36	0
3	0.3	33 201	2.13	1.64	8
4	1.0	35 414	2.07	1.50	8

Layer	Water content w_t, %	Clay content <0.002 mm, %	Dry density ρ_d, t/m^3
1	8	0	1.9
2	15.4	0	1.8
3	21	25	1.7
4	23.8	23	1.6

Month	Freezing index F, Kh	Frost penetration z_f, mm	Frost heave h, mm
12	2 827	782	1
1	7 365	1 024	45
2	15 900	1 393	111
3	19 545	1 492	133

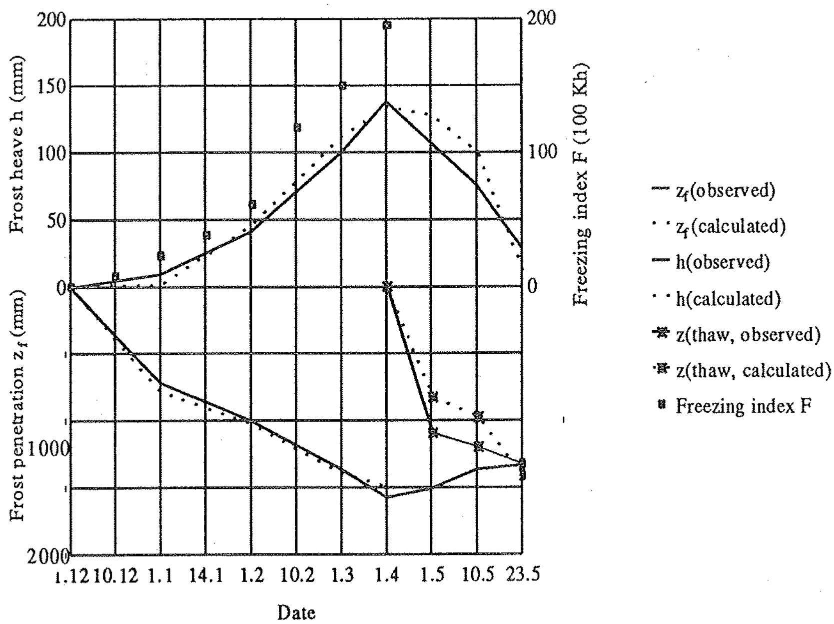

Fig. 46. Joensuu, Lehmiportintie, Point 14. Observed and calculated frost heave and frost penetration in the winter of 1982 - 1983. Thaw settlement and thaw penetration in the spring of 1983.

5.3.4 Discussion on results from Joensuu, Point 14

No information about the earlier frost behaviour at the site was available. Frost observations and testing showed that frost heaving at the site followed a regular pattern.

Ground conditions at the observation site were homogeneous: a constructed, non-frost-susceptible street embankment resting on a relatively uniform silty subgrade. Thus, the start of frost heave was distinct once the freezing front had proceeded into the frost-susceptible subgrade.

Frost penetration and heave followed a linear relationship with the square root of the freezing index. The relative frost heave was fairly constant down to the maximum freezing depth (Figs. 42, 43) and was comparable to in-situ thaw compression. Thaw penetration developed in a linear relationship with the square root of the thawing index.

The SSR model described the spatial development of frost heave and frost penetration fairly well. Laboratory tests showed that the average unloaded segregation potential was about 6.7 mm^2/Kh. The unloaded value estimated for observations by the SSR model was about 8 mm^2/Kh. The average in-situ segregation potential derived from observations (eq. 16) was about 7.8 mm^2/Kh.

In laboratory tests the thaw compression was 8 - 30%, but in the field 17%.

The degree of ice saturation of frozen samples was 89 - 100%. The frozen subgrade can thus be considered saturated. The difference in porosity between frozen and unfrozen soils was approximately 15%. This suggests that the inaccuracy in the thaw compression testing may have been partly due to errors in the measurement of the specimen volume. The estimated change in porosity is of the same order of magnitude as the relative frost heave or in-situ thaw compression (17%).

5.4 JOENSUU, KARJAMÄENTIE, POINT 20

5.4.1 Site location and ground conditions

The site was located in east Joensuu, eastern Finland, about 300 metres west of point 14. The ground surface in the area varied between +87 and +103 metres above sea level.

The observation point was sited on the eastern slope of Niinivaara, a moraine hill covered by silt deposits at levels below +90 metres. The original, natural ground level at the point was about +90.7 metres, as was the pavement level.

According to weight sounding, a layer of coarse-grained soil, about one metre thick, was underlain by finer-grained soil, presumably sand, to a depth of 1.8 metres.

In the test pit investigation of the unfrozen ground, gravelly street materials were found down to a depth of 0.75 metres underlain by 0.2 metres of sand. The subgrade to a depth of 1.8 metres was sandy till containing stones and boulders. Weight sounding and test pit investigations were brought to an end by stones at a depth of 1.8 metres.

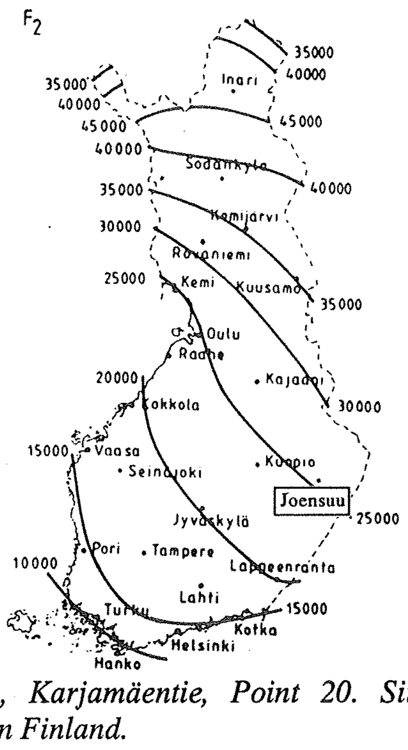

Fig. 47. Joensuu, Karjamäentie, Point 20. Site location. Mean freezing index F_2 in Finland.

The groundwater table was not detected. The subgrade was gravelly sandy till with a clay content of 3% and a water content of 6.9% (Figs. 48 and 49). Frozen ground was not sampled.

5.4.2 Frost observations

The temperature data from the winter of 1982 - 1983 are illustrated in Fig. 50. Estimated from temperature observations, the maximum frost penetration, about 1.9 metres, was in late April 1983.

The temperature gradient of unfrozen ground at the freezing front in November 1982 was about 4 °C/m and in late winter 1983 about 2.5 °C/m.

Observations of frost heave and frost penetration together with regional climatic data from the observation station at Joensuu airport are shown in Fig. 51. The maximum frost penetration observed in the frost tube, about 1.8 metres, occurred in late March 1983. Frost heave, about 20 mm, was observed in February, when frost penetration was within 1.2 - 1.5 metres. The groundwater table sank from a depth of about 2 metres at the beginning of the freezing period to 2.5 metres at the end, in late March.

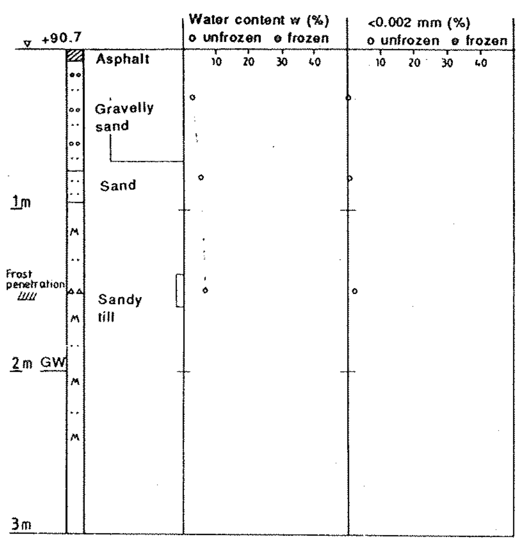

Fig. 48. Joensuu, Karjamäentie, Point 20. Soil profile and properties according to investigations and testing of unfrozen soils.

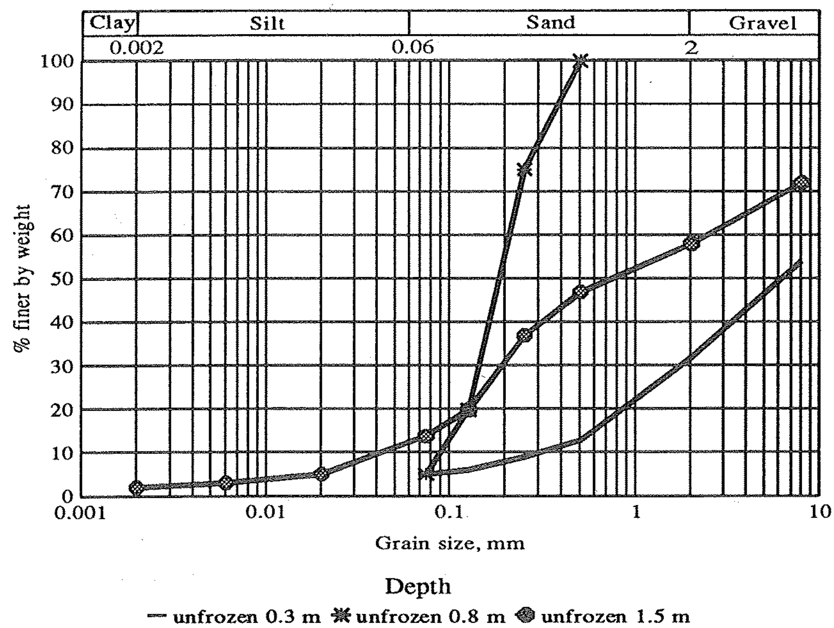

Fig. 49. Joensuu, Karjamäentie, Point 20. Grain size distribution of unfrozen samples.

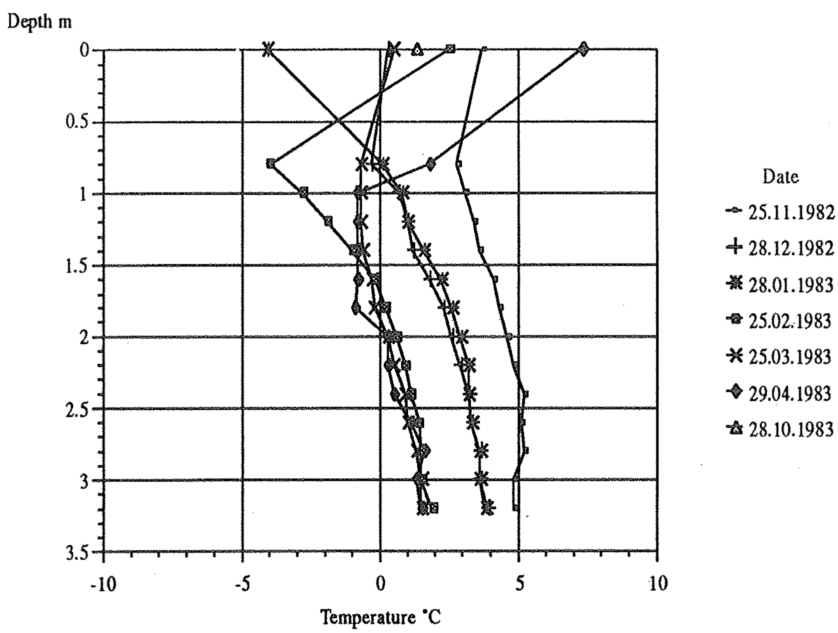

Fig. 50. Joensuu, Karjamäentie, Point 20. Temperature data from in the winter of 1982 - 1983.

The thaw started in March 1983 and was completed in mid-May 1983. Thaw settlement was practically equal to frost heave (Fig. 51).

In autumn 1983 freezing started in November. At the beginning of the following March frost penetration was about 1.56 metres. Frost heave, 15 mm, was observed when frost penetration was within 1.3 - 1.5 metres. The groundwater table sank during the observation season from 2 to 2.5 metres, lying at about 1 metre below the freezing front (Fig. 52).

5.4.3 Modelling of frost heave and frost penetration

Frost penetration vs. freezing index

The relationship between frost penetration and the square root of the freezing index in the winters of 1982 - 1983 and 1983 - 1984 is illustrated in Fig. 53. The observed relationship followed the form

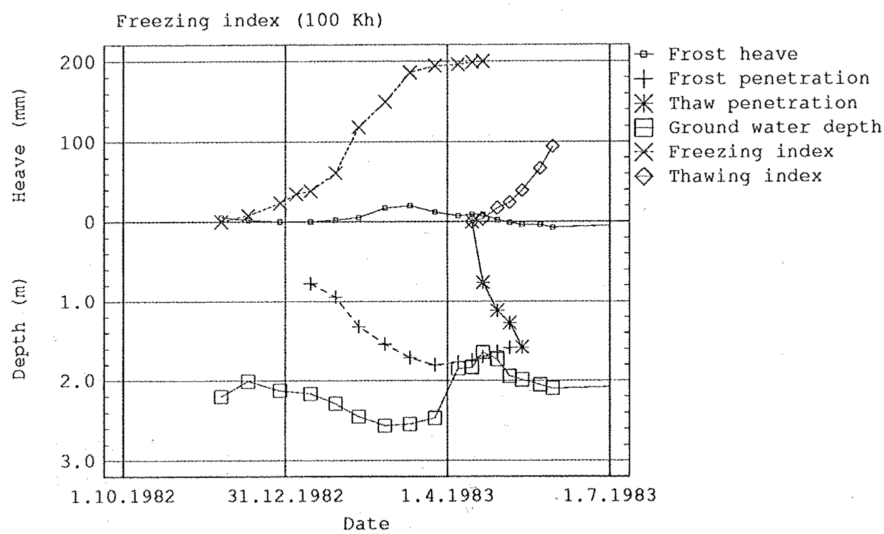

Fig. 51. Joensuu, Karjamäentie, Point 20. Frost heave and frost penetration in the winter of 1982 - 1983.

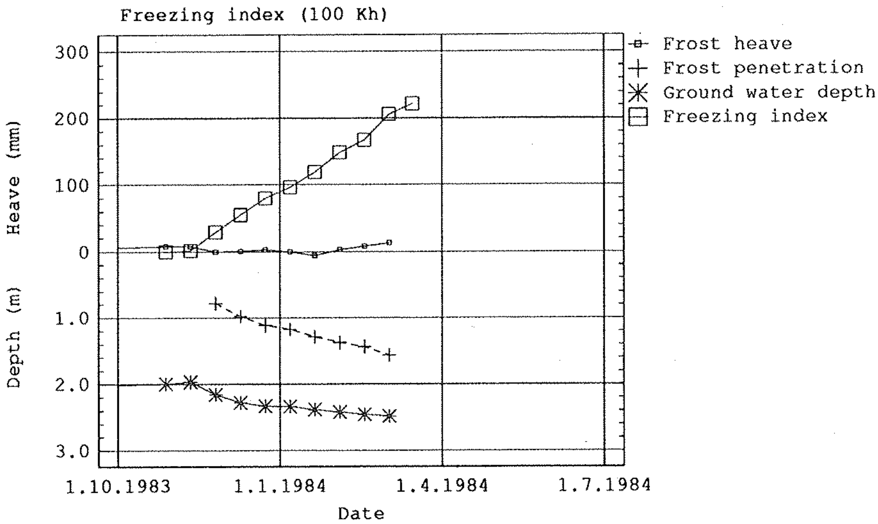

Fig. 52. Joensuu, Karjamäentie, Point 20. Frost heave and frost penetration in the winter of 1983 - 1984.

$$z_f = 11.2\sqrt{F} + 117 \quad (29)$$

where z_f is frost penetration, mm
F freezing index, Kh

Thaw penetration vs. thawing index

Thaw penetration as a function of the cumulative thawing index in spring 1983 is illustrated in Fig. 54. Thaw penetration was related to the thawing index as follows

$$z_f = 23.7\sqrt{F_t} + 133 \quad (30)$$

where z_f is thaw penetration, mm
F_t thawing index (air temperatures), Kh

Evaluation of frost heave and frost penetration using the SSR model

Frost penetration and frost heave were modelled also with the SSR model. The soil profile and properties, the monthly freezing index and

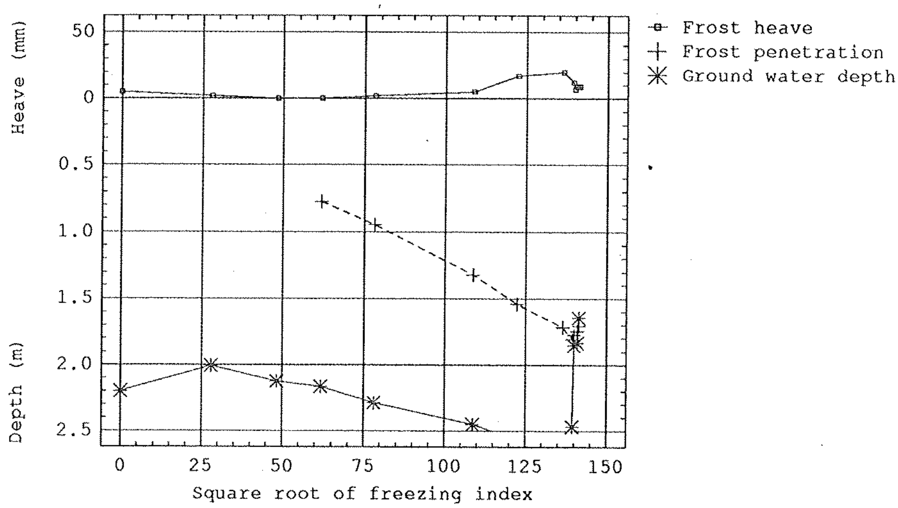

Fig. 53. Joensuu, Karjamäentie, Point 20. Frost penetration vs. freezing index in the winters of 1982 - 1983 and 1983 - 1984.

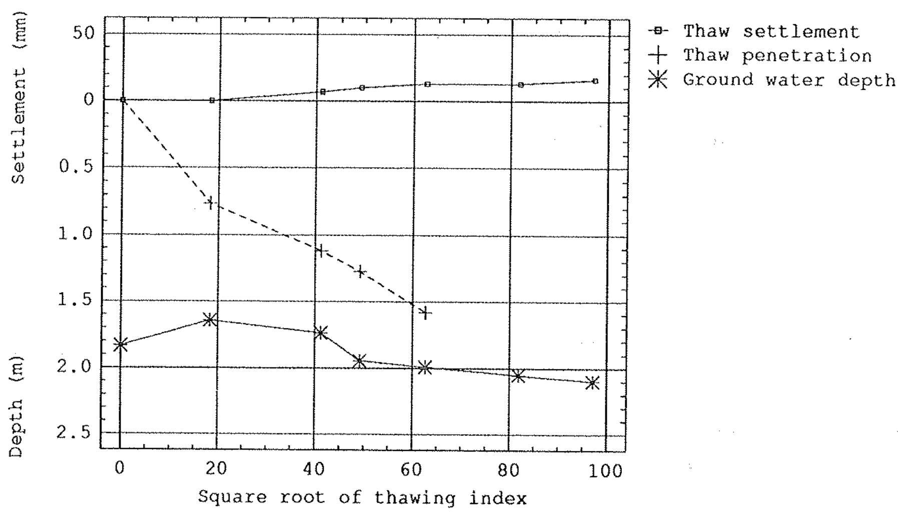

Fig. 54. Joensuu, Karjamäentie, Point 20. Thaw penetration vs. thawing index in the spring of 1983.

calculated monthly frost penetration and frost heave in the winter of 1982 - 1983 are presented in Table 4. The estimated, unloaded segregation potential producing the observed frost heave at the freezing depth of 1 - 1.5 metres was about 2 mm^2/Kh.

Table 4. Joensuu, Karjamäentie, Point 20. The soil layers and their properties, freezing index for winter months, and the calculated frost penetration and frost heave at the end of each month in the winter of 1982 - 1983. Mean annual air temperature 2.5 °C.

Layer	Thickness dz, m	Volumetric latent heat L, Wh/m^3	Thermal conductivity Frozen λ_f, W/Km	Unfrozen λ_t, W/Km	Segregation potential SP_o, mm^2/Kh
1	0.75	8 835	1.62	1.97	0
2	0.2	10 044	1.52	1.81	0
3	0.5	11 067	1.40	1.65	2
4	0.5	29 760	2.85	1.89	2

Layer	Water content w_t, %	Clay content <0.002 mm, %	Dry density ρ_d, t/m^3
1	5	0	1.9
2	6	0	1.8
3	7	2	1.7
4	20	2	1.6

Month	Freezing index F, Kh	Frost penetration z_f, mm	Frost heave h, mm
12	2 827	830	0
1	7 365	1 241	5
2	15 900	1 612	15
3	19 545	1 668	18

The observed and calculated frost penetration and frost heave in the winter of 1982 - 1983 is illustrated in Fig. 55.

5.4.4 Discussion on results from Joensuu, Point 20

The subgrade within the freezing zone was only slightly susceptible to frost heaving, and from the engineering point of view the frost heave was small. The frost heave cannot, however, be attributed expansion of the in-situ pore water alone, but to some extent to ice segregation as well.

Frost penetration and thaw penetration followed the square root relationship with the corresponding freezing or thawing index. The calculation model SSR gave spatial values for frost heave and frost penetration comparable with those observed.

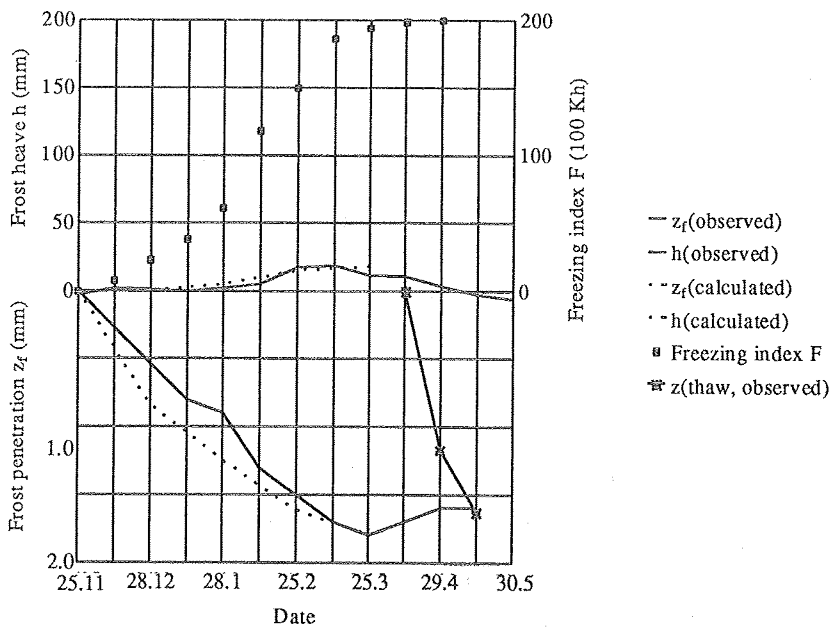

Fig. 55. Joensuu, Karjamäentie, Point 20. Observed and calculated frost heave and frost penetration in the winter of 1982-1983.

5.5 JOENSUU, SOMMELOTIE, POINT 33

5.5.1 Site location and ground conditions

The site was located in the northeast Joensuu, eastern Finland. The natural ground surface in the area varied between +77 and +80 metres above sea level (Fig. 56).

The area was flat, moist lowland. According to the topographic information the natural ground surface had been at a level slightly under +80 metres. The actual level of the pavement was at +80.4 metres. The constructed street embankment was about one metre thick, and was underlain by natural silty soil to a depth of 2.55 metres. The silt was underlain by coarse grained soil, presumably till, down to 5.6 metres.

In the test pit investigation of unfrozen ground the upper part of the street embankment was found to consist of base and subbase layers of gravelly sand about 0.6 metres thick. These layers were underlain by a filter layer of sand about 0.4 metres thick. At the top of the subgrade a thin layer of organic soil, presumably peat, was detected, and on this

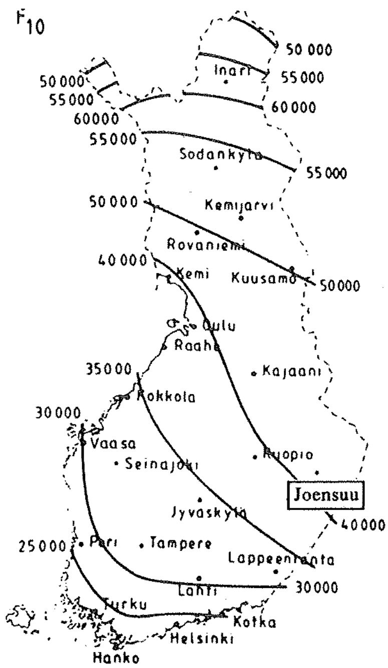

Fig. 56. Joensuu, Sommelotie, Point 33. Site location. Maximum freezing index F_{10} occurring once in ten years.

a small basin of perched water was observed. The subgrade soil was clayey silt, changing with increasing depth to lean clay.

The sampling of frozen ground was carried out in early March 1983, when the frost penetration according to frost tube was about 1.5 metres. The frozen core was gained from the depth interval 0.9 - 1.45 metres.

Visual examination of the core showed that the soil at a depth of 0.9 - 1.02 metres was brown silty sand with no inclusions of segregated ice. Below 1.09 metres the soil became grey and fine-grained, with slight ice segregation. At a depth interval of 1.18 - 1.25 metres, five to ten ice lenses with an average thickness of about 1 mm were observed. Below 1.25 metres depth the soil became grey-brown and fine-grained, without any ice inclusions.

The ground profile at the observation point, the water content of unfrozen and frozen soils, and the bulk density, dry density and specific density of frozen soils are illustrated in Fig. 57.

The grain size distributions of the investigated unfrozen and frozen samples are plotted in Fig. 58.

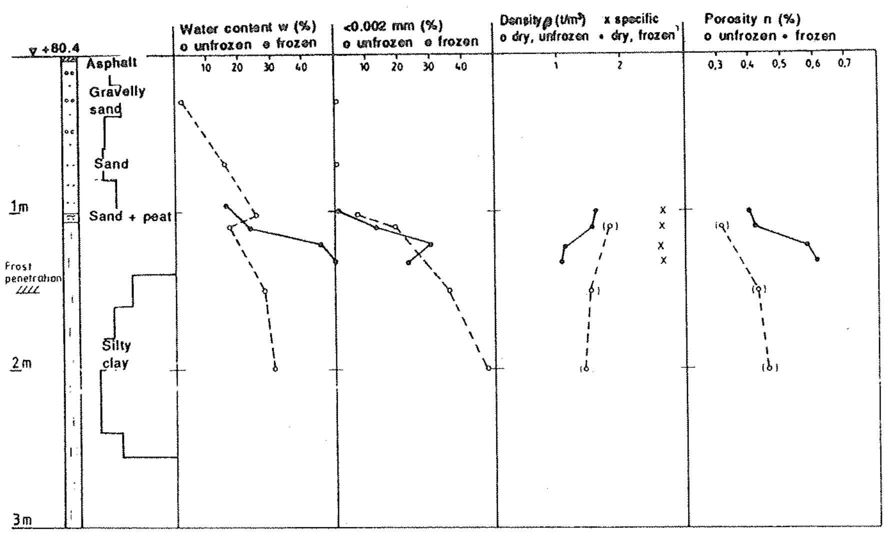

Fig. 57. Joensuu, Sommelotie, Point 33. Soil profile and properties of unfrozen and frozen soils.

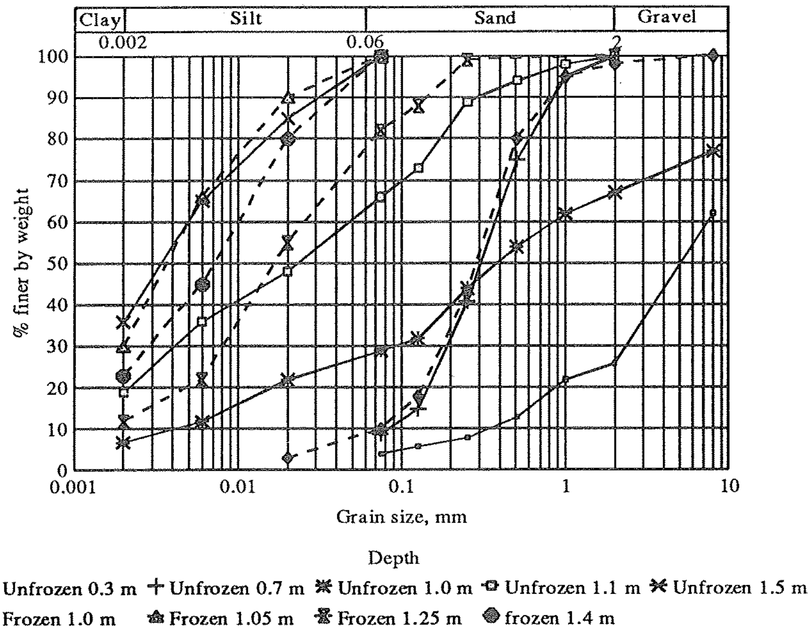

Fig. 58. Joensuu, Sommelotie, Point 33. Grain size distributions of unfrozen and frozen samples.

The ice saturation and thaw compression of a frozen sample, the hydraulic conductivity of a thawed sample, and the segregation potential of a freezing sample in the frost-heave test are illustrated in Fig. 59.

5.5.2 Frost observations

The temperature data from the winter of 1982 - 1983 are shown in Fig. 60. The maximum depth of the 0°C isotherm, about 1.6 metres, was observed in March 1983. The temperature gradient of unfrozen ground at the freezing front in December 1982 was about 3 °C/m, and in April 1983 about 2 °C/m.

The maximum frost penetration, 1.6 metres, was observed with a frost tube in early April 1983. Frost heave occurred after frost penetration had exceeded one metre, and it reached its maximum value, 100 - 110 mm, at the end of March 1983. The ratio of observed frost heave to the thickness of the frozen, frost-susceptible subgrade was about 0.18. Observations of frost heave and frost penetration together with data on local climatic conditions taken from the observation station at Joensuu airport are given in Fig. 61.

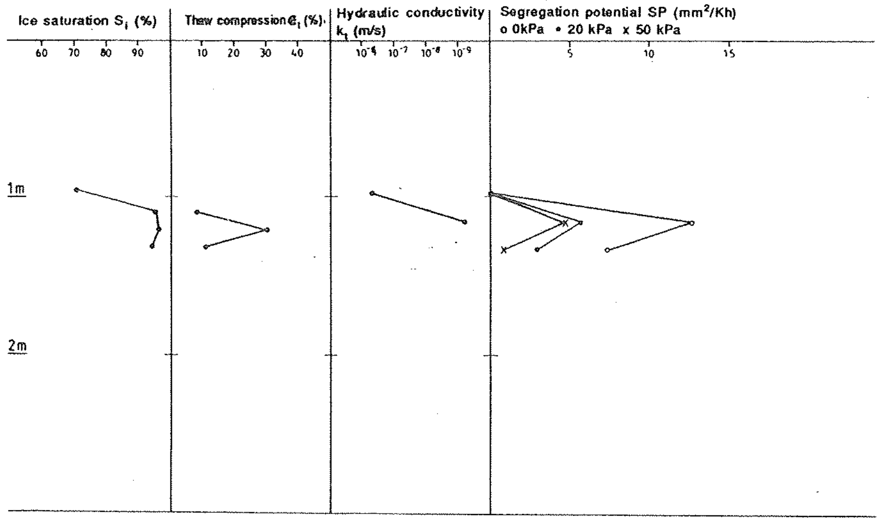

Fig. 59. Joensuu, Sommelotie, Point 33. Ice saturation, thaw compression, unfrozen hydraulic conductivity and segregation potential of frozen samples.

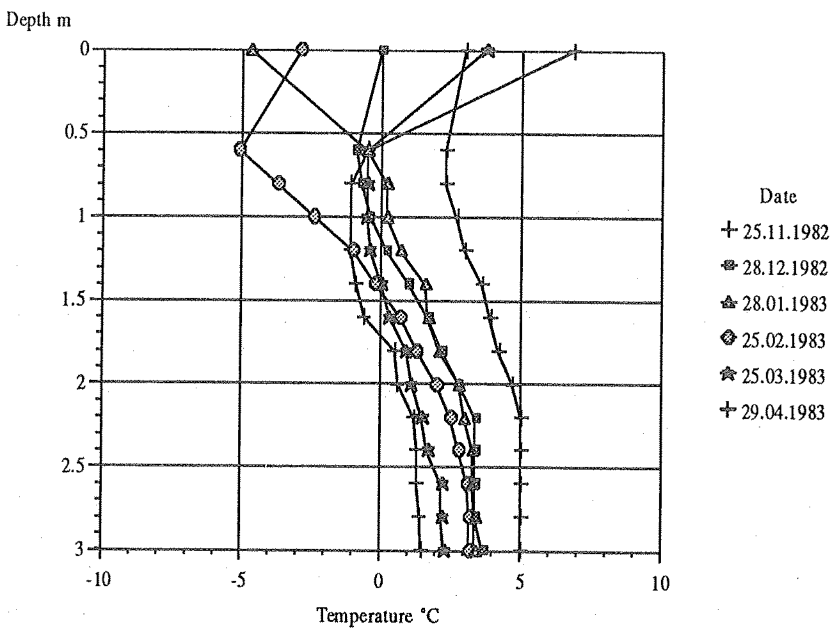

Fig. 60. Joensuu, Sommelotie, Point 33. Temperature observations in the winter of 1982 - 1983.

The thaw started in early April and was completed in the mid-May 1983. Thaw settlement started to develop in the soil below the thaw penetration of about 1.1 metres. The magnitude of total thaw settlement in spring was about 10 mm greater than that of the preceding frost heave (Fig. 61).

Observations of frost heave and frost penetration in the winter of 1983 - 1984 are depicted in Fig. 62. Frost penetration in the beginning of March 1984 was about 1.5 metres, and the corresponding frost heave 110 - 120 mm. The groundwater table was lowered during freezing 0.6 - 0.8 metres below the freezing front.

5.5.3 Modelling of frost heave and frost penetration

Frost heave and frost penetration vs. freezing index

The relationships of frost heave and frost penetration vs. freezing index were according to the data in the winters of 1982 - 1983 and 1983 - 1984 as follows (Fig. 63):

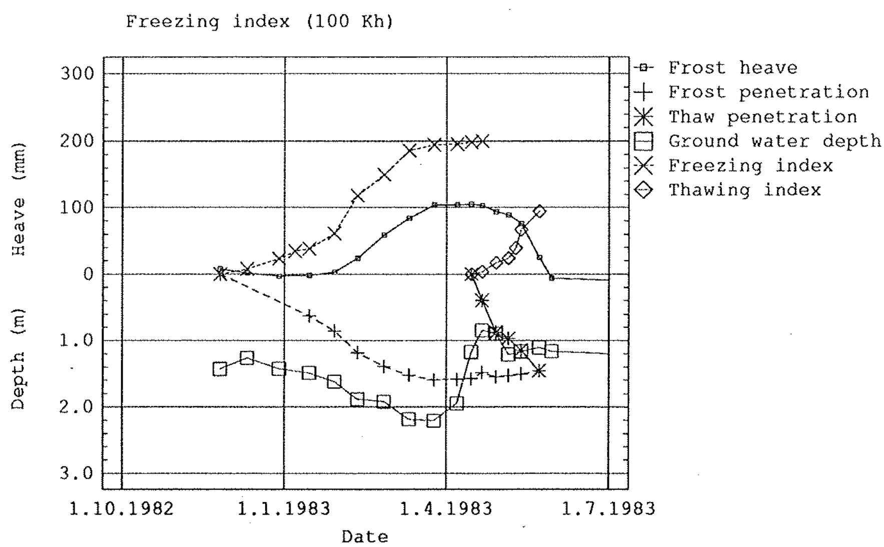

Fig. 61. Joensuu, Sommelotie, Point 33. Frost heave and frost penetration in the winter of 1982 - 1983.

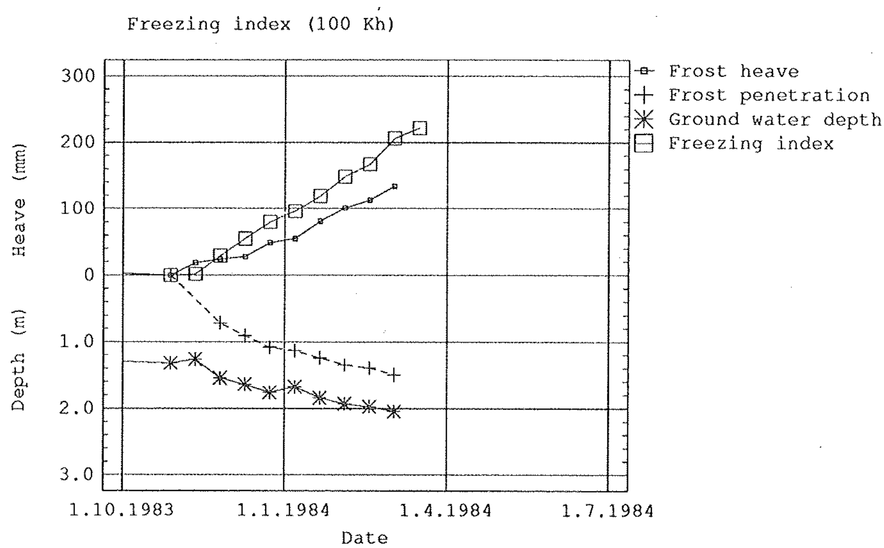

Fig. 62. Joensuu, Sommelotie, Point 33. Frost heave and frost penetration in the winter of 1983 - 1984.

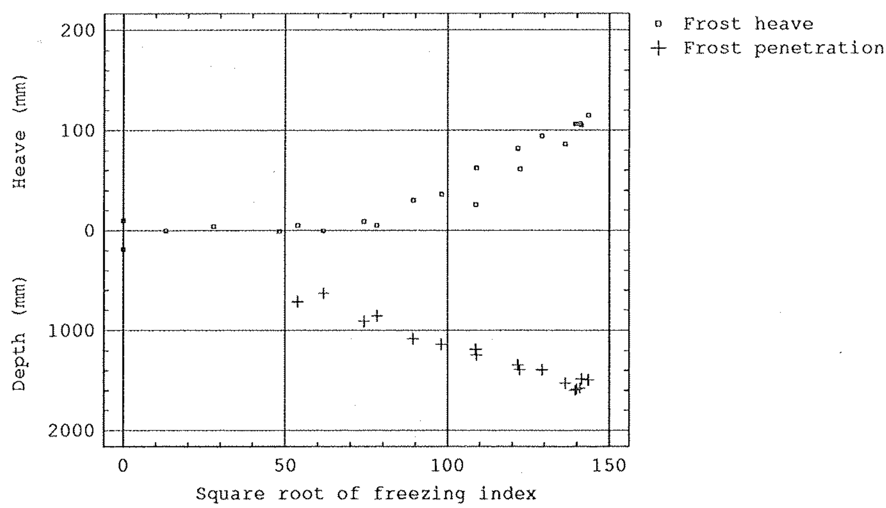

Fig. 63. Joensuu, Sommelotie, Point 33. Frost heave and frost penetration as a function of freezing index in the winters of 1982 - 1983 and 1983 - 1984.

$$h = 1.83\sqrt{F} - 150 \tag{31}$$

$$z_f = 10.7\sqrt{F} + 36 \tag{32}$$

where h is frost heave, mm
z_f frost penetration, mm
F freezing index, Kh

Relative frost heave, frost-heave factor β and segregation potential in situ SP

The ratio of frost heave to the thickness of frost-susceptible, frozen subgrade was about 0.18. The frost-heave factor β was about 0.38, when relative frost heave was 0.18 and the volumetric water content of the frozen soil about 0.50. For the properties of the ground (h/z_f = 0.18, unfrozen dry density ρ_d = 1.65 t/m^3, the water content of unfrozen soil w_t = 0.23 and the coefficient of frost penetration 10.7 mm/$\sqrt{Kh}$) the average in-situ segregation potential was 8.4 mm^2/Kh.

Thaw penetration vs. thaw index

In spring 1983 thaw penetration as a function of the thawing index was as follows (Fig. 64)

$$z_t = 13.9\sqrt{F_t} - 143 \tag{33}$$

where z_t is thaw penetration, mm
F_t thawing index (air temperatures), Kh

The relationship of thaw settlement and thaw penetration is illustrated in Fig. 65. Thaw settlement was observed after a thaw had penetrated below depth of 1 metre.

Evaluation of frost heave and frost penetration using the SSR model

The soil profile and properties used in the SSR model, the monthly freezing index and the resulting frost heave and frost penetration at the end of the month are presented in Table 5.

The estimated, unloaded segregation potential was 13 mm^2/Kh. The observed and calculated frost heave and frost penetration values for the winter of 1982 - 1983 are plotted in Fig. 66.

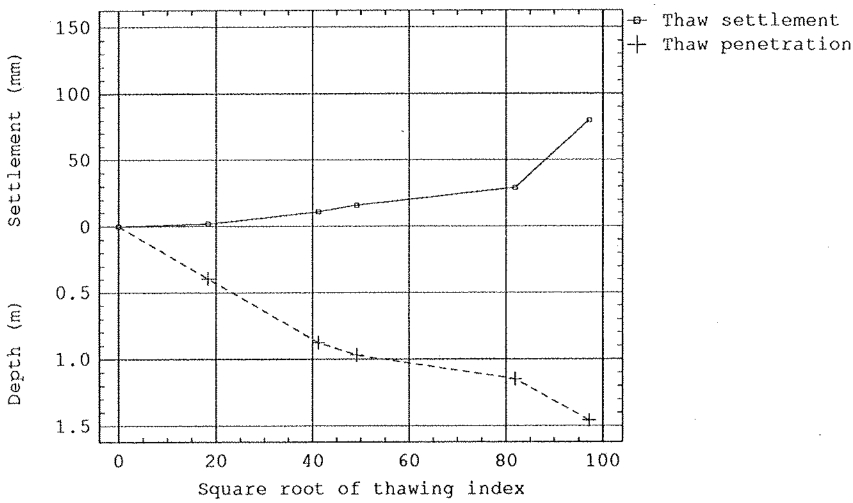

Fig. 64. Joensuu, Sommelotie, Point 33. Thaw settlement and thaw penetration vs. thawing index in 1983.

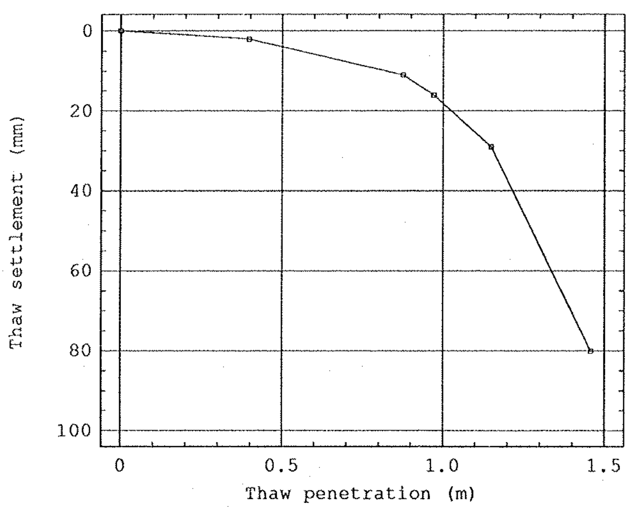

Fig. 65. Joensuu, Sommelotie, Point 33. Thaw settlement vs. thaw penetration in the spring of 1983.

Table 5. Joensuu, Sommelotie, Point 33. The soil layers and properties, cumulative freezing index for winter months, and the calculated frost penetration and frost heave in the winter of 1982 - 1983. Mean annual air temperature 2,5 °C.

Layer	Thickness dz, m	Volumetric latent heat L, Wh/m^3	Thermal conductivity Frozen λ_f, W/Km	Thermal conductivity Unfrozen λ_t, W/Km	Segregation potential SP_0, mm^2/Kh
1	0.6	8 835	1.62	1.97	0
2	0.5	25 110	3.32	2.35	0
3	0.3	28 458	1.87	1.55	13
4	0.5	39 060	2.09	1.37	10

Layer	Water content w_t, %	Clay content <0.002 mm, %	Dry density ρ_d, t/m^3
1	5	0	1.9
2	15	0	1.8
3	18	19	1.7

Month	Freezing index F, Kh	Frost penetration z_f, mm	Frost heave h, mm
12	2 827	698	2
1	7 365	1 004	9
2	15 900	1 346	85

5.5.4 Discussion on results from Joensuu, Point 33

The subgrade at the observation point was frost-susceptible. Frost heave and frost penetration were in a linear relationship with the square root of the freezing index. Relative frost heave was practically

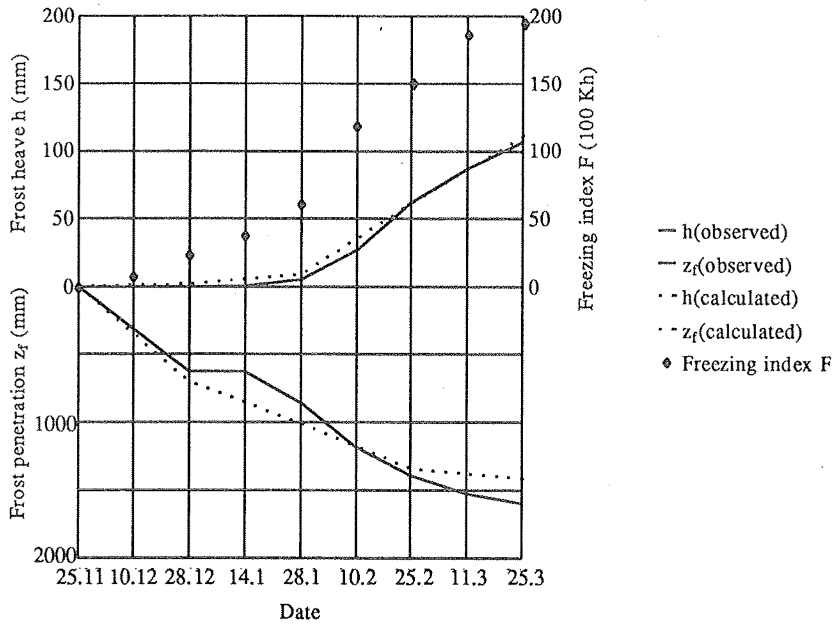

Fig. 66. Joensuu, Sommelotie, Point 33. Observed and calculated frost heave and frost penetration in the winter of 1982 - 1983.

constant in the frozen, frost-susceptible subgrade. Thaw settlement at the end of the thawing season was slightly smaller than the preceding frost heave. The settlement was completed before the next freezing season began.

The spatial development of frost heave and frost penetration calculated with the SSR model followed the observed behaviour when the unloaded segregation potential used in the model was about 13 mm^2/Kh. The unloaded segregation potential determined with a laboratory frost-heave test was 7 - 13 mm^2/Kh (average 10 mm^2/Kh). The average in-situ segregation potential estimated from Eq. (16) was about 8.4 mm^2/Kh.

The degree of ice saturation in the frozen samples was 94 - 96%, and the frozen subgrade could be considered saturated. The estimated difference in porosity due to frost heave was about 17%, which corresponds to the relative in-situ frost heave. The thaw compression in laboratory tests was 8 - 30%, and the in-situ value was about 18%.

5.6 JOENSUU, VÄRTTINÄTIE, POINT 38

5.6.1 Site location and ground conditions

The site was located in the northeast Joensuu, eastern Finland. The natural ground surface in the area varied between +79 and +80 metres above sea level (Fig. 67). The area was flat, moist lowland. Point 38 was located on a paved street about 200 metres to the east of point 33.

The level of the natural ground at the point was about +79 - 80 metres, and that of the street pavement about +80.4 metres. The street embankment was underlain by fairly dense silt or silty till to a depth of about 2.9 metres, where the soil changed into till. Weight sounding was stopped by stones at a depth of 4.7 metres below the pavement surface. At the beginning of December 1982 the groundwater table at a depth of about 1.8 metres.

In the test pit investigations of unfrozen ground the thickness of street embankment was about 0.7 metres. It was underlain by clayey silt. The clay content of silt was 20 - 30% and the water content 25 - 28% (Figs. 68 - 69).

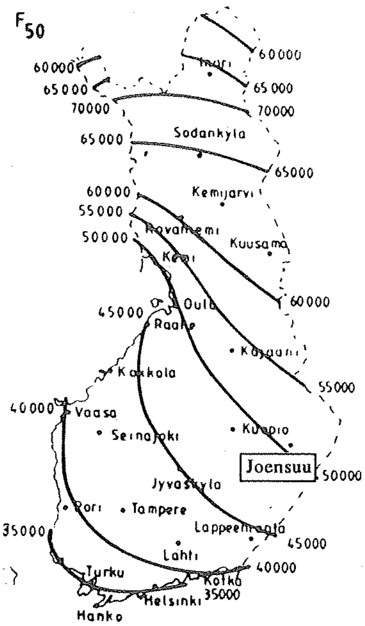

Fig. 67. Joensuu, Värttinätie, Point 38. Site location. Maximum freezing index F_{50} occurring in 50 years.

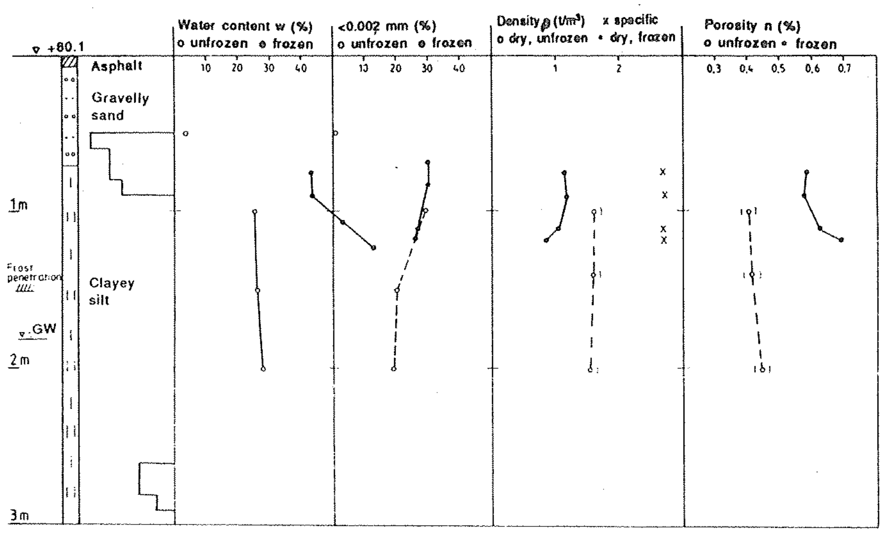

Fig. 68. Joensuu, Värttinätie, Point 38. Soil profile and properties according to investigations of unfrozen and frozen soils.

Frozen samples were taken in early March 1983, when the frost tube indicated that frost penetration at the point was about 1.5 metres. Frozen samples were taken from a depth of 0.66 - 1.32 metres. At 0.66 - 0.98 metres depth these samples were lean clay with a clay content of about 30%. Deeper, the soil was clayey silt with a clay content of about 25% (Fig. 69).

The water content, bulk density, dry density and specific density of the frozen samples are shown in Fig. 68. The estimated degree of ice saturation was 83 - 97%.

Thaw compression of the samples was 23 - 50%. During the preparation of the samples for the frost-heave test the observed thaw compression was 30 - 38% (Fig. 70).

The unloaded segregation potential of samples from a depth interval of 0.66 - 0.98 metres was 6.5 - 11 mm^2/Kh, and from the 0.98 - 1.32 metres depth 6 - 7 mm^2/Kh. With a load of 20 kPa the segregation potential varied in the range 1.3 - 3.5 mm^2/Kh, and with a load of 50 kPa between 0 and 1.5 mm^2/Kh (Fig. 70).

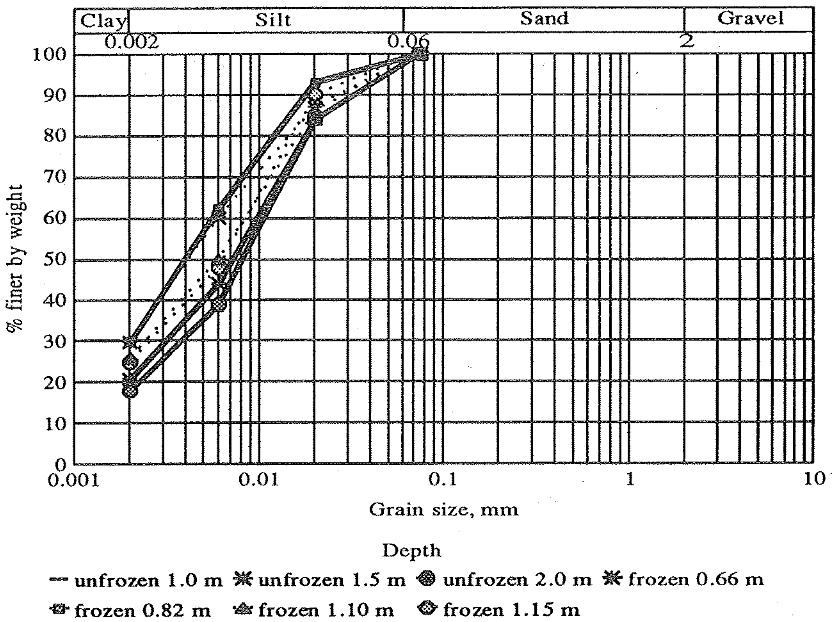

Fig. 69. Joensuu, Värttinätie, Point 38. Grain size distributions of unfrozen and frozen samples.

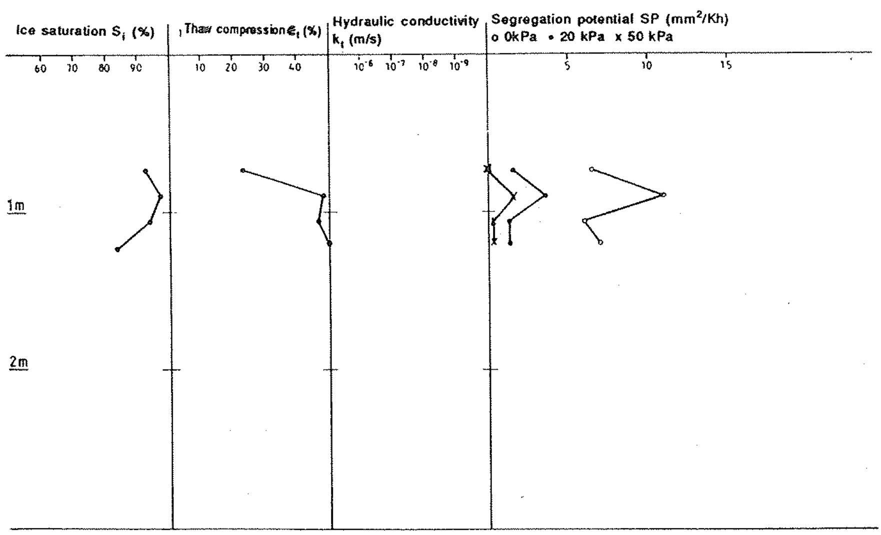

Fig. 70. Joensuu, Värttinätie, Point 38. Ice saturation, thaw compression, unfrozen hydraulic conductivity and segregation potential of frozen samples.

5.6.2 Frost observations

The temperature data from the winter of 1982 - 1983 are plotted in Fig. 71. The maximum depth of the 0°C isotherm in late March 1983 was about 1.3 metres. The temperature gradient of unfrozen ground below the freezing front was about 2 °C/m in January 1983, and about 0.5 °C/m in April 1983.

The observations on frost heave and frost penetration in the winter of 1982 - 1983 are plotted in Fig. 72. The maximum frost penetration, 1.55 metres, was recorded in early April 1983. Intense frost heaving was observed when the freezing depth was below 0.6 - 0.7 metres. Maximum frost heave, 220 - 226 mm, was observed in early April. The relative frost heave at 0.6 - 1.55 metres depth was about 23%. The groundwater table sank from a depth of 1.2 metres before the frost season to a depth of about 2 metres in spring 1983.

In spring 1983, the thaw started after mid-April, and was completed in mid-May. Thaw settlement was observed after thaw penetration had proceeded below a depth of about 0.5 metres. At the end of the

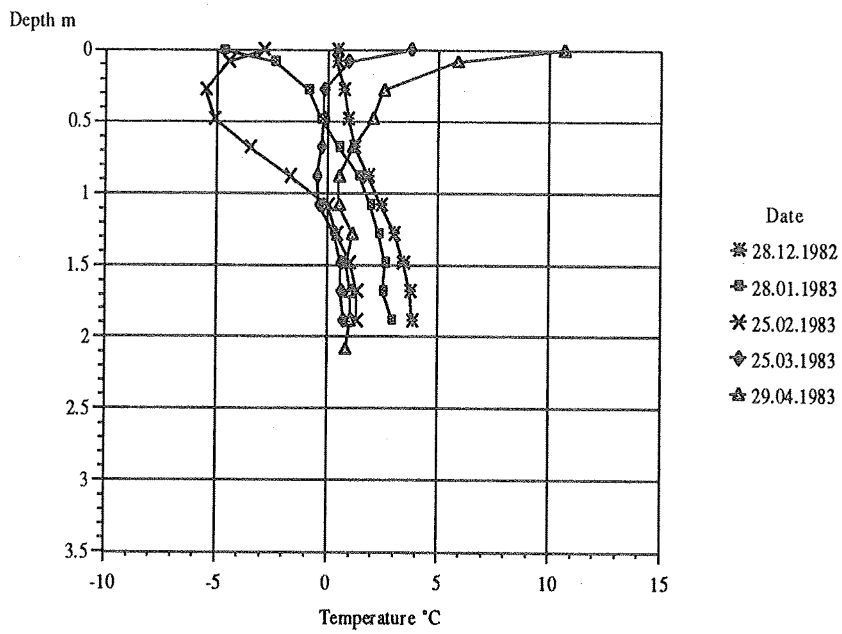

Fig. 71. Joensuu, Värttinätie, Point 38. Temperature data from the winter of 1982 - 1983.

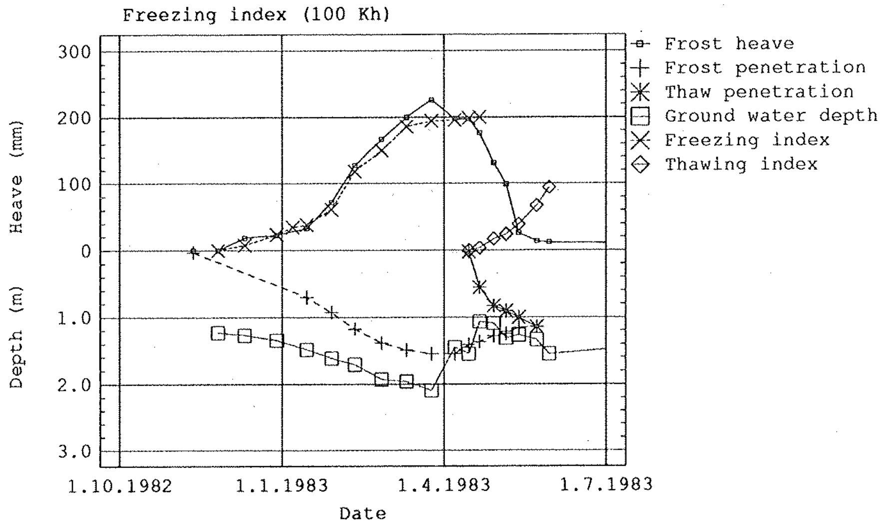

Fig. 72. Joensuu, Värttinätie, Point 38. Frost heave and frost penetration in the winter of 1982 - 1983.

thaw, thaw settlement was almost as great as the preceding frost heave. The rest of thaw settlement occurred during the following summer. After the start of thawing the groundwater table rose to a depth of about 1 metre from the pavement surface. It later sank to a depth of 1.5 metres.

The temperature data from the winter of 1983 - 1984 are plotted in Fig. 73. The depth of the 0°C isotherm was about 1.2 metres in March 1984. The temperature gradient of unfrozen ground below the freezing front was about 3 °C/m in autumn 1983, and about 2 °C/m in March 1984.

The data on frost heave and frost penetration in the winter of 1983 - 1984 are plotted in Fig. 74. In March 1984 frost penetration was about 1.5 metres, and frost heave about 200 mm. Frost heaving started when frost penetration exceeded 0.7 metres. The depth to the groundwater table was about 1.2 metres in autumn 1983 while about 2 metres in March 1984.

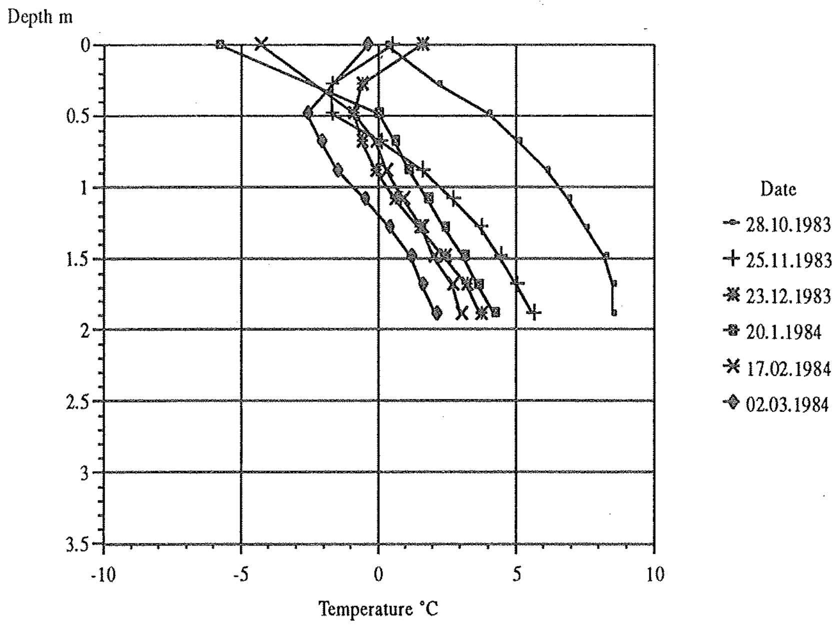

Fig. 73. Joensuu, Värttinätie, Point 38. Temperature data from the winter of 1983 - 1984.

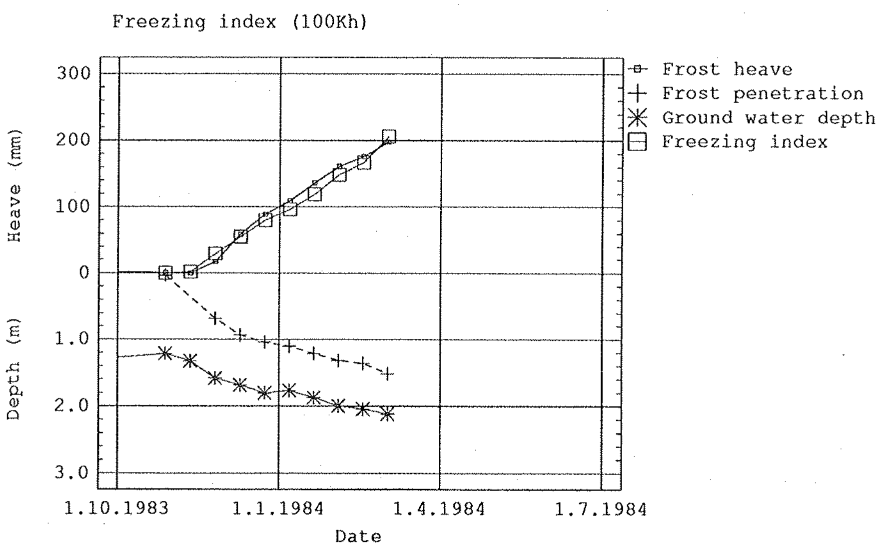

Fig. 74. Joensuu, Värttinätie, Point 38. Frost heave and frost penetration in the winter of 1983 - 1984.

5.6.3 Modelling of frost heave and frost penetration

Frost heave and frost penetration vs. freezing index

Frost heave and frost penetration were related to the freezing index in the winters of 1982 - 1983 and 1983 - 1984 as follows (Fig. 75):

$$h = 2.25 \sqrt{F} - 125 \tag{34}$$

$$z_f = 9.8 \sqrt{F} + 126 \tag{35}$$

where h is frost heave, mm
z_f frost penetration, mm
F freezing index, Kh

Relative frost heave h/z_f, frost-heave factor β and segregation potential in situ SP

Frost heave is plotted against frost penetration in Fig. 76. Relative frost heave within the frozen, frost-susceptible subgrade was about 0.23, and the frost-heave factor β about 0.46 ($n_w = 0.50$, $h/z_f = 0.23$). The observed in-situ thaw compression was approximately as great as the preceding relative frost heave. For the ground properties ($h/z_f = 0.23$, unfrozen dry density $\rho_d = 1.6$ t/m^3, the water content of unfrozen soil $w_t = 0.25$, coefficient of frost penetration $k = 9.8$ mm/$\sqrt{Kh}$), the in-situ segregation potential was 9.3 mm^2/Kh.

Thaw penetration and thawing index

The following relationship was found to exist between thaw penetration and the thawing index in the spring of 1983:

$$z_t = 15.5 \sqrt{F_t} + 180 \tag{36}$$

where z_t is thaw penetration, mm
F_t thawing index (air temperatures), Kh

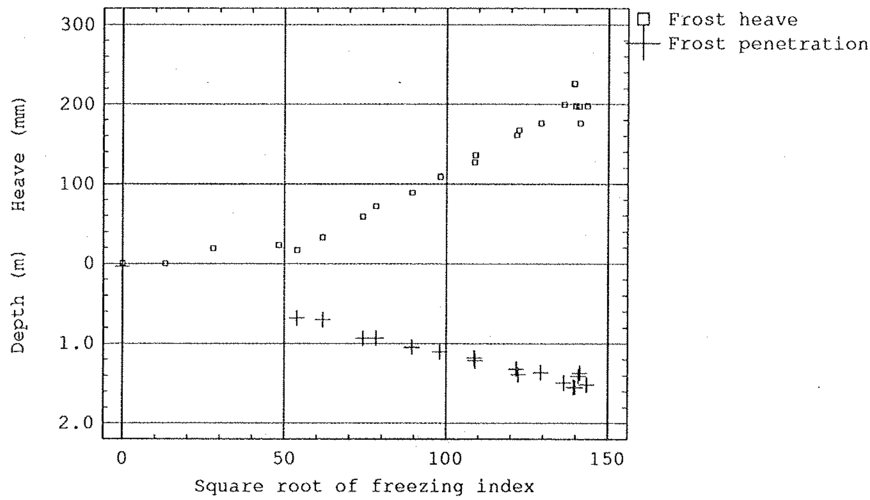

Fig. 75. Joensuu, Värttinätie, Point 38. Frost heave and frost penetration as a function of freezing index in the winters of 1982 - 1983 and 1983 - 1984.

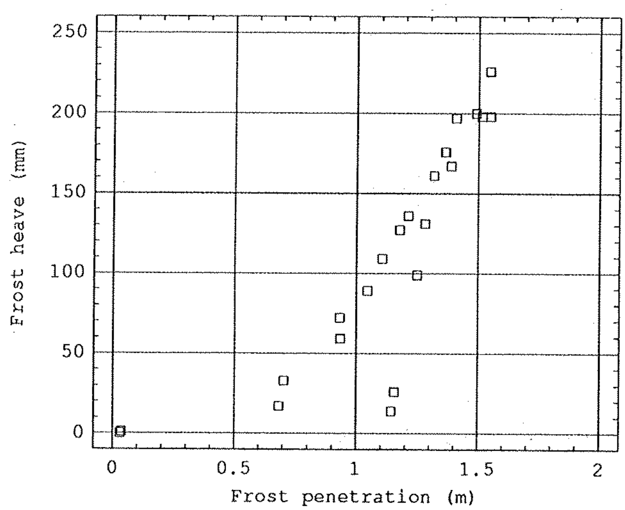

Fig. 76. Joensuu, Värttinätie, Point 38. Frost heave vs. frost penetration in the winters of 1982 - 1983 and 1983 - 1984.

Evaluation of frost heave and frost penetration with the SSR model

The frost heave and frost penetration were estimated with the SSR model. Soil layers and properties were evaluated on the basis of soil investigation results. In the analysis, the values of the segregation potential for which the calculated frost-heave and frost penetration values corresponded to the observed ones in the winter of 1982 - 1983 were back-calculated. the soil layers and properties used in the calculation are presented in Table 6. The estimated, unloaded segregation potential of the frost-susceptible subgrade was 10 mm^2/Kh. The observed and calculated frost heave and frost penetration in the winter of 1982 - 1983 are illustrated in Fig. 77.

5.6.4 Discussion on results from Joensuu, Point 38

As at points 14, 20 and 33, frost heave and frost penetration showed a linear relation to the square root of the freezing index. Relative frost heave was also fairly constant and was as great as the thaw compression in the following spring.

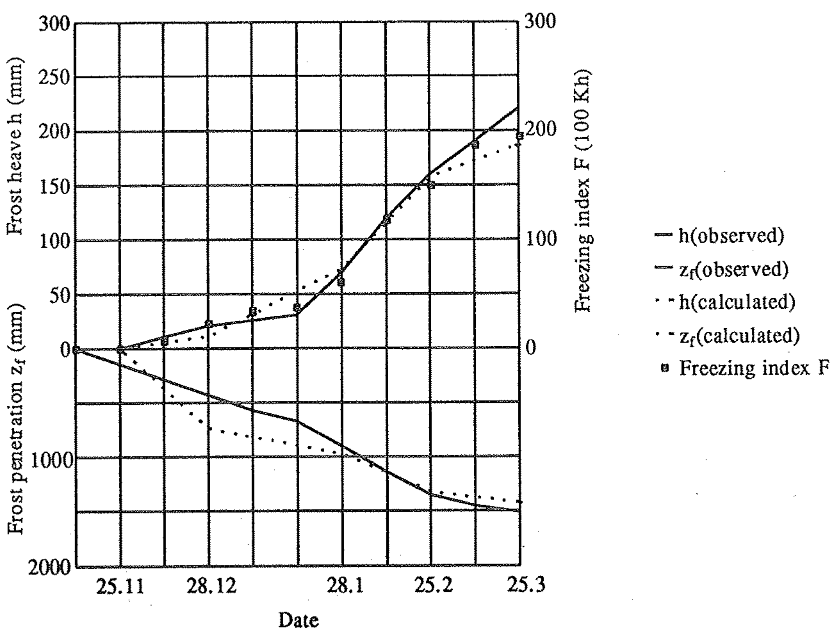

Fig. 77. Joensuu, Värttinätie, Point 38. Observed and calculated frost heave and frost penetration in the winter of 1982 - 1983.

Table 6. Joensuu, Värttinätie, Point 38. Soil layers and properties, the freezing index, and the calculated frost penetration and frost heave for the winter of 1982 - 1983. Mean annual air temperature 2.5 °C.

Layer	Thickness dz, m	Volumetric latent heat L, Wh/m^3	Thermal conductivity Frozen λ_f, W/Km	Thermal conductivity Unfrozen λ_t, W/Km	Segregation potential SP_o, mm^2/Kh
1	0.7	17 632	2.56	2.33	0
2	0.5	37 200	2.16	1.52	10
3	0.5	37 200	2.16	1.52	10
4	0.5	37 200	2.16	1.52	10

Layer	Water content w_t, %	Clay content <0.002 mm, %	Dry density ρ_d, t/m^3
1	10	0	1.9
2	25	30	1.6
3	25	20	1.6
4	25	20	1.6

Month	Freezing index F, Kh	Frost penetration z_f, mm	Frost heave h, mm
12	2 827	735	10
1	7 365	971	73
2	15 900	1 339	161
3	19 545	1 446	191

Measured in the laboratory, thaw compression was 23 - 50%, which is greater than the field value of 23%. The estimated difference between frozen and unfrozen porosities, based on laboratory characteristics, was on average 16%.

The loaded, average in-situ segregation potential, determined from the site observations (eq. (16)) was about 9.3 mm^2/Kh, while the estimated, unloaded value given by the SSR model was about 10 mm^2/Kh. The unloaded segregation potential in the laboratory tests varied in the range 6.5 - 11 mm^2/Kh (average value 7.2 mm^2/Kh), and with a load of 20 kPa, about 1.3 - 3.5 mm^2/Kh.

According to the estimated degree of ice saturation, 83 - 97% (average 91.5%), the subgrade was saturated.

5.7 DISCUSSION ON SITE INVESTIGATIONS

5.7.1 Observations of frost penetration and frost heaving

The ratio observed frost penetration to the square root of the freezing index varied in the range 9.8 - 11.2 mm/$\sqrt{Kh}$. The relationship was linear at all sites.

The observed ground temperature gradient below the freezing front at Alajärvi was 2.5 - 2 °C/m, while according to Skaven-Haug (1971) it should be 2.2 °C/m. At Piippola the observed gradient was 4 - 1.5 °C/m (Skaven-Haug 1.95 °C/m), and in Joensuu 4 - 0.5 °C/m (Skaven-Haug 2.1 °C/m).

The coefficient of proportionality m between the observed frost heave and the square root of the freezing index was 0.81 - 2.3 mm/$\sqrt{Kh}$. The relative frost heave at the observation points varied in the range 0.03 - 0.23. At Piippola, a variation in the frost heave was observed during the winters of 1982 - 1986, when the relative frost heave was smaller than the long-term average.

The thaw settlement and the thaw compression values were close to those of the preceding absolute and relative frost heave. No significant irreversible, perennial effects were detected.

5.7.2 Laboratory investigations of unfrozen and frozen soils

The soils at the observation points varied both in grain size distribution and in the content of fines and clay. The average content of grain size classes are presented in Table 7.

The soil type at the Piippola and Alajärvi sites was till, at Joensuu 20 sandy gravel, and at Joensuu 14, 33 and 38 clayey silt.

The average physical properties of tested unfrozen and frozen soils at the observation sites are presented in Table 8.

The degree of ice saturation of the samples varied between 65% and 100%. The average degree of ice saturation of the sampling profiles at the points varied between 80 and 94%.

Table 7. Average grain size distribution of the frost-susceptible, frozen subgrade at different points.

Site	<0.002 mm %	<0.02 mm %	<0.06 mm %
Alajärvi	5	24	47
Piippola	10	24	44
Joensuu 14	29	75	90
Joensuu 20	2	5	12
Joensuu 33	22	75	94
Joensuu 38	28	90	100

Table 8. Average water content, dry density, specific density and degree of ice saturation of unfrozen and frozen samples at observation points.

Site	Water content w_f	w_t, %	Dry density ρ_{df}	ρ_{dt}, t/m^3	Specific density ρ_s, t/m^3	Degree of ice saturation S_i, %
Alajärvi	15	15	1.62	1.75	2.65	79
Piippola	20	14	1.7	1.8	2.65	87
Joensuu 14	37	23	1.26	1.65	2.67	94
Joensuu 20	-	7	-	-	-	-
Joensuu 33	40	23	1.2	1.65	2.66	89
Joensuu 38	51	25	1.0	1.6	2.7	92

The porosities of unfrozen and frozen soils are presented in Table 9. The determined increase of porosity in freezing is comparable to the relative frost heave and to the frost-heave factor β.

The segregation potential at different sites, determined in situ (average, loaded), with SSR method (average, unloaded) and in the laboratory (average, unloaded), is presented in Table 10.

Table 9. Average porosities of frozen and unfrozen soils, relative frost heave and frost heave factor at observation sites.

Site	Porosity Frozen n_f	Unfrozen n_t, %	Difference of porosity Δn, %	Relative frost heave ε_f, %	Frost-heave factor β
Alajärvi	39	34	5	10	0.41
Piippola	36	32	4	7	0.21
Joensuu 14	53	38	15	17	0.36
Joensuu 20	-	-	-	3	-
Joensuu 33	55	38	17	18	0.38
Joensuu 38	63	41	22	23	0.46

Table 10. Average segregation potential determined in situ (loaded), with the SSR method, and in laboratory at different sites.

Site	SP(in situ) mm^2/Kh	SP_0(SSR) mm^2/Kh	SP_0(laboratory) mm^2/Kh
Alajärvi	5.2	5	3.5
Piippola	2.7	7.8	8
Joensuu 14	7.8	8	6.7
Joensuu 20	1.8	2	-
Joensuu 33	8.4	13	10
Joensuu 38	9.3	10	7.2

Comparison of the sets of unfrozen and frozen soil properties revealed an increase in water content, and a decrease in dry density due to ice segregation. The increase in porosity was close to the relative frost-heave values observed in situ.

According to the frost-heave factor β (Saetersdal 1980), the ground was very frost-susceptible at Alajärvi and at Joensuu, points 14, 33 and 38; medium frost-susceptible at Piippola; and slightly frost-susceptible at Joensuu, point 20.

Measured in the laboratory, thaw compression was, in general, greater than that observed in situ. The difference may be partly due to the small size of the specimens (d = 50 mm, h = 20 mm), which reduced their representativeness in relation to the thickness of ice lenses. The roughness of the worked surfaces of the frozen samples may have increased thaw compression.

Compared with the observations, the SSR model was capable of estimating frost heave and frost penetration well. The estimated segregation potential was in reasonably good agreement with the segregation potential estimated from the site data direct.

6 RELIABILITY OF THE SSR MODEL

6.1 INFLUENCE OF FREEEZING CONDITIONS AND SOIL PARAMETERS

In the estimation of frost heave and frost penetration the relationships are approximately the following

$$z_f = k\sqrt{F} \tag{37}$$

$$h = (2\,SP\sqrt{F})/k \tag{38}$$

The coefficient k is proportional to thermal conductivity and volumetric latent heat in square root terms. Thus, frost heave is directly proportional to the freezing index and thermal properties under the square root, but its relationship with the segregation potential is linear. The relative error in the frost-heave estimate due to an inaccuracy in the thermal properties is smaller, by about half, than the error due to an inaccuracy in the assumed segregation potential or relative frost heave.

The inaccuracy in the SSR model follows the principle described above. The inaccuracy in calculated vs. observed values in the spatial modelling of frost-heave behaviour at the sites is shown in Fig. 78. The accuracy of modelling depends not only on the correctness of the process description in general, but also on the accuracy of the model in terms of the geological stratification of the site.

The soil profiles and properties applied were determined from the soil data available. The segregation potential was determined as a "scale factor" to fit the calculated frost heave and frost penetration to the observed values. The coefficient of variation in observed vs. calculated frost heave and frost penetration was about 10 - 15%. This can be taken as a measure of the accuracy of the modelling.

Due to the stochastic nature of climatic conditions, a pure "before - after" - comparison is not reasonable. To illustrate the accuracy of the model in a more realistic situation, an example from the Arctic Road Project (1985 - 1990) is presented (Fig. 79). On the test sections, the

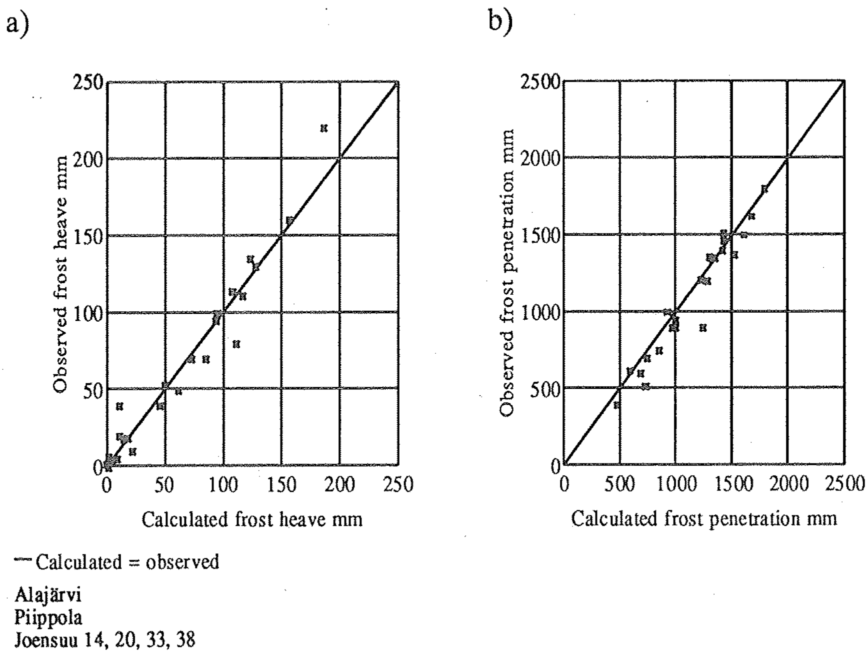

Fig. 78. Calculated vs. observed frost heave (a) and frost penetration (b) at observation sites in the winter of 1982 - 1983.

frost heave and frost penetration were measured under the conditions prevailing before construction. The segregation potential of the subgrade was determined from the maximum frost heave of each section. The test structures were designed using the maximum freezing index that statistically occurs once in 10 years and an allowable frost heave of 30 - 65 mm.

The 1987 - 1988 observation season was a winter with a freezing index close to the design value. The layer thicknesses and properties of the structure were, naturally, somewhat different from those assumed in the design. The calculated frost heave and frost penetration corresponded to the freezing index of the observation winter and to the actual thicknesses and properties of the embankment. The value of the segregation potential of the subgrade was based on that for the frost heave of the old road. Thus the calculated frost heave should have been as great as or smaller than the observed one. In all the sections the observed frost heave was, in fact, as great as or smaller than the calculated value. The estimated frost penetration was well comparable to the observed value for the embankments with or without frost insulation.

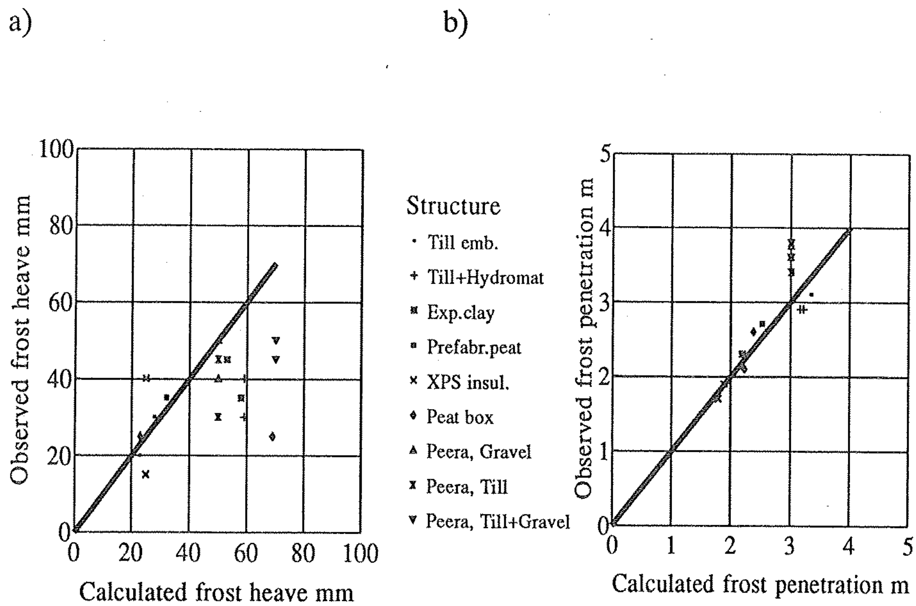

Fig. 79. Calculated vs. observed frost heave (a) and frost penetration (b) on the test road sections at Tulli and Peera sites, Kilpisjärvi, northern Lapland, in the winter of 1987 - 1988 (Saarelainen 1990a, 1990b).

In laboratory frost-heave tests, conditions often poorly correspond to those in situ. The effects of the test cell, for instance, shaft friction, increase frost-heave resistance in the specimen (see Kujala & Ravaska 1989, Jessberger & Jagow 1989). The representativeness of the samples compared with the soil profile is poor if the ground is anisotropic. In the frost-heave test applied above, the segregation potential was determined at the stage when the frost penetration stopped at one level. Thus the determined frost-heave property referred to this thin section which had a thickness of only a few millimetres.

Undisturbed samples drilled from frozen ground were used in the frost-heave tests. Their structure corresponded to that of natural soil, and their density returned to the unfrozen balance value in the thaw.

When a specimen is reconstituted in the laboratory, the natural structure of the soil is lost. If reconstituted specimens are used in the frost-heave tests, the irreversible deformations due to the freeze - thaw cycle may influence the value of frost-heave susceptibility.

6.2 ESTIMATION OF FROST-HEAVE CHARACTERISTICS

The SSR model, applying the segregation potential concept, explained the in-situ frost-heave behaviour of freezing ground reasonably well, so indicating the validity of the concept in situ. Segregation potentials of the same order of magnitude were obtained from the laboratory tests. Thus it seems to be possible to determine frost-heave parameters without preliminary information about in-situ heave behaviour.

The segregation potential is assumed to be a material property in the sense of the segregation potential concept. It is also heavily dependent on environmental conditions such as in-situ stress, suction pressure, the rate of frost penetration, and to a limited extent on the climatic variation. However, the most convenient way to approach the in-situ value is to determine it under in-situ conditions. Then the influence of the frost penetration rate and suction are already scaled. The main drawbacks to this approach are the difficulty of organising field observations and the lack of time.

Nevertheless, in-situ observations should be made whenever possible. If field measurements alone are applied and the observation season is warm, the frost heave may differ dramatically from the design winter behaviour. Thus the observations should be carried out over several winters, they should be confirmed with representative laboratory tests.

7 APPLICATION OF THE SSR MODEL

7.1 APPLICATION OF FROST-HEAVE INVESTIGATIONS IN PLANNING AND DESIGN

Under conditions such as prevail in Finland, there is often a need to limit the effects of frost action, e.g. heave, in soil. Road designers have to estimate the probable frost heave of a structure from the soil data available. Thus, when making pre-evaluations of frost heave they have to take into consideration the soil type, the depth to the groundwater table, the weight, dimensions and thermal properties of the structure, and the design winter at the location. At the preliminary stage, some order of magnitude of relative frost heave or the segregation potential is needed. The design includes the determination of frost penetration and the thickness of the frozen subgrade. Frost heave can be estimated by applying the relative frost-heave concept. If frost heave seems to be a critical factor in the design, a specific investigation should be carried out to determine the frost-heave properties of the ground more precisely. The magnitude of frost heave and frost penetration could then be analysed with a sophisticated calculation procedure such as the SSR model.

A road can be constructed at optimal cost if its structure is adapted to local environmental conditions and traffic loading, and if it is constructed using local materials and applying a controlled level of quality and maintenance. Construction costs can be optimized in a strict sense if the quality of the structure is known. In a cold climate the quality of the product "pavement" depends on the effects of frost action. The quality can be better controlled by applying frost-heave analysis and by designing the road for in-situ conditions.

To date, frost-heave assessment has not been a part of design. It has seldom been applied under real conditions and even then only to structures on specific experimental sites. Thus, considerable research and development efforts are needed to make frost-heave design routine practice in geotechnical investigation and design.

7.2 EXAMPLES

The SSR model was developed in 1985, and was first applied in the design of the test road sections at Kilpisjärvi. A design chart was compiled that linked the observed frost-heave values of the old road line to the new frost-insulated structure in which frost heave is limited to a given level (Fig. 80).

The thickness of the old road embankment was assumed to be one metre, the subgrade soil was silt (w_t = 25%, ρ_d = 1.6 t/m^3), and the climatic conditions were assumed to correspond to those of northern Lapland (mean annual air temperature about -2.5°C, F_{10} = 50 000 Kh). The properties of road aggregates were assumed to correspond to those determined during construction.

The method has also been applied to the frost-heave design of a highway embankment on a frost-susceptible subgrade (Saarelainen & Toivonen 1991). In this case, the thickness of the mineral structure was such that the frost heave in the given freezing index would not

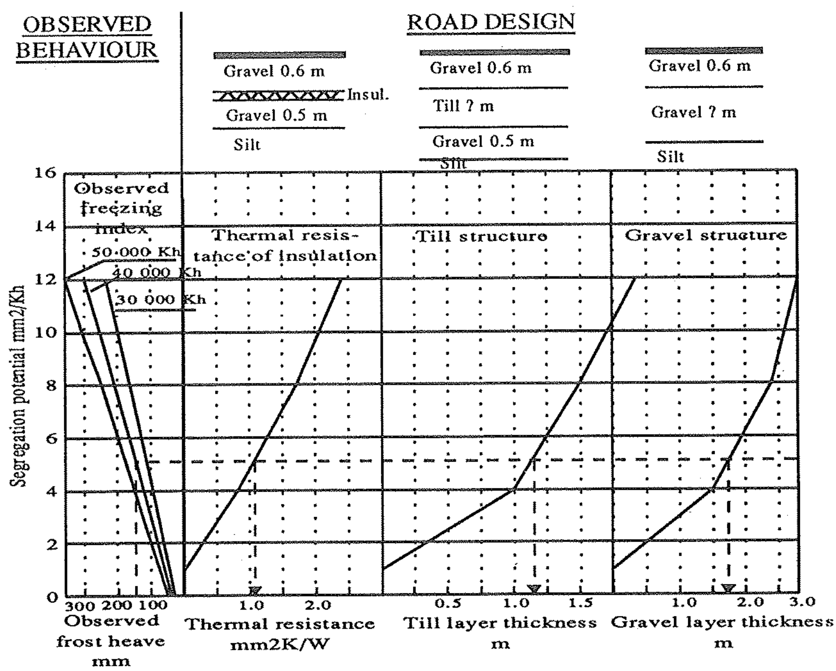

Fig. 80. A design chart to determine the dimensions of frost insulation needed to limit the frost heaving to a given level (in this case, about 50 mm once in ten years, Saarelainen 1990b).

exceed an allowable value (30 or 50 mm) when the segregation potential of the subgrade was varied. A soil map of the road line section was compiled, and the soils were classified according to the frost-heave conditions. The criteria used in the mapping were soil type, the clay content in particular, the depth to the groundwater table, and soil stratification (depth to the groundwater-bearing stratum). Miniature samples of surface soil were taken during the field work to study the variability of surface soils on the road line. The frost-heave properties were determined with frost-heave tests carried out on undisturbed specimens, and the in-situ frost penetration and frost heave were monitored at some locations. The observations were only of secondary value because the winter happened to be milder than an average one.

The frost design was made using the SSR model. Within each section, the thickness of road embankment necessary to restrict frost heaving to a level of 30 - 50 mm was determined.

The examples presented above show that the SSR model can be successfully used as a practical tool in the planning and design of a road embankment for a controlled frost heave.

Its use makes it possible to consider the influence of local climate, local ground conditions and properties of available materials on the frost-heave prognosis.

8 CONCLUSIONS

In summary, the following conclusions can be drawn:

1. Frost heave and frost penetration in uniform soils are in a linear relationship with the square root of the freezing index.

2. Relative frost heave,or the ratio of frost heave to the corresponding frost penetration, is fairly constant in homogeneous ground.

3. Relative frost heave is linearly proportional to the segregation potential SP and the frost-heave factor β.

4. The segregation potential can be determined both in situ and with laboratory tests, but the frost-heave factor only in situ.

5. Frost heave and frost penetration can be estimated applying the SSR model if the stratification of the ground, the properties of the soil layers, and the frost-heave characteristics, e.g. segregation potentials, are known.

6. The segregation potential values determined with laboratory frost-heave tests were, in general, comparable to, but somewhat smaller than, the values deduced from site observations. The use of undisturbed samples drilled from frozen ground is feasible and recommended. The frost-heave test device should be refined by reducing the influence of wall friction on the frost heave of the specimen.

7. The undisturbed specimen installed in the cell should be consolidated to the stress prevailing in the ground, and saturated before the frost-heave test. Reconstituted specimens should be sufficiently compacted and overconsolidated to eliminate any reduction in frost heave due to compression of the soil below the freezing front.

REFERENCES

Aldrich, H.P. & Paynter, H.M. 1953. Frost investigations, fiscal year 1953, first interim report: Analytical studies of freezing and thawing of soils. U.S. Army Arctic Construction and Frost Effects Laboratory (ACFEL), Technical Report 42. 66 p.

Anderson, D.M., Williams, P.J., Guymon, G-L. & Kane, D.L. 1984. Principles of soil freezing and frost heaving. In: Frost action and its control. New York, American Society of Civil Engineers (ASCE), pp. 1 - 21.

Apostolopoulos, C. 1981. Näherungsverfahren zur Errechnung der Frosttiefe in Strassenkonstruktionen [Approximate methods for the calculation of frost penetration in street structures]. Cold Regions Science and Technology 4, 4, pp. 195 - 213. (in German).

Arakawa, K. 1966. Theoretical studies of ice segregation in soil. Journal of Glaciology 44, 6, pp. 255 - 260.

Berg, R.L., Guymon, G.L. & Johnson, T.C. 1980. Mathematical model to correlate frost heave of pavements with laboratory predictions. Hanover, N.H., U. S. Army Cold Regions Research and Engineering Laboratory (CRREL), Report 80-10. 54 p.

Beskow, G. 1935. Tjälbildningen of tjällyftningen med särskild hänsyn till vägar och järnvägar. [Freezing and frost heaving with special consideration to roads and airfields.] Stockholm, Statens väginstitut, Meddelande 48. 242 p. (in Swedish).

Casagrande, A. 1931. Discussion on "A new theory of frost heaving" by Benkelman and Olmstead. Proceedings, Highway Research Board, Vol.11, pp. 168 - 172.

Chamberlain, E.J. 1981. Frost-susceptibility of soils. Review of index tests. Hanover, N.H. U. S., Army Cold Regions Research and Engineering Laboratory (CRREL), Monograph 81-2. 88 p. + app. 22 p.

Chamberlain, E.J. & Carbee, D.L. 1981. The CRREL frost-heave test, USA. Oslo, Frost i Jord 22, pp. 55 - 63.

Duquennoi, C., Fremond, M. & Levy, M. 1989. Modelling of thermal soil behaviour. Proc. Int. Symp. on Frost in Geotechnical Engineering. Saariselkä, Finland, March 1989. Espoo, Technical Research Centre of Finland, Symposium 95, pp. 895 - 915.

Ehrola, E. 1973. Ilmastollisten ja rakenteellisten tekijöiden vaikutuksesta tien routaantumiseen ja routimiseen. [On the influence of climatic and structural factors on the freezing and frost heaving of roads.] Oulu, University of Oulu, Department of Civil Engineering, Licentiate thesis. 144 p. (in Finnish).

Everett, D.H. 1961. The thermodynamics of frost damage to porous solids. Transactions of Faraday Society, Vol. 57, pp. 1541 - 1551.

Fel'dman, G.M. 1988. Peredvizhenie vlagi v talykh i promerzayushchikh gruntakh. [Migration of moisture in unfrozen and freezing grounds.] Novosibirsk, Nauka, Sibirian branch.
257 p. (in Russian).

Friberg, P. & Slunga, E. 1989. Maalajien routivuuskriteerien kehittäminen. [Development of frost-susceptibility criteria of soils.] Otaniemi, Helsinki University of Technology, Institute of Structural Engineering, Soil mechanics and foundation engineering. 130 p. + app. 18 p. (in Finnish with English summary).

Horiguchi, K. & Miller, R.D. 1983. Hydraulic conductivity functions of frozen materials. Proceedings of IV International Conference on Permafrost. Fairbanks, Alaska, June 1983. Washington D.C., National Academy Press, pp. 504 - 508.

ISSMFE Technical Committee on Frost 1989. Work report 1985 - 1989. Proc. Int. Symp. on Frost in Geotechnical Engineering. Saariselkä, Finland, March 1989. Espoo, Technical Research Centre of Finland, Symposium 94, pp. 15 - 70.

Jessberger, H.L. & Jagow, R. 1989. Determination of frost-susceptibility of soils. Proc. Int. Symp. on Frost in Geotechnical Engineering. Saariselkä, Finland, March 1989. Espoo, Technical Research Centre of Finland, Symposium 95, pp. 449 - 470.

Keinonen, L.S. 1977. A thermodynamic description of the ice lensing process. Proc. Int. Symp. on Frost Action in Soils, Luleå, February 1977. Luleå, University of Luleå, Vol. 1, pp. 54 - 58.

Kersten, M.S. 1949. Thermal properties of soils. University of Minnesota, Engineering Experiment Station, Bulletin 28.

King, L. & Seppälä, M. 1988. Permafrost sites in Finnish Lapland and their environment. Proc. 5th Int. Conf. on Permafrost, Trondheim, 2 - 5. August 1988. Trondheim, Tapir Publishers, Vol. 1, pp. 183 - 188.

Kivikoski, H. 1983. Roudan syvyyteen ja routanousuun vaikuttavista tekijöistä eräillä havaintopaikoilla Suomessa. [On factors influencing frost depth and frost heave at some observation sites in Finland.] Tampere, Tampere University of Technology, Department of Civil Engineering, Diploma thesis. 112 p. (in Finnish).

Knutsson, S., Domaschuk, L. & Chandler, N. 1985. Analysis of large scale laboratory and in.situ frost-heave tests. Proc. IV Int. Symp. on Ground Freezing. Sapporo, August 5 - 7,1985. Rotterdam, Balkema, pp. 65 - 70.

Konrad, J-M. 1980. Frost-heave mechanics. Edmonton, Alberta, University of Alberta, Ph.D. thesis. 472 p.

Konrad, J-M. & Morgenstern, N.R. 1980. A mechanistic theory of ice lens formation in fine-grained soils. Canadian Geotechnical Journal, Vol. 17, pp. 473 - 486.

Konrad, J-M. & Morgenstern, N.R. 1981. The segregation potential of freezing soil. Canadian Geotechnical Journal, Vol. 18, pp. 482 - 491.

Konrad, J-M. & Morgenstern, N.R. 1982a. Prediction of frost heave in the laboratory during transient freezing. Canadian Geotechnical Journal, Vol. 19, pp. 250 - 259.

Konrad, J-M. & Morgenstern, N.R. 1982b. Effects of applied pressure on freezing soils. Canadian Geotechnical Journal, Vol. 19, pp. 494 - 505.

Kujala, K. & Ravaska, O. 1989. Influence of test conditions and equipment on the frost-heave test. Proc. Int. Symp. on Frost in Geotechnical Engineering. Saariselkä, March 1989. Espoo, Technical Research Centre of Finland, Symposium 95, pp. 931 - 944.

Loch, J.P.G. 1979. Influence of the heat extraction rate on the ice segregation rate of soils. Frost i Jord 20, pp. 19 - 30.

Lunardini, V.J. 1978. Theory of n-factors and correlation of data. Proc. III Int. Conf. on Permafrost. Edmonton, Alberta, July 1978. Ottawa, National Research Council of Canada, Vol. 1, pp. 40 - 46.

Lunardini, V.J. 1981. Heat transfer in cold climates. New York, Van Nostrand Reinhold. 731 p.

Lunardini, V.J. 1988. Heat conduction with freezing and thawing. Hanover, N.H., U. S. Army Cold Regions Research and Engineering Laboratory (CRREL), Monograph 88-1. 344 p.

Miller, R. 1972. Freezing and thawing of saturated and unsaturated soils. Highway Research Record 393, pp. 1 - 11.

Nieminen, P. 1985. Moreenin hienoaineksen laatu ja sen vaikutus routimisherkkyyteen. [The quality of the fine fractions of till and its influence on frost susceptibility.]. Tampere, Tampere University of Technology, Julkaisuja 34. 81 p. (in Finnish with English summary)

Nixon, J.F. 1982. Field frost-heave predictions using the segregation potential concept. Canadian Geotechnical Journal, Vol. 19, pp. 526 - 529.

O'Neill, K. & Miller, R.D. 1982. Numerical solutions for a rigid-ice model of secondary frost heave. Hanover, N.H., U. S. Army Cold Regions Research and Engineering Laboratory (CRREL), Special report 82-13. 11 p.

Orlov, V.O., Dubnov, Yu.D. & Merenkov, N.D. 1977. Puchenye promerzayushchikh gruntov i ego vliyaniya na fundamenty sooruzhenii. [Heaving of freezing grounds and its influence on the foundations of structures.] Leningrad, Stroiizdat. (in Russian).

Penner, E. & Ueda, T. 1977. The dependence of frost heaving on load application. Proc. Int. Symp. on Frost action in soils. Luleå, February 16.-18.1977. Luleå, University of Luleå. Vol. 1, pp. 92 - 101.

Roggensack, W.D. 1977. Geotechnical properties of fine-grained permafrost soils. Edmonton, Alberta. The University of Alberta, Ph. D. thesis. 347 p. + 3 app.

Saarelainen, S. 1984. Frost heave and frost penetration at some observation sites in Finland. Proc. Nordiskt Geoteknikermöte 1984. Linköping, 1.-3. juni 1984. Linköping, Statens Geotekniska Institut. Vol. 2, pp. 373 - 380.

Saarelainen, S. 1989. Evaluation of frost-heave properties of soils. Proc Int. Symp. on Frost in Geotechnical Engineering, Saariselkä, March 1989. Espoo, Technical Research Centre of Finland, Symposium 95. pp. 471 - 480.

Saarelainen, S. 1990a. Routavaurioiden korjausrakenteet valtatiellä 21 Peerassa. Mitoitus, koerakentaminen ja seuranta v. 1986 - 1988. [Repair structures of frost damage on main road 21 at Peera, Northern Finland. Design, construction and monitoring during 1986 - 1988.] Espoo, Technical Research Centre of Finland, Research Notes 1102. 62 p. + app. 15 p. (in Finnish with English summary).

Saarelainen, S. 1990b. Routavaurioiden korjaus valtatiellä 21 Tullissa, Kilpisjärvellä. Mitoitus, koerakentaminen ja seuranta v. 1987 - 1988. [Repair of frost damage on main road 21 at Tulli, Kilpisjärvi. Design, construction and monitoring in 1987 - 1988.] Espoo, Technical Research Centre of Finland, Research Notes 1107. 54 p. + app. 52 p. (in Finnish with English summary).

Saarelainen, S. & Toivonen, T. 1991. Valtatien 3 routamitoitus routanousun mukaan välillä Riihimäki P - Virala. [The frost design of main road 3 according to frost heave between Riihimäki P - Virala] Rakennustekniikka 47, 1, pp. 13 - 16. (in Finnish).

Saetersdal, R. (ed.) 1976. Sikring mot teleskader. [Prevention against frost damage.] Oslo, Norges teknisk-naturviten skapelige forskningsråd og statens vegvesens utvalg for frost i Jord, Nr. 17. 400 p. (in Norwegian).

Saetersdal, R. 1980. Heaving conditions by freezing of soils. Proc. Int. Symp. on Ground Freezing. Trondheim, June 24.-26. 1980. Trondheim, University of Trondheim & Norwegian Institute of Technology, pp. 824 - 836.

Skaven-Haug, S. 1971. Frostfundamenters dimensionering, frysevarme og jordvarme. [Design of frost foundations, freezing heat and ground heat.] Frost i Jord 3, pp. 9 - 27. (in Norwegian).

Slunga, E. & Saarelainen, S. 1989. Determination of frost-susceptibility of soil. In: Proc. Int. Conf. on Soil Mechanics and Foundation Engineering, Rio de Janeiro, August 1989. Rotterdam, Balkema. Vol.4, pp. 1465 - 1468.

Stenberg, L. 1981. Frost heaving tests with constant rate of heat extraction. Linköping, Swedish Road and Traffic Institute, VTI, Rapport 220 A. 22 p.

Stefan, J. 1891. Uber die Theorie der Eisbildung im Polarmeere [On the theory of ice formation in the Arctic Ocean]. Ann. Phys. u. Chem., Neue Folge, Bd.2, Heft 2, pp. 269 - 286. (in German).

Taber, S. 1930. The mechanics of frost heaving. Journal of geology 38, 4, pp. 303 - 317.

Takagi, S. 1980. The adsorption force theory of frost heaving. Cold regions science and technology 3, 1, pp. 57 - 81.

Talonrakennuksen routasuojausohjeet. [Instructions for the frost design in house construction.] 1987. Helsinki, Technical Research Centre of Finland, Geotechnical Laboratory and Rakentajain Kustannus Oy. 94 p. (in Finnish).

Watzinger, A., Kindem, E. & Michelsen, B. 1938. Undersøkelser av masseutskiftningsmaterialer for vei- og jernbanebygning. [Investigations of excavate-and-fill materials for road and railway construction.] Oslo, Medd. fra veidirektion 15. (in Norwegian).

Williams, P.J. 1967. Properties and behaviour of freezing soils. Oslo. Norwegian Geotechnical Institute, Publikation Nr. 72. 120 p.

Williams, P.J. & Smith, M.W. 1989. The frozen earth. Cambridge, Cambridge University Press. 306 p.

APPENDIX

Kersten's equations for estimation of thermal conductivity of unfrozen and frozen soils (Kersten 1949, Berg et al. 1980)

Unfrozen soil

$$\lambda_t = (\alpha \mathrm{Log}_{10} w + \beta)\, 10^{0.62\rho d} \quad (1)$$

where λ_t is thermal conductivity of unfrozen soil, W/Km
- α, β coefficients
- w water content, %
- ρd dry density, t/m^3

clays and silts: $\alpha = 0.13$ $\beta = -0.029$
sands $\alpha = 0.10$ $\beta = 0.058$

Frozen soil

$$\lambda_f = a\, 10^{b\rho d} + c\, 10^{0.62\rho d}\, w \quad (2)$$

where λ_f is thermal conductivity of frozen soil, W/Km
- a, b,
- c, d coefficients
- w water content, %
- ρd dry density, t/m^3

clays and silts: a = 0.0014, b = 1.4, c = 0.012, d = 0.50
sands a = 0.011, b = 0.81, c = 0.0046, d = 0.91

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Modelling frost heaving and frost penetration in soils at some observation sites in Finland

The SSR model

Abstract

The purpose of this study was to monitor frost heaving and frost penetration at six observation sites in Finland in 1982 - 1984. Frost heaving was also studied in the laboratory with frost-heave tests carried out on undisturbed specimens.

The observed freezing behaviour was compared with the climatic conditions. The frost penetration and frost heave were found to correlate with the freezing index. Relative frost heave was fairly constant at each site, varying between 0.03 and 0.23.

A calculation model based on heat balance at the freezing front was tested for the estimation of frost heave and frost penetration. The spatial description of frost heaving and frost penetration was reasonably good. Estimation of the in-situ segregation potential from the observed frost heaving and frost penetration data was also successful.

Comparison of the back-calculated segregation potentials from site observations with those from laboratory frost-heave tests revealed a good correlation between the average value of frost-heave tests and the in-situ estimate. The laboratory values were, in general, slightly smaller than the in-situ values. This may reflect the influence of side friction on the laboratory test values.

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