INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

SIMSG ISSMGE

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Artificial ground freezing: How to model and calculate the frost-heave?

N.M. Naaktgeboren
Public Works and Water Management, The Netherlands

ABSTRACT: In the Netherlands the cross passages in the Westerscheldetunnel were built by using artificial ground freezing. In order to know the behaviour of frozen soil, measurements were made around some cross passages and some frost-heave and triaxial experiments were carried out. To explain the results of the experiments and later the measurements a two dimensional numeric model is developed. This model can describe both the heat conduction, the water flow and the deformation of the soil. In this paper both the model and the problems with modelling frost-heave experiments are described. The results of the calculations are compared with the experiments and these correspond very well. To analyze a cross passage in the Westerscheldetunnel a three dimensional model is required which will be developed in the future.

1 INTRODUCTION

1.1 *History*

In the Netherlands the Westerscheldetunnel was constructed by two TBM's. The two tubes were connected with 26 cross passages in every 250 m to increase the tunnel safety. The cross passages were built by using artificial ground freezing in order to make underground excavations possible. During the construction phase of the cross passages monitoring was carried out for both ground and tunnel behaviour by measuring temperatures, (frost-heave) loads and deformation of the frozen ground and the tunnels. Measurements were taken in three different directions – perpendicular and parallel to the tunnel tubes – with stress-monitoring stations, spade cells, extensometers and thermocouples. These measurements were done in cooperation with two organizations in the Netherlands; the "Centrum voor Ondergronds Bouwen (COB)" and "Delfts Cluster (DC)". The project was called: F100 Ground Freezing.

1.2 *Monitoring and measurements*

Large differences in ground stresses have been measured between the perpendicular and parallel direction of the freezing tubes. These differences have also been measured in special laboratory experiments with triaxial cells under frozen conditions. The in-situ measurements also indicate that the temperature variation in the freezing-pipes has a large influence on frost heave loads on the main tunnel. All separate phases of the construction activities of the cross passages (freezing, excavation, lining, thawing) are recognized clearly in the data (Rijkers et al, 2002 and F100 Report F100-E-02-079).

1.3 *Experiments*

In the same period frost-heave experiments have been done on different types of typical Dutch soil to get more insight into their behaviour in frozen conditions. Two soil types were the same as the soils where the cross passages in the Westerscheldetunnel were made. The results were presented in F100 Report F100-E-03-092.

1.4 *Freezing model*

To explain the results of the experiments and later the measurements a two dimensional numeric model is developed. This model can describe both the heat conduction, the water flow and the deformation of the soil. Only if these three parts are handled together a good calculation result is possible. The starting point was the use of simple or well known parameters. Of course all the parameters in the model had to be dependent on the temperature.

1.5 *Calculations*

With the freezing model some calculations have been made and compared with the frost-heave experiments. In this paper not only the results are described but also the assumptions which are made in order to match the calculations with the experiments.

Copyright © 2006 Taylor & Francis Group plc, London, UK

2 GEOMECHANICAL BEHAVIOUR OF FROZEN SOIL

In sand the water contents shall freeze almost instantaneously due to the high percentage of free water. Clay shows a different behaviour in frozen state due to the strongly bonding forces between water and clay minerals. In clay a percentage of water will remain unfrozen at temperatures of −35°C. Consequently the grain size distribution also controls differences in frost heave and strength development. In the following paragraphs the frost-heave phenomena and the frost-heave experiments will be described.

2.1 *Frost-heave and ice lenses*

In freezing soil the formation water can segregate into ice lenses before it is frozen (Konrad & Morgenstern, 1981). As a result of growing ice lenses a water pressure gradient will develop that depends on grain size and permeability of the soil (Penner, 1986). The thickness of ice lenses can range from <10 μm to several cm's. The freezing expansion of clay is partly caused by ice lenses. The growth of the ice lenses is enhanced by the (slow) migration of water at this frozen front. That is the reason why soils with low permeability such as silts and clays are frost heave susceptible and (drained) sand is not. The process of migration of water due to freezing temperatures is referred to as cryosuction. Konrad & Morgenstern (1981) have defined experimentally a linear relation between the frost heave rate *h* of a soil, the segregation potential SP and the temperature gradient T:

$$\frac{dh}{dt} = SP * \frac{dT}{dx} \qquad (1)$$

This linear relation between temperature gradient and frost-heave rate has been established experimentally using samples of a particular clay called Boom clay.

Three dimensional frost-heave behaviour of Boom clay has been experimentally investigated (figure 1) and reported by (Rijkers et al, 2000).

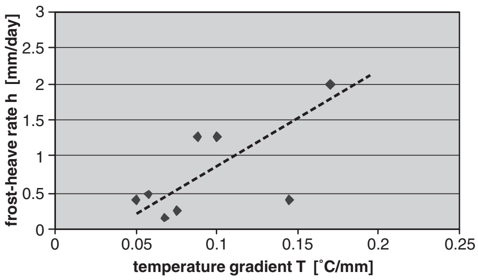

Figure 1. Frost-heave rate vs temperature gradient of BK1/BK2 soil samples.

2.2 *Frost-heave experiments*

To measure the Segregation Potential (SP) a constant temperature gradient is chosen by frost-heave experiments. Normally these experiments are done by a vertical placed specimen which is kept constant below 0°C at one side and at the other side the temperature is kept constant above 0°C for a long period of time. Measured is the speed of heave at the chosen temperature gradient. According to equation 1 the SP-value can be calculated.

3 GROUND FREEZING MODEL

3.1 *Introduction*

As mentioned before a two dimensional numeric model is developed to explain the results of the frost-heave experiments. Later the model can be expanded to three dimensions to validate the measurements of the frozen soil besides some cross passages in the Westerscheldetunnel. If it is possible to explain all the results of the measurements by calculations, new freezing projects can be designed with the freezing model.

In this paper the frost-heave experiments and the calculations are compared with the two dimensional model.

Three basic equations are used for the model, one for heat conduction, water flow (Darcy and some additions) and soil deformation. All these equations are given for two dimensions, but the equations can of course also be expanded for three dimensions.

3.2 *Heat conduction*

The standard equations for heat transfer are used:

$$\frac{\partial q_{temp,x}}{\partial x} + \frac{\partial q_{temp,y}}{\partial y} + \rho c \frac{\partial T}{\partial t} = 0 \qquad (2)$$

$$\begin{bmatrix} q_{temp,x} \\ q_{temp,y} \end{bmatrix} = \begin{bmatrix} k_{temp,x} & 0 \\ 0 & k_{temp,y} \end{bmatrix} \begin{bmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \end{bmatrix} \qquad (3)$$

where q_{temp} = heat flux; ρ = soil density; c = soil heat capacity; T = temperature; t = time; x,y = direction; k_{temp} = soil thermal conductivity.

Of course for the heat capacity and the thermal conductivity a combination of the properties of soil, water and ice is necessary.

3.3 *Water flow*

In the ground freezing often frost-heave experiments are done. The description of these one dimensional experiments is already written in paragraph 2.2. The

Copyright © 2006 Taylor & Francis Group plc, London, UK

effect of a temperature gradient is a continuous heave of the soil (Konrad & Morgenstern 1981) in the time and leads to equation 1.

The frost-heave is caused by the different pressures in the capillaries in the frozen and unfrozen parts of the soil. Due to these difference in pore pressures suction occurs. This suction and the mean permeability in the soil define the frost-heave. In the model a suction parameter (SUC) is used, which is defined as the Segregation Potential divided by the mean permeability of the frozen fringe (equation 4).

$$SUC = \frac{SP_0}{k_{mean}} \quad (4)$$

Equation 5 gives the rule for the total mass of water and ice. Because very little air in water can strongly change the compressibility of water it's important to get the parameter for compressibility of water (β) in equation 5.

Equation 6 is divided in two parts. Part one is the Darcy law and the second part is the suction of water suction due to the freezing as described in equation 4.

$$\frac{\partial q_{hydr,x}}{\partial x} + \frac{\partial q_{hydr,y}}{\partial y} + \frac{d}{dt}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = -n\beta\frac{dp}{dt} + \alpha_{water}\frac{dT}{dt} \quad (5)$$

$$\begin{bmatrix} q_{hydr,x} \\ q_{hydr,y} \end{bmatrix} = \frac{1}{\gamma_w}\begin{bmatrix} k_{hydr,x} & 0 \\ 0 & k_{hydr,y} \end{bmatrix}\begin{bmatrix} \frac{\partial p}{\partial x} \\ \frac{\partial p}{\partial y} \end{bmatrix} - SUC\begin{bmatrix} k_{hydr,x} & 0 \\ 0 & k_{hydr,y} \end{bmatrix}\begin{bmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \end{bmatrix} \quad (6)$$

where q_{hydr} = water flow; γ_w = density of water; p = pressure; u,v = displacements in x and y direction; β = compressibility of water; n = porosity of the soil; α_{water} = expansion of water and ice; T = temperature; t = time; x,y = direction; k_{hydr} = permeability of the soil; SUC = Suction.

3.4 *Deformation*

The standard equations are used to describe the strain and stresses in the soil. The equations are written for the plain strain situation.

$$\frac{\partial \sigma'_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial p}{\partial x} + f_x = 0 \quad (7)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma'_{yy}}{\partial y} + \frac{\partial p}{\partial y} + f_y = 0 \quad (8)$$

$$\begin{bmatrix} \sigma'_{xx} \\ \sigma'_{yy} \\ \tau_{xy} \end{bmatrix} = \frac{E'(1-\nu')}{(1+\nu')(1-2\nu')}\begin{bmatrix} 1 & \frac{\nu'}{1-\nu'} & 0 \\ \frac{\nu'}{1-\nu'} & 1 & 0 \\ 0 & 0 & \frac{1-2\nu'}{2(1-\nu')} \end{bmatrix}\left(\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix} - \begin{bmatrix} \alpha\Delta T \\ \alpha\Delta T \\ 0 \end{bmatrix}\right) \quad (9)$$

$$\sigma'_{zz} = \nu'(\sigma'_{xx} + \sigma'_{yy}) \quad (10)$$

where σ = normal stress component; τ = shear stress component; ε = normal strain; γ = distortion; x,y = direction; p = water pressure; F = load on the soil; E = elasticity of the soil; υ = Poisson's ratio; α = expansion of the soil due to the temperature; T = temperature.

3.5 *New model*

The equations for heat, water flow and deformation are combined into one system to calculate some experiments. The great advantage is the use of standard properties, which normally are used in a water flow, heat or stiffness calculation except the suction.

Most of these parameters are temperature dependent but in some cases it is very difficult to get good values for them.

4 EXPERIMENTS AND PROPERTIES

4.1 *Frost-heave*

As mentioned before in the project "F100 Ground Freezing", frost-heave experiments have been done.

The height of the specimen in the experiment was approximately 140 mm and the diameter was not given. After placing the specimen in the apparatus the loads were applied and it was placed 24 hours at a temperature of +1°C. At the start of the experiment the lower side of the specimen is set to the desired temperature. In this research program different types of soil are used: Peat (HV), Holocene Clay (ZPK), Boom Clay (BK2) and Sand (Z1).

The Segregation Potential also depends on the actual stress as seen in equation 10 (Konrad & Morgenstern, 1981).

$$SP = SP_0 \exp(\alpha * \sigma_n) \quad (10)$$

Where α = material parameter, σ_n = normal stress, SP = Segregation Potential, SP_0 = Segregation Potential without normal stress.

The frost-heave experiments have been done at different temperature gradients and different loadings (Table 1) to get a good idea of the behaviour of the analyzed soil types. In the table the value of measured SP is already given.

Copyright © 2006 Taylor & Francis Group plc, London, UK

Table 1. Frost-heave experiments.

Type of soil	Bottom temperature [°C]	Loading [kPa]	Initial height [mm]	Measured SP [mm^2/°Cs]
Peat	−10	10	134	0.00
	−10	20	140	0.00
	−10	40	142	0.00
	−20	10	142	0.47
	−20	20	140	0.56
	−20	40	140	0.58
	−20	10	140	0.17
	−20	20	140	0.11
Holocene Clay	−10	10	135	0.77
	−10	35	132	1.63
	−10	100	135	1.63
	−20	100	140	0.38
	−20	10	140	0.50
	−20	50	140	0.32
Boom Clay	−5	100	140	0.12
	−5	100	140	0.12
	−10	100	141	0.14
	−20	100	140	0.18
	−5	300	140	0.03
	−20	300	141	0.25
	−5	5	141	0.33
	−10	5	141	0.54
	−20	5	141	0.55
	−10	300	141	0.01
Sand	−10	100	141	0.00
	−20	100	141	0.00

The initial temperature of the specimen was +1°C.

As expected the used sand gives no frost-heave. The presented results of the Holocene clay and Peat are diverged. In this paper the results of the Sand and Boom Clay are used to explain the newly developed model. In table 2 and 3 the material properties are given for these materials.

The measured SP-values for the Boom Clay are also given in figure 2.

Also is seen the fit of all the experiments as calculated in F100 Report F100-E-03-092:

$$SP(\sigma_n) = 0.466 \exp(-11.1\,\sigma_n)\ [mm^2/°C.hr]$$

Jessberger also had defined the frost-heave of Boom Clay. The curve which Jessberger had found was:

$$SP(\sigma_n) = 0.38 \exp(-5.2\,\sigma_n)\ [mm^2/°C.hr]$$

4.2 *Properties of Sand*

The properties of Sand are also measured in the frozen and unfrozen part. In table 2 the values as used in the calculations are given as function of the temperature. The temperature range for transition phase from unfrozen to frozen is chosen.

4.3 *Properties of Boom Clay*

The properties of Boom Clay are measured in the frozen and unfrozen part. In table 3 the values as used in the calculations are given as function of the temperature.

5 CALCULATION RESULTS

5.1 *Sand*

The first example is the calculation of the expulsion of water in a sandy specimen with a temperature of the bottom plate of −10°C. In figure 3 is shown the expulsion of the water in the sand, which corresponds with the results of the experiments.

The calculation results correspond well with the measurements. In this case the suction due to the freezing process is zero and only the expulsion is calculated to see if the program is correct. The expulsion of water is caused by the expansion of water when the temperature drops below zero. The deformation of the specimen is only caused by the load on the specimen.

After approximately 70 hours the specimen is thawed and the expulsion of water is decreasing.

5.2 *Boom Clay*

In the second example a calculation is made of a Boom Clay frost-heave experiment with a bottom plate temperature of −20°C and an external load of 100 kPa. In this case there is not only the water expulsion due to the expansion of freezing water but also the suction due to the freezing process.

In the Report F100-E-03-092 is observed that the temperature only fits if it is assumed that the bottom plate is −16°C instead of −20°C. Maybe there is a heat resistance between the plate and the soil. In this calculation a bottom plate temperature of −16°C is assumed.

The difference between elongation and expulsion gives the frozen water content. In this particular case 60% of the water content can be frozen. Assumed is that 40% of the water is bound to the clay particles.

In the calculation 23% (60% of 38% porosity) of the total volume is assumed to be filled with free water that can be frozen and expand.

In figure 4 the results are shown for the Boom Clay frost-heave experiment. Both the elongation and the expulsion of water can be calculated.

In figure 4 only the elongation and the expulsion as function of the time is shown, but it is also important where the elongation takes place. In figure 5 is shown

Copyright © 2006 Taylor & Francis Group plc, London, UK

Table 2. Used Sand properties in calculation.

Temperature calculation			Deformation calculation							Water flow calculation		
T [°C]	$\lambda_{sand}(T)$ [W/m°C]	$H_{sand}(T)$ [J/m^3]	T [°C]	$E_{pressure}(T)$ [kN/m^3]	$E_{tension}(T)$ [kN/m^3]	T [°C]	Vol(T) [−]	ν [−]	n [%]	T [°C]	$k_{sand}(T)$ [m/s]	SUC [m/°C]
100	2.08	0.63 10^6	100	50 10^3	5	0	1.00	0.3	0.4	100	0.25 10^{-3}	0.0
0	2.08	0.33 10^6	0	50 10^3	5	−1	1.075			0	0.25 10^{-3}	
−1	3.05	0.22 10^6	−5	1 10^6	5	−2	1.085			−5	0.25 10^{-6}	
−100	3.05	0.0	−100	1 10^6	5	−10	1.09			−100	0.25 10^{-6}	

Table 3. Used Boom Clay properties in calculation.

Temperature calculation			Deformation calculation							Water flow calculation		
T [°C]	$\lambda_{clay}(T)$ [W/m°C]	$H_{clay}(T)$ [J/m^3]	T [°C]	$E_{pressure}(T)$ [kN/m^3]	$E_{tension}(T)$ [kN/m^3]	T [°C]	Vol(T) [−]	ν [−]	n [%]	T [°C]	$k_{clay}(T)$ [m/s]	SUC [m/°C]
100	1.37	0.65 10^6	100	50 10^3	5	0	1.00	0.3	0.38	100	0.22 10^{-9}	0.0
0	1.37	0.36 10^6	0	50 10^3	5	−5	1.075			0	0.22 10^{-9}	0.0
−1	2.42	0.22 10^6	−5	1 10^6	5	−15	1.085			−5	0.22 10^{-12}	13.0
−100	2.42	0.0	−100	1 10^6	5	−50	1.09			−100	0.22 10^{-12}	13.0

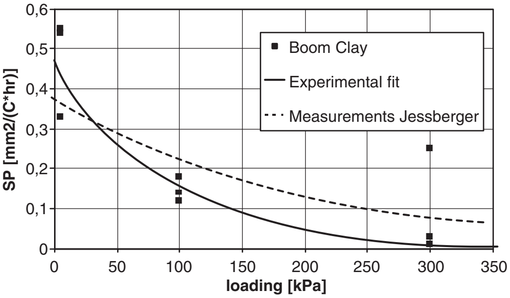

Figure 2. Segregation Potential Boom Clay as function of loading.

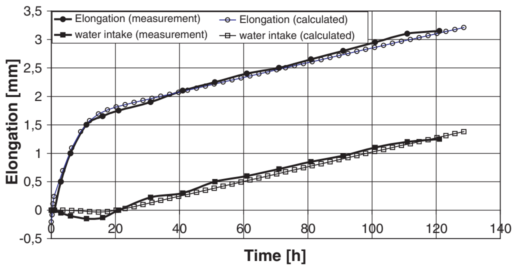

Figure 4. Elongation and expulsion of water in a Boom Clay specimen.

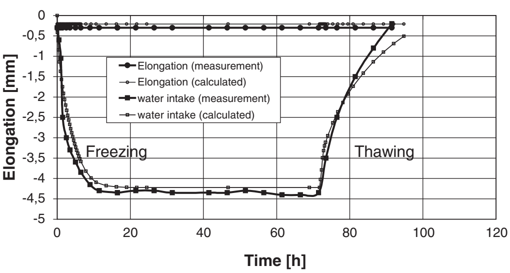

Figure 3. Elongation and expulsion of water in a sandy specimen.

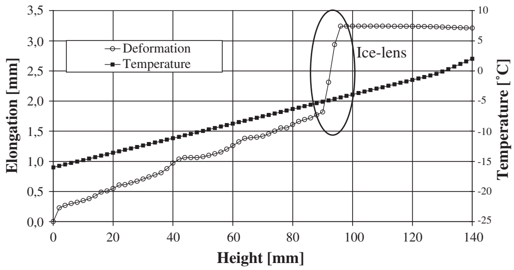

Figure 5. Elongation and temperature as function of the specimen height.

the deformation over the height of the specimen and the corresponding temperature field. At the greatest deformations an ice-lens is formed. It is clear to see in figure 5.

If instead of the suction (equation 6) the Segregation Potential is used to define the frost-heave (see equation 11) the greatest deformation appears at the coldest plate. In this case at the height of the specimen

Copyright © 2006 Taylor & Francis Group plc, London, UK

of 0 mm. So the calculated ice-lens does not arise at the expected place.

$$\begin{bmatrix} q_{hydr,x} \\ q_{hydr,y} \end{bmatrix} = \frac{1}{\gamma_w} \begin{bmatrix} k_{hydr,x} & 0 \\ 0 & k_{hydr,y} \end{bmatrix} \begin{bmatrix} \frac{\partial p}{\partial x} \\ \frac{\partial p}{\partial y} \end{bmatrix} - SP \begin{bmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \end{bmatrix} \quad (11)$$

6 CONCLUSIONS

To explain the results of the frost-heave experiments a numeric model is developed. This model can describe both the heat conduction, the water flow and the deformation of the soil. All the parameters can be given as function of the temperature. The model uses the suction as an important parameter instead of the Segregation Potential.

For sand the expulsion of water can be calculated correctly. The frost-heave of Boom Clay can be calculated with the assumption that 40% of the water content is bound by the clay particles and cannot freeze (and expand). Both the elongation and the expulsion of water agree with the experiment.

So more research had to be done to know the percentage of the bound water which is not expanding due to the freezing process.

To make calculations for in-situ artificial ground freezing it is necessary to know all the parameters as function of the temperature.

To validate the model better a monitored cross passage in the Westerschelde tunnel will be analyzed with a three dimensional model. If it is possible to explain all the monitored results of a cross passage in the Westerschelde tunnel by calculations new freezing projects can be designed with the freezing model.

LITERATURE

Konrad, J.M. & Morgenstern, N.R. (1981) The segregation potential of a freezing soil, *Cndn Geotech*. J. 18, pp. 482–491

Rijkers, R.H.B., Naaktgeboren, N.M., Côté, H., Thimus, J.-F., Visschedijk, M. (2000) Soil behaviour during artificial freezing – Part 2: Application in bored tunnels, In: ISGF2000 – Frost action in soils (ed. J.F. Thimus), Louvain-la-Neuve, pp. 237–242

Rijkers, R.H.B, Naaktgeboren, N.M., Hemmen, B., Weigl, H. (2002) In-situ frost heave loads in artificially frozen ground for tunneling, In: Proceedings of the ITA world tunneling congress 2002, Australia, maart 2002

Rijkers, R.H.B., Lange, G. de, Naaktgeboren, N.M. (2003) Geomechanical behavior of frozen soil and AGF safe constraint method, In: Proceedings of the ITA world tunneling congress 2003, the Netherlands, april 2003

Report F100-E-02-079, Aanleg dwarsverbindingen met grondbevriezing bij de Westerscheldetunnel, December 2002, COB, Gouda (dutch)

Report F100-E-03-092, deel 2, Dwarsverbindingen met grondbevriezing, Frost-Heave onderzoek in nederlandse grond, mei 2003, COB, Gouda (dutch)

Copyright © 2006 Taylor & Francis Group plc, London, UK