Ground Freezing

CT3300 Use of Underground Space

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1 Preface

For the course CT3300 “Use of Underground Space” at the Technical University Delft it required to write a report about a subject that has to do with underground construction. As a group we decided to write the report about the subject; Ground Freezing. Ground freezing is a relative young technique of underground construction and is being used more often as a result of increasing complexity in underground construction. As a group we wanted to get a better of the understanding of this technique and the application areas. In Chapter 4 different freezing techniques will be discussed and the application area of these different freezing techniques. Chapter 5 discusses the design of a frozen soil body and different influences that should be taken into account. Chapter 6 elaborates monitoring techniques that can be used and the need of monitoring programs. Chapter 7 discuses the change of ground properties during and after freezing. Chapter 8 gives information about causes of failures related to ground freezing. In Chapter 9 three case studies are presented where ground freezing has been used and measurements of these freezing have been made.

2 Contents

3 Summary

4 Freezing methods and system installation

A standard soil freezing installation consists of a refrigeration source, a distribution system and freeze pipes. The distribution system circulates the coolant from the refrigeration source to the freeze pipes which extract the heat from the soil. There are two main types of coolant: (1) brine solutions or (2) liquid nitrogen. Liquid nitrogen is sometimes replaced by carbon dioxide, but works according to the same principle. Both types have their own specifications, (dis)advantages and are used depending on the circumstances of the project. In this chapter, these two types of coolant are discussed, along with the installation of a refrigeration plant, a coolant distribution manifold and freeze pipes.

4.1 Primary plant and pumped loop secondary coolant

A common used refrigeration source is a one or two stage ammonia refrigeration plant. A two stage plant is used when one wants to obtain temperatures below -25°C. These plants are widespread and available in a wide range of capacities. They are driven by diesel or electric engines and have a high thermal efficiency.

The schematic diagram in Figure 1 illustrates how a system with a primary plant and a pumped loop secondary coolant works (brine system). The compressor liquefies ammonia gas at a pressure around 0,8 - 1,2 MPa. Hereby, the temperature of the liquid ammonia increases up to 100 °C. A pump then transfers the liquid ammonia under high pressure to a condenser. There it is cooled during passage through a system of coils. The cooling occurs by circulating water which removes the excessive heat. Then, the cooled liquid ammonia leaves the condenser and passes through an expansion valve. Hereby, a fine nozzle sprays the ammonia under a constant high pressure into another system of coils. In these coils the pressure is also constant, but lower, i.e. around 0,15 MPa. This drop in pressure leads to the evaporation of the liquid ammonia and is also accompanied with a drop in temperature. The ammonia gas is now at a temperature of ca. -25°C. The brine cooler, or evaporator, includes a series of coils for circulating the ammonia and helps to convert any remaining liquid ammonia into vapor. Eventually, all the vaporized ammonia is transferred back into the compressor for another cycle.

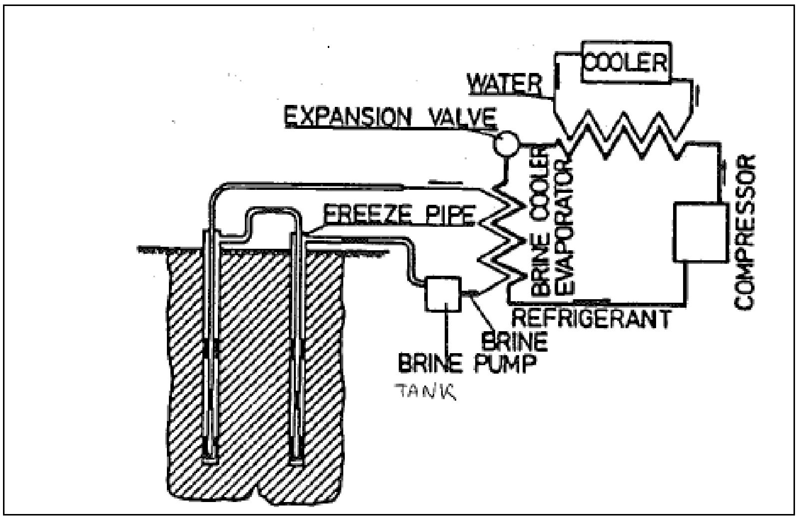

Figure 1; schematic drawing of a ground freezing installation (after Andersland, B. and Ladanyi, B., (2005))

The brine circu it for th e freezer sy stem includes a brine tank, a brine pum p, an insulated coolant supply manifold, a number of parallel connected freezing elements in the ground with inner supply and outer return lines and an insulated return manifold. Different types of coolant have been used with the system . Among others, one tried using diesel oil, propane, glycol-water mixtures and mixtures. Nowadays, the most commonly used is a calcium chloride brine.

Another possibility is to use liquid nitrogen or liquid car bon dioxide instead of the brine liquids. When this m ethod is used, there is no need of a refrigeration plant. Liquid nitrogen/oxygen is supplied directly or through a storage tank into the freeze p ipes and after circulation, nitrogen/oxygen is re leased directly into the atm osphere through an exhaust pipe (Figure 2). Neither carbon dioxide nor nitrogen is flamm able or toxic. Nevertheless, they are heavier than air and in larg e quantities they can cause suffocation. Thus, a good ve ntilation system is an absolute requirement when working with these kind of systems.

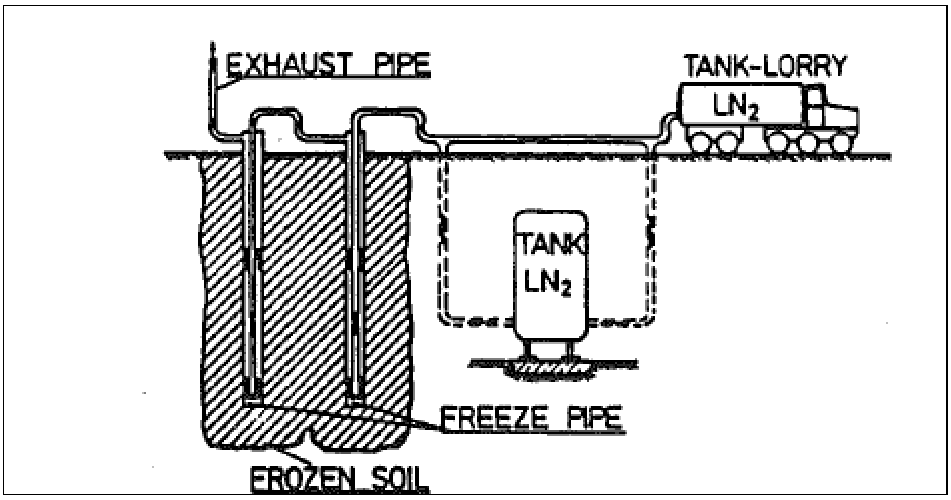

Figure 2; principle of liquid nitrogen freezing (after Andersland, B. and Ladanyi, B., (2005))

Which of the two methods is the best? And should one use liquid nitrogen (LN_2) or liquid carbon dioxide (LCO_2)? Each method, each installation, each coolant has his own characteristics and it truly depends on the purpose of the soil freezing use and the amount of budget available.

The brine freezing method is a simple method, but rather cumbersome and thermally inefficient. In this system, heat transfer between the coolant and the freeze pipes occurs through convection; no phase changes occur. This method of cooling requires large quantities of coolant and it implies a thermal gradient into the system during the freezing process. The availability of individual freezing elements which can be independently controlled is an advantage. It facilitates controlling localized wall conditions and unexpected water flows. As mentioned before, the most commonly used brine is calcium chloride. It is added in large quantities to water in order to depress its freezing point below that attainable by the refrigeration plant. These brines have high specific heat, but on the other hand, they are also dense, relatively viscous and corrosive. Other fluids may have more attractive properties under the same conditions, but flammable or toxic coolants should be avoided for obvious reasons.

The use of LN2 and LCO2 methods are much more expensive than brine freezing. That is why they are only very attractive to use in single projects of a short duration (hours-days), where only small volumes of soil need to be frozen or when rapid formation of the wall is important (high delay costs). The fastest and thermally most efficient way of ground freezing is the uniform boiling of liquid nitrogen throughout a series of freeze pipes. In Table 1 the major differences between LN2 ground freezing and brine freezing are listed. One of the major difficulties of using this method is controlling the system. The unconfined venting of LN2 in a series of vertical or horizontal freezing elements frequently results in a waste of refrigerant and a very irregular frozen zone. This irregularity is dependent on the quality of the vapor-liquid mixture and its velocity throughout the system. Different velocities and qualities of mixtures can cause a difference in heat transfer coefficient up to one order of magnitude. A solution for this problem could be a supply and exhaust manifold with appropriate valves at each end of a series of freezing elements. This allows reverse flow which could cancel out the irregular freezing characteristics. This ways of working is efficient up to 4 in series connected freezing elements. Another feature to keep in mind has to do with sudden geysering of super cold LN2. Nitrogen can boil at atmospheric pressure, so if a series of open vertical freezing elements are filled with LN2 and are allowed to boil, the fluid may be ejected after a short period of boiling. This sudden geysering is wasteful and may be dangerous. In many cases, this situation is controlled by placing a supply tube with a smaller diameter inside the freezing element. To ensure success, the supply tube should be nearly as large as the freezing element and the supply of LN2 should be regulated to match the rate of boil-off. Sublimating CO2 is thermally less efficient than sublimating LN2 and the process itself is in most of the cases also harder to control. Dry ice used in combination with a mixing tank and a circulating secondary coolant is probably one of the most efficient ways to use expendable CO2 (Shuster 1972).

Characteristics of Liquid Nitrogen (LN2) and Brine Freezing		
ITEM	**LN2**	**BRINE**
Site installation		
Electric power	Not required	Required
Water for cooling	Not required	Required
Refrigeration plant	Not required	Required
Storage tank	Required	Required
Circulation Pumps	Not required	Required
Pipe system for distribution of coolant	Supply only	Supply and return
Low-T material for surface	Required	Not required

pipes, valves, etc.		
Low-T material for freeze pipes	Not required	Not required
Execution of freezing		
Physical condition of coolant	Liquid/vapor	Liquid
Min T achievable (in theory)	-196°C	-34°C ($MgCl_2$) -55°C ($CaCl_2$)
Reuse of coolant	Impracticable	Standard
Control of system	Difficult	Easy
Shape of freeze wall	Often irregular	Regular
Temperature profile in freeze wall	Great differences	Small differences
Frost penetration	Fast	Slow
Impact on freeze wall in case of damage to freeze pipe	None	Thawing effect
Noise	None	Little

Table 1; comparison between different freezing techniques after Stoss and Valk (1979)

4.2 Installation of the cooling system

The temperature geometry and performance of the frozen earth structure formed by a given freeze pipe installation is dependent on the specific refrigeration plant and coolant distribution system employed. Construction operations necessary to successfully install a ground freezing system include site preparation, subsurface installation of the freeze pipes and installation of the refrigeration plant and the coolant distribution manifold.

4.2.1 Site preparation

It is important to collect and drain any surface water away from the site with the planned frozen earth structure. Inadequate drainage can cause severe damage to the frozen wall. Water that bumps against the frozen wall or pours over it, can cause severe damage. Once the wall is eroded by water, it is generally very difficult and costly to repair the affected area.

Another thing to keep in mind is the possible proximity of all kinds of utility lines (e.g. sewers, gas pipes,…), especially in urban areas. Although it is unlikely that the amount of energy used to freeze the ground is sufficient to freeze e.g. the water in the sewers, one should consider the possibility. An effective way of dealing with this problem is to expose the utility line and insulate it. In many cases sprayed polyurethane foam has been successfully used. This will prevent the utility from freezing and also will prevent thawing of frozen ground surrounding the utility. Extra attention should go to steam pipes that are still in use during the construction works. The slightest drop in temperature could cause the steam to condensate and build up water in the lines.

On every site there are also electric power lines nearby to run the refrigerator plant. Sometimes, one also uses an internal combustion engine to run the refrigeration plant, but in general this is not advised. The starting and stopping of this engine for maintenance and/or fluctuations in the delivered voltage could result in damage to the electrical motors and the compressor of the refrigeration plant. In some cases where the frozen wall has to function in highly stressed cases or very remote areas, there is also demand for immediately available back-up power. Nevertheless, in general, the time-temperature response of frozen earth permits refrigeration downtime on the order of several days. If there is a possibility that the downtime is longer than 72h, one should foresee back-up power.

4.2.2 Subsurface installation of freeze pipes

Freezing pipes are made of steel, both for the brine as for the liquid nitrogen/carbon dioxide applications. If blasting occurs nearby the freezing installation, it is recommended to uses reinforced steel pipes (ASTM A-120 or A-53). These pipes contain 8% nickel (ASTM-333). Furthermore it is recommended that all connections are welded and that no threaded couplings are used. This is to prevent leakage when working under high pressures. To be sure that the pipes do not leak, they should be testes prior to installation at a pressure that is at least 120% of the working pressure.

The techniques of pipe installation vary widely depending on requirements of the particular application, but some factors are basic for each application. One of the most important factors is the spacing of the freeze pipes and their subsurface alignment. The spacing of the freezing pipes is decisive for the time required for the freezing wall to develop. Empirical data reveal that the time required to close a frozen wall, consisting of a single row of freeze pipes is exponentially proportional to the pipe spacing. Thus, for example, if the pipe spacing is decreased with a factor 2, the realization of the frozen will occur 4-5 times faster. A general rule for pipe spacing is that the distance in between the different pipes should not exceed 13 times the pipe diameter. It is very important that after the installation, a thorough verification of the vertical (or horizontal, depending on the installed system) alignment occurs. This can be done with downhole inclinometers (or deflectometers for horizontal pipes). If this is not done and the alignment of the freezing pipes is not ideal, the constructed frozen earth wall will not have the ideal form. This increases the risk of ineffectiveness of the wall and potential failures. An example of possible deviations of boreholes is illustrated in Figure 3.

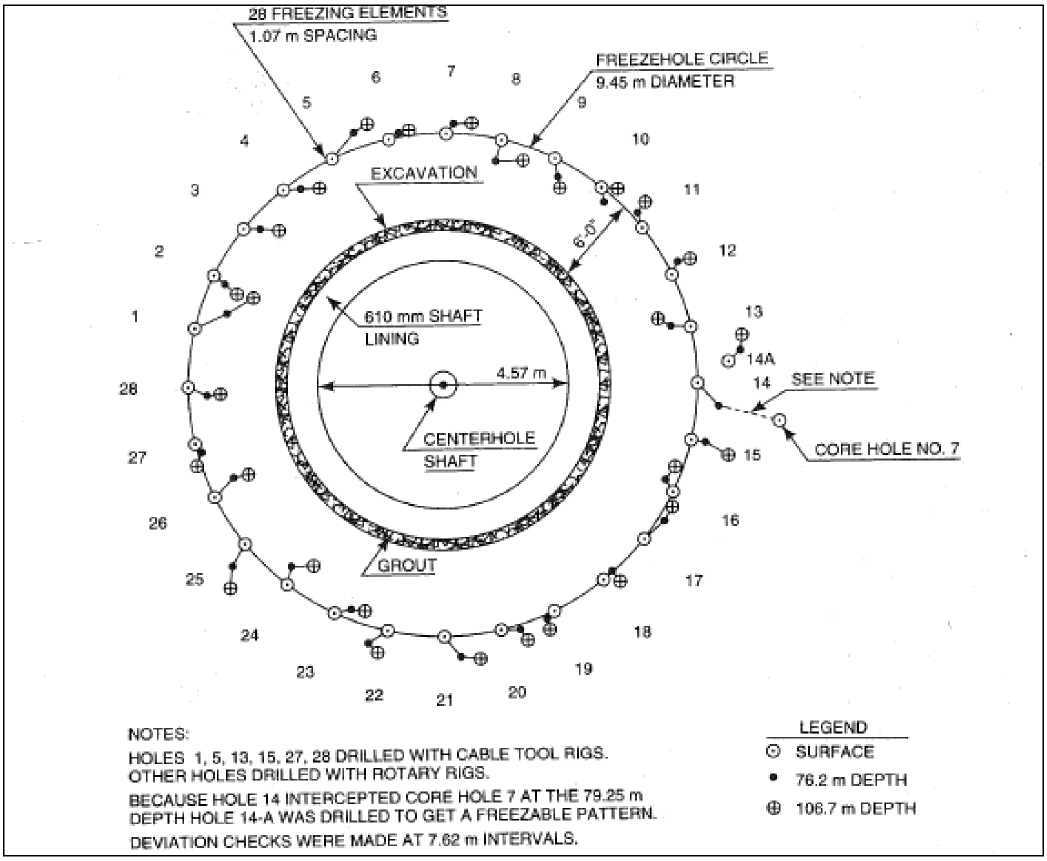

Figure 3; possible deviations in boreholes (after Andersland, B. and Ladanyi, B., (2005))

If one drills a borehole and then places the freezing pipe inside, it is obvious that there might be an annular void in between both pipes. This involves a non-optimal contact between the freezing pipe and the surrounding ground and thus a non-optimal heat transfer. If this condition is left uncorrected, it may lead to unexpected degradation of a part of the wall or even collapse. To overcome this problem, the void is filled by grouting techniques (e.g bentonite, sand-bentonite, cement-bentonite, plain cement, etc.).

The method of drilling the boreholes depends on the lithology of the subsoil. Rotary drilling is commonly used. Oil and saltwater based drilling techniques are not recommended because they may prevent soil freezing and/or reduce the strength of the soil. If the surrounding lithology is characterized by high porosity and permeability, loss of drilling fluid may occur. These fluids could affect in a later stadium the durability of the frozen ground structure and thus measures should be taken to prevent this. Remedial grouting is a frequently used measure.

4.2.3 Refrigeration plant and coolant distribution manifold

Refrigeration plants for ground freezing systems are low-temperature machines that should be able to achieve rapidly temperatures of -30°C to -40°C, even in warm, humid ambient air conditions. In order to freeze the ground, the suction capacity of the system at -30°C should be around 100-230 Watt per meter of freeze pipe. If a high head pressure, a low suction pressure or loss of hydraulic pressure in the pipes occurs, then the plant should be capable of shutting down automatically.

The coolant distribution system consists of a network of freezing pipes that are connected in parallel and series configuration. Each group of in series connected freeze pipes should usually not exceed about 50 m^2. of heat transfer in the ground. The freeze pipes consist of an inner pipe and a larger diameter outer pipe. The coolant flows through the inner pipe down and returns through the outer pipes to the surface. The difference in temperature between the supply and return temperature is measured with thermocouples and is called “the split”. The split varies with the number of pipes in the system; the more pipes, the larges the difference in temperature between in and out.

The presence of sufficient valves in the distribution system is also important. They have two functions. First type of valves are the manual valves. They are capable of shutting down a part of the coolant system for e.g. reparation, without the loss of coolant in the entire system or the need to shut down the remainder of the system. Second type of valves are the “air-bleed” valves. They are capable of releasing excess air from the system. Air can get trapped in the pipes by two processes. First of all air can get trapped during the startup phase of the system. Secondly, air can also escape from the solution itself. A brine solution contains quite some air. This is no problem during the startup phase, but when at a certain moment a temperature rise in the system occurs, the air escapes from the solution and forms airlocks in the system.

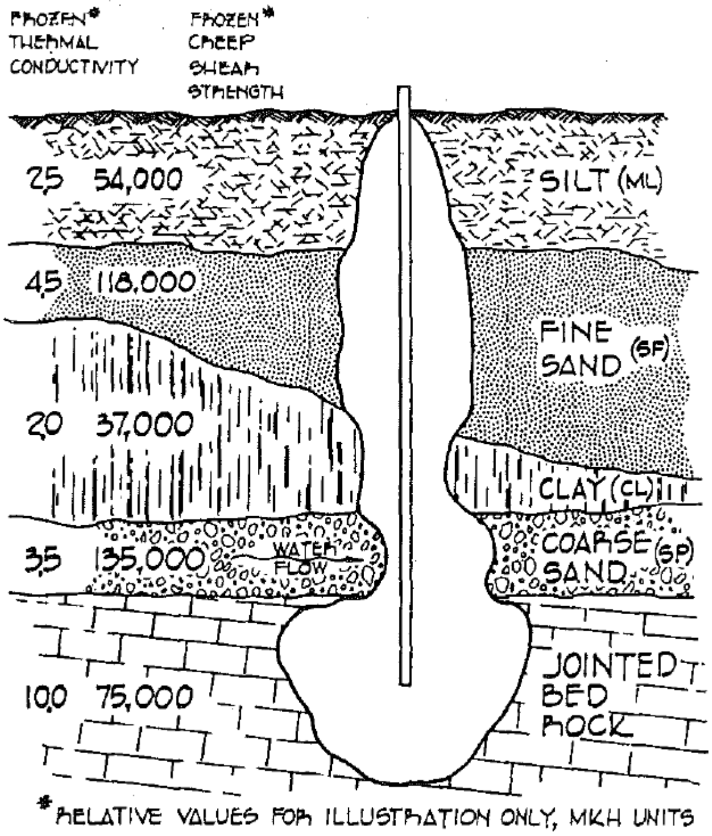

Figure 4; affect of soil on frozen body (after Andersland, B. and Ladanyi, B., (2005))

An important feature or vertical installed freezing pipes, as indicated in Figure 4, is the tapering of the frozen soil body towards the surface. This results in less stable or even absent frozen soil. Furthermore, close to the surface there is an increased impact of weathering effects and also heavy machinery is nearby. To overcome this problem and increase the streghts of the soil at the top, one usually installs a ring line system. This is a PVC hose buried ca 30 cm deep, completely around the perimeter of the area to be excavated immediately inside the freeze pipe perimeter (Figure 5). The coolant fluids circulate through this hose and form a strong, continuous body of frozen earth near the surface. In this way the "bottleneck effect" is completely eliminated.

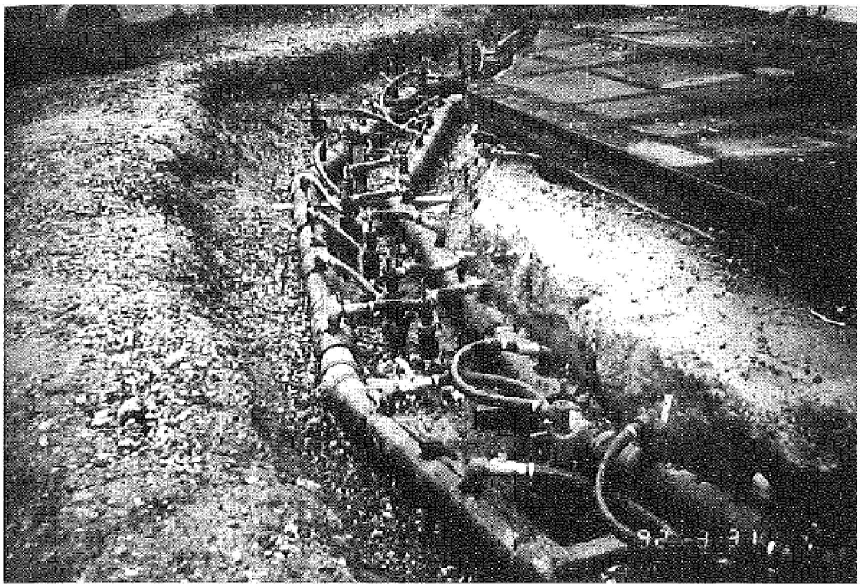

Figure 5

5 Design considerations

In this chapter we discuss different aspects which have influence on the design of ground freezing. First we consider the geometry of the freezing, followed by the influence of ground parameters and properties on the design.

5.1 *Geometry*

The choice to use freezing techniques is for the greater part determined by the complexity of the building pit. In milder climates freezing techniques are often used when soil conditions are poor and space for building activities is limited. In colder climates freezing techniques can also be used profitable for more common building activities. In milder climates the limitations of construction space (for example in a city centre) influence the possibility for a preferred geometry of the frozen soil body. Frozen soil has high compressive strength and a low tensile strength, this can be compared with the properties of concrete although not in magnitude. In the middle ages people already knew that by constructing arches the tensile stresses can be maintained at a low level. Therefore if possible the frozen soil body should be arched.

5.1.1 *Freezing as walls*

For frozen soil bodies the strongest solution is by the use of arching. When the conditions at site are not favorable to perform the freezing in a circular or elliptical way one can choose to make a straight wall. To be able to resist the tensile force the wall has to increase in its dimensions by 2 to 5 times. There is also a third possibility, the use of an anchor. Different construction types are shown in Figure 6. The constructions principle for anchors is the same as used in the construction of sheet piles. Experiences with this type of constructions in ground freezing tell us that the use of an anchored frozen soil body is very complex, and can not be used reliably in the field (Braun, Shuster, and Burnham 1979). Monitoring in these kinds of constructions is of great importance. The installation of the anchor is done by drilling a hole through the frozen soil body. The freezing pipes can be damaged in this way. It is also possible to install the anchors on before hand, but anchor depth is limited in this way. The anchor is a possible source for leakages in the wall. A small water flow through the wall can lead to bigger thawing areas and damage or even destroy it.

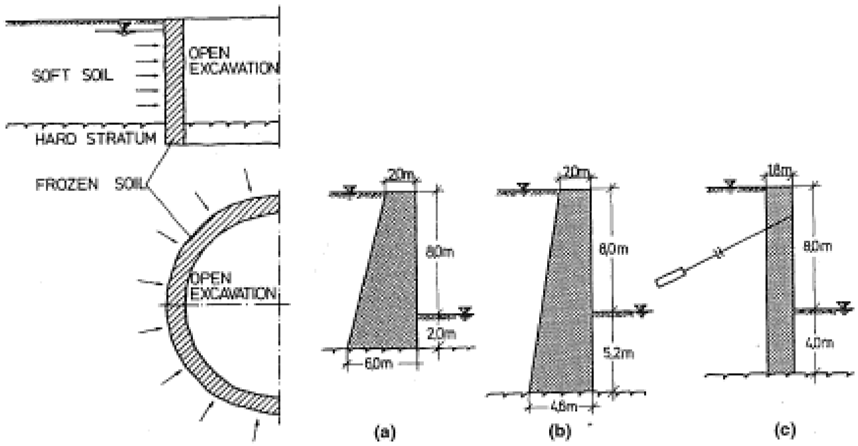

Figure 6; the principle of frozen soil bodies (Jessberger 1980)

5.1.2 Freezing in tunneling

There are multiple possibilities to use the aspects of ground freezing in tunneling. One can choose to perform the freezing for only a part of the tunnel for example as a shield covering the roof of the tunnel. Another possibility is to perform a complete freezing of the tunnel in a circular or elliptical way. A schematic drawing is shown in Figure 7. There is also the possibility to freeze the whole tunnel area, or more. This depends on the stability or the minimum settlements that are required for the design. This does increase the volume of frozen ground and is rather costly.

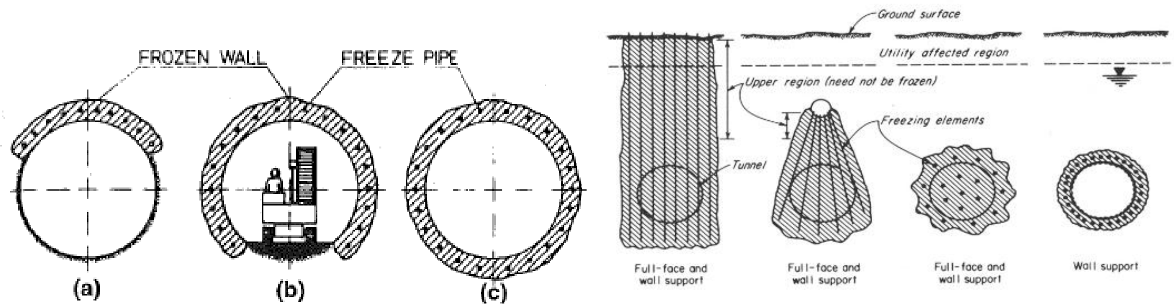

Figure 7; different methods to use freezing techniques in tunnelling (Jessberger 1980)

The drilling of the freezing pipes is performed from a start shaft. The drilling is somewhat outwards from the center of the tunnel. Lengths up to 60m can be frozen and constructed in one stage. In Theory lengths up to 110m should be possible with a steered drilling bit (Jessberger 1980). The frozen section can be dug out and a support can be made, when this is complete another section is frozen and the process is repeated. Because the freezing pipes diverge close attention is needed that at the end the frozen body is still solid and thick enough to support the soil. The principle of this method is shown in Figure 8.

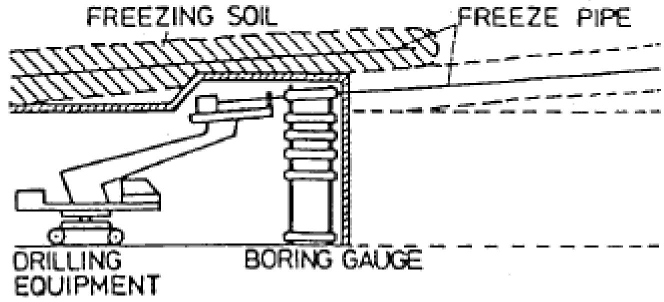

Figure 8; principle of frozen tunnel construction (Jessberger 1980)

5.1.3 Soil conditions

For a good design in ground freezing good soil parameters are essential. Other then with conventional underground construction the thermal conductivity of soil is of great importance. Also the strength parameters of the soil in frozen condition are important. With the frozen soil parameters the stability of the frozen soil body can be determined. To determine the stability of the frozen body we need to know the size of the frozen ground. The size of the frozen body can not be determined by measurements at sight, this is major difficulty. The prediction of the size of the soil body is depending on a variety of factors, which we will discuss in this chapter.

Thermal conductivity

The thermal conductivity can vary with a factor 4 or 5 between different soil layers. This leads to difference in the size of the frozen body. A high thermal conductivity means that heat (or cold) is easily transported through the medium. A very low thermal conductivity will lead to a small expansion of the frost front from the freezing pipe. At all depths the minimum thickness off the frozen body is required so the lowest thermal conductivity is leading in the design. The lower values of thermal conductivity are for clay or silt and high thermal conductivity for sands and rock. A schematic drawing of this principle is shown in **Error! Reference source not found.**. But also other factors can influence the thermal conductivity. As the pore water has contaminants in it or is saline it can affect the thermal conductivity and even cause the freezing temperature of the soil to drop below zero. In soils which are not completely saturated the moisture content will be of influence.

Groundwater flow

In aquifers the frozen soil body is affected by the groundwater flow. If the groundwater flow is too high it is possible that difficulties arise in closing the body between the freezing pipes. Additional measures can be taken to close the body. Like cooling the water down upstream, or using a different freezing technique. For liquid nitrogen freezing systems it is reported that flows up to 50m/d have been stopped (Shuster 1972). So freezing with high groundwater flow is possible but it takes a lot of effort, and additional measures. If groundwater is stopped or hindered by a frozen soil body it can cause a build up of water pressures. When there is a possibility that this happens these additional loads should be taken into account in the design.

Groundwater flow can cause the frozen body to shift along with the flow. The water will be warmer and cause thawing as water is a good thermal conductor. These problems also occur at the bottom of the frozen body. Ideal a water tight soil layer should seal the bottom, conventional problems like heave and up burst should still be taken into account. If the bottom is not sealed water can flow underneath the wall, transporting heat, and hereby cause thawing. The same yields for groundwater lowering by pumping. The pumping will increase the groundwater flow and hereby increase the transport of heath.

Groundwater contaminants

Fresh water has a freezing temperature of about 0 ^{o} Celsius. Contaminants or dissolved material can influence the freezing temperature. One of the most common dissolved materials is salt. The salinity of water influences the freezing temperature as well as the strength of the frozen ground, so the effect is double. A smaller soil body will be frozen, and the strength of it will be lower. Other substances will have other affects on the proceedings of the freezing and the strength of the frozen ground. To determine the strength of the frozen soil and the speed of the freezing often large scale in situ freezing tests are performed to determine the required parameters.

Ground temperature

In the time that there will be made use of ground freezing techniques it is likely that weather conditions will change due to season changing. In the first 6m of the soil this change is noticeable in the ground temperature. If freezing takes place in this upper layer of the soil one should be aware of this phenomena.

6 Temperature Monitoring/Ground Thermometry

The selection of the appropriate sensor and the design of a system for ground thermometry depends on the required accuracy and spatial distribution of temperatures and temperature gradients, on the needed frequency of readings, and on costs and budget. The fact that the installation and even the monitoring of some systems can alter the natural surface conditions and the ground temperatures should be considered in the selection and design of the system.

The accuracy of the measured temperatures can be quite high. Typical requirements for civil engineering work call for accuracies of 1° C to 0.1° C. Because the freezing point of pore water can be depressed by salts or soil minerals, a more accurate measurement is sometimes needed in the range of 0° C to 2° C.

Today an even greater accuracy can be achieved with specially calibrated systems. Off the shelf equipment can measure ground temperatures to accuracies of 0.1° C with all system and installation-caused errors accounted for.

The required spatial distribution of temperature readings depends on the purpose of the measurements, which can vary widely. The points of measurement can range from as simple as a single reading at the bottom of a boring to complex vertical and horizontal arrays for evaluating three-dimensional heat flow problems. Probably, the most commonly measured spatial distribution is the one-dimensional, vertical array. This kind of array is used to measure over time the vertical propagation of temperatures into the ground resulting from surface temperature variations. Figure 9 shows the seasonal variations in ground temperatures measured between the months, August to June (Esch 1994).

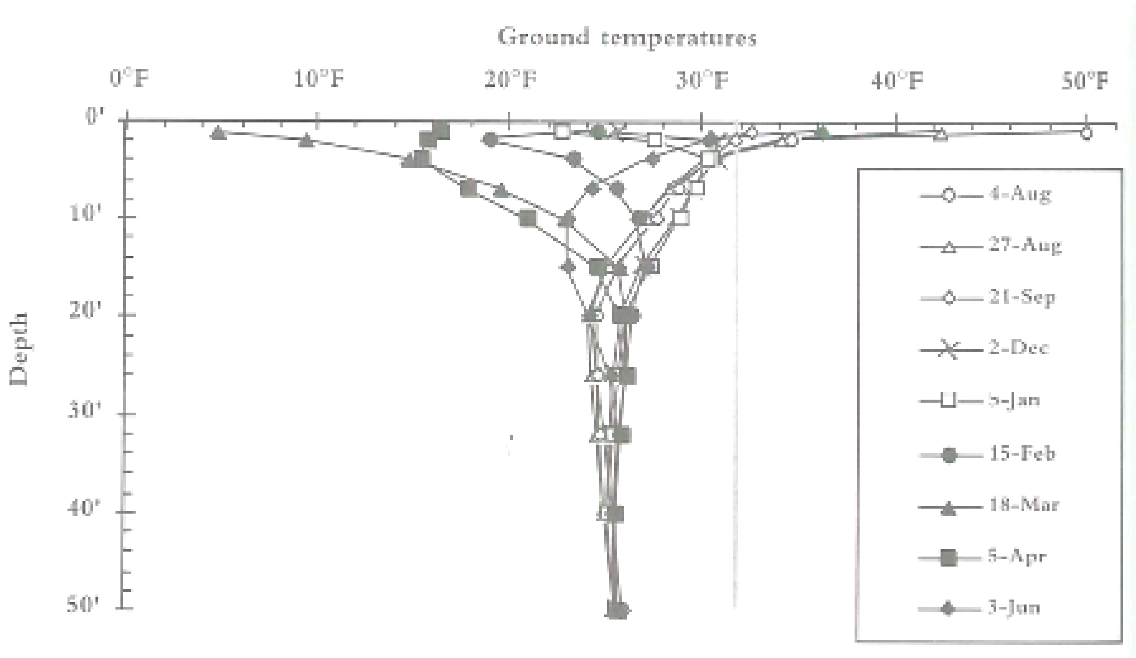

Figure 9 Seasonal ground temperatures

As it is observed, the amplitude of the conducted temperature waves is attenuated exponentially with depth. Consequently, the temperature curve can be defined with readings measured at increasingly greater spacings with depth.

The required frequency of readings also varies with the project. Remote investigations for routine foundation designs might allow only one set of readings to be obtained. Monitoring the thermal changes induced by construction or the near-surface temperatures that vary widely because of varying temperatures can require frequent periodic readings.

6.1 Thermometric time lag

As with any temperature measurement, the effect of thermometric time lag must be accounted for in determining the accuracy of ground thermometry system. Thermometric lag is the time required for the sensor to come to equilibrium with the natural temperature of the soil. The lag time results from the need for heat to flow to or away from the sensor to bring it to equilibrium with the surrounding soil.

For installations in the ground, thermometric time lag can be divided into two parts:

1. the time required for the sensor to respond to changes in the ground temperature, and
2. the time required for the thermal disturbance caused by the installation to dissipate.

The lag time of the sensor itself is usually only significant if the temperatures are measured by sounding (lowering the sensor in the ground) or if the temperature of the soil is rapidly changing (as when the samples are brought to the surface).

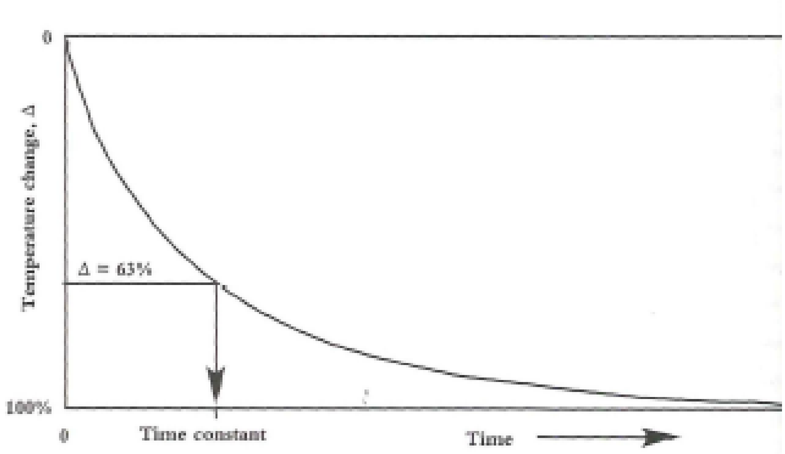

Figure 10 Thermometric time lag

The change from the natural temperature depends on the drilling factors and the soil types penetrated by the boring. The effect of these factors on the soil temperatures depends on the soil types and on the moisture content and thermal properties of the soil that the boring penetrates. If the soil is permeable so that the drilling fluid can penetrate outside the boring, the radius of the thermal disturbance can be greatly increased. Once the drilling is completed and the temperature monitoring system is in place, additional thermal disturbance can result from the surface water or ground water flowing down the hole from the type of backfill and its temperature.

6.2 Types of Sensors

The types of sensors that are used for ground thermometry vary between, glass thermometers, bimetal dial thermometers, frost tubes, linear resistance thermometers, thermocouples, and thermistors. The selection of the appropriate sensor depends on the desired accuracy, access to the point of measurement, stability over time, and planned frequency of readings.

6.3 Calibration

The accuracy of all these sensors should be checked by calibration. The manufacturer's calibration is usually relied on the accuracy since few laboratories have the facilities to calibrate the sensor over a broad range of temperatures. However, the accuracy or interchangeability given by the manufacturer can be lost by mishandling sensors during construction of the instruments or during field use.

6.4 Installations and Measurements

Soil temperatures can be obtained in a variety of ways using any of these sensors, but in general, the methods can be divided into two approaches:

1. Measurements made during the drilling, and
2. Measurements made after the disturbance from the installation has dissipated.

Regardless of the method used, the simple exercise of recording the depth of seasonal frost or thaw should always be made if the change is found during drilling. Temperatures taken during drilling can be fast and cheap, but their accuracy depends on avoiding or compensating for the drilling disturbance. Measurements made with permanent or semi permanent installations give the highest accuracy and permit long-term changes to be monitored, but are more expensive.

7 Changes in Ground Properties during the freezing process.

It is very important from an engineering point of view to analyze the properties of the ground during the freezing procedure. The basic two steps of the freezing method that affect the soil properties are presented schematically in the following picture:

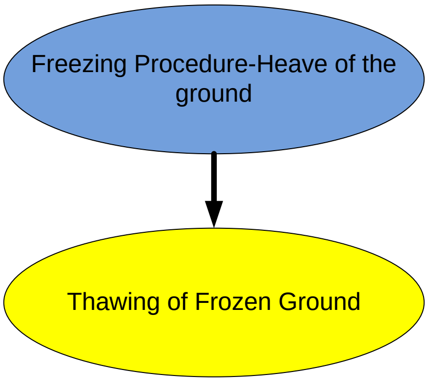

Figure 11 Ground behavior during the freezing process.

In this chapter, the changes in the properties of the ground that effect engineering works will be discussed thoroughly. Ground freezing technique has a wide use for a soil improvement technique but sometimes causes many problems to the surrounding existing works. The effect of the process to the design and construction of the work or its environment is a result of the soil behavior during the two above mentioned phases.

7.1 *Freezing Process-Heave of the Ground*

7.1.1 *Volume Change-Frost Heave Forces*

During the freezing process, water contained in the voids of moist or saturated sand and gravels freezes in situ when the temperature is lowered below the freezing point. The freezing is associated with volume expansion of the water about 9+%. This expansion does not necessarily lead to a 9+% increase in the voids of a saturated sand or gravel, because part of the water may be expelled during freezing (Andersland and Ladanyi 2004).
On the other hand, for a saturated silt or silty sand, the effects of freezing depend on the rate at which the temperature is lowered. Rapid cooling of a saturated specimen in the laboratory causes the water to freeze in situ. If the temperature is lowered gradually, a large part of the frozen water accumulates in the form of layers of clear ice oriented parallel to the surface

exposed to the freezing temperature. As a consequence, the frozen silt or silty sand consists of a series of layers of frozen soil separated from each other by layers of clear ice (Harris 1995). During this process, frost-heave forces are acting to the ground. Foundations embedded in frost-susceptible soils can be subjected to large uplift forces resulting from frost heaving of the soils (Figure 12).

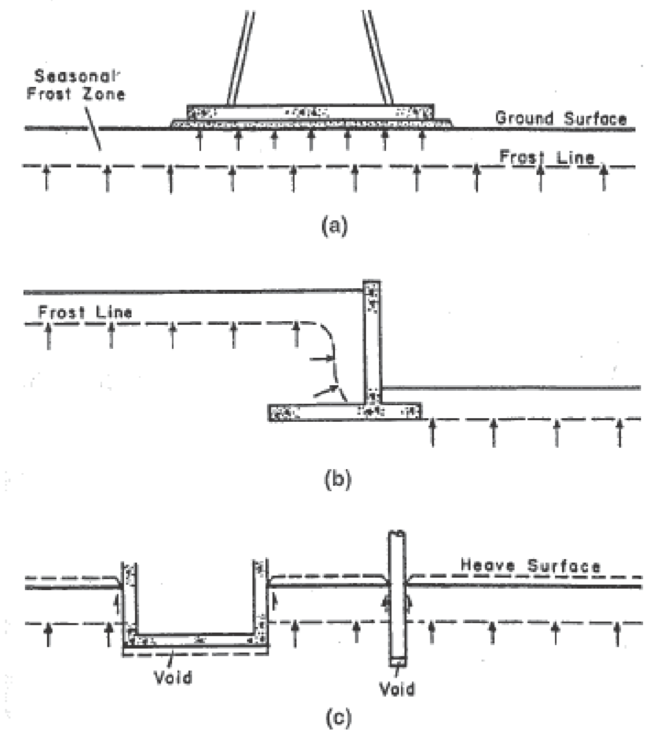

Figure 12 Frost heave effects on structures. (a) upward thrust on the foundation underside; (b) lateral thrust behind walls; (c) adfreeze and uplift on the sides of a foundation (Linell and Lobacz 1990).

It is difficult to predict the magnitude of these mobilized heave forces because of the many variables involved. These variables include soil type and heterogeneity, rate of freezing, soil temperature with dept, availability of water, foundation surface type, overburden pressure and foundation loads. Observations based on the weight of buildings known to have been lifted by frost-heaving soil indicate forces approaching 760 kPa (Andersland and Ladanyi 2004).

7.1.2 Compression Strength of Frozen Ground

After the freezing process, the frozen ground has significantly greater strength than the previous condition. This strength involves a combination of frictional resistance and interface between soil particles, a dilatancy component, and interaction between the ice matrix and the soil skeleton. Stress-strain curves for a frozen quartz (Ottawa) sand and frozen (Sault Ste.

Marie) clay illustrate comparative compression strengths for two soil types at -12.0° (Figure 13).

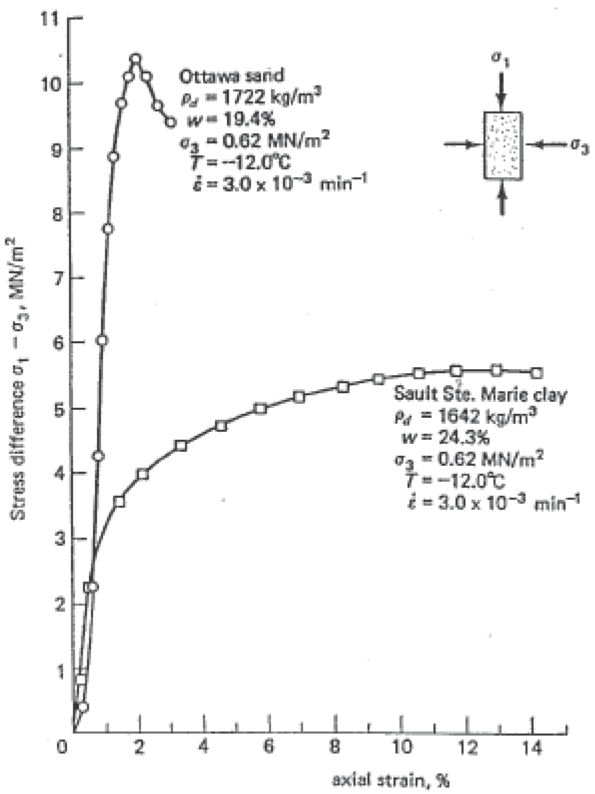

Figure 13 Stress-train curves for compression tests on frozen Ottawa sand and Sault Ste. Marie clay (Al-Naouri 1969).

The clay, with smaller particles and more surface area, has longer unfrozen water content. It displays a more plastic behaviour in comparison with the more brittle sand with essentially no unfrozen water. The frozen sand seems to have compression strength close to that of a weak Portland cement concrete. Strength comparisons with the same soil material in the unfrozen condition are very significant. Frozen sand with the same confinement has strength close to 8.5 times greater than that of the confined unfrozen sand (Andersland and Ladanyi 2004). High strength will increase bearing capacity as required for foundations placed on frozen soil materials.

7.1.3 Shear Behavior

To determine the shear behavior of frozen soils is a complex procedure. As in unfrozen soils, the concept of failure includes both rupture and extensive deformations. Depending on soil type, temperature, strain rate, and confining pressure, the mode of failure may vary from brittle, similar to that in a weak rock, through brittle-plastic, with formation of a single failure plane or several slip planes, to purely plastic failure without any visible strain discontinuities (Andersland and Ladanyi 2004). The behavior of frozen sands, for example, is controlled essentially by the following four physical mechanisms: (1) pore ice strength; (2) soil strength; (3) increase in the effective stress due to the adhesive ice bonds resisting dilation during shear of a dense soil; and (4) synergistic strengthening effects between the soil and ice matrix preventing the collapse of the soil skeleton (Ting et all 1983). Extensive lab tests are needed to access the strength parameters of the frozen soil specimens, if it is necessary for the construction progress.

7.1.4 Permeability

In coarse grain soil like sand and gravel mixtures the permeability in frozen condition will approach zero. For large excavations, this reduced permeability can remove the need of dewatering system when the frozen earth support system extends down into an impermeable soil layer. For groundwater remediation projects, a subsurface frozen soil wall can provide a temporary impermeable barrier around and under the contaminated site (Andersland and Ladanyi 2004). The imperviousness of frozen soil can remove the need for pumping, greatly reducing the cost.

7.2 Thawing of Frozen Ground

7.2.1 Variation in the Strength of the soil- Thaw Settlements

During the thawing process all the ice in the soil profile will disappear and the soil skeleton must adapt itself to the new equilibrium void ratio. The amount of water resulting from ice melting may exceed the absorption capacity of the soil skeleton. Until drainage is completed, excess pore pressures may develop temporarily in fine-grained soils with low permabilities. If thawing occurs fast enough, frozen ground may be liquefied and become unable to support any significant load. Volume change will result from both the phase change and flow of excess water out of the soil.

Moreover, the melting of ice will lead to a thaw-settlement phenomenon, which is very important for the construction on or in the frozen soils.

7.2.2 Freeze-Thaw Effects on Permeability

Repeated freezing and thawing of clayey soils will produce an increase in the effective void ratio and finally an increase in vertical hydraulic conductivity (Harris 1995).

8 Ground Freezing Failutes Causes and Preventions

Firstly, it should be defined failure as a term . It is known that the rick of failure is inherent in relatively unknown and unpredictable works as the underground space is. Because of this it is inappropriate to call failure to something that was predicted since the beginning. If the problem is anticipated, the risk evaluated and the cost as well as the remedial work considered, then it is not a really failure. Since, it was taken into account from the beginning and it is known how it can be figured out. (J .A. Shuster. GEOFREEZE Incorporated, Lorton, Va., USA**).**

8.1 Structural Considerations

Saturated frozen ground (FG) redistributes the high stresses due to its creep behavior provided by the inter-granular ice. The ice is the main issue that determines the plasticity of the structure, so the temperature. High plasticity implies more creep, therefore high stresses are better redistributed. However, if it creeps too much, it can cause rupture in the refrigeration pipes, particularly in the interfaces. The geology is the second main issue that affects.
Sloughing and deterioration of the exposed surfaced should be. Insufficient refrigeration of the FG, poor thermal contact between the refrigeration pipe and the surrounding area (hole diameter larger than pipe diameter), instability in unsaturated soils above the groundwater table, uncovered, exposed and vertical excavations exposed to the weather and excessive refrigeration load.
To avoid the warming of the FG for insufficient refrigeration, just increase the refrigeration load or the insulation required. Regarding to the excessively large hole diameter, the solution is harder. Because once the hole is done it is difficult to adjust. So, it should be control during the drilling. For the unsaturated soils and the uncovered, exposed vertical excavations the surface should be covered with a reflective, waterproof material, in order to avoid the sublimation in the unsaturated soil and to protect from the weather in the exposed excavation.

8.2 Groundwater Considerations

The great majority of all the problems associated with GF system has been caused by groundwater table. There are three relevant points to check about underground water, quality (composition), quantity (it has to be enough) and possible movements (lateral or vertical). Regarding to the quality the salinity is important because it can vary largely the freezing point depression. In seawater environments the effective practical freezing point may be taken as -2 degrees, and for clayed could be soils as -10 degrees. Therefore, the effective freezing point of the soil/water systems to be frozen should be determined previously, as well as the mechanical properties of the soils once they got frozen. In addition the GWT quality may be decrease due to hydrocarbons contaminants. Where there is a shallow groundwater table a petroleum layer may float on it. This upper layer created has no apparent strength and sloughs or flows away from the other competent frozen material. The contaminated soils are not strengthened by freezing at any reasonable temperature. It can be much worse if the contaminant is heavy oil instead of petroleum . Secondly there is the quantity of groundwater in the soil, because it needs to be enough. It is considered that at least is needed a 10% saturated soil. Because as less water, as more refrigeration load needed. That increases costs and makes the work harder. Third and final is the movement of water (vertical or horizontal), which supplies energy at a rate greater than the refrigeration plant can remove. When the movement occurs after the initial frozen, problems as aggravation to piping, ground loss and flooding can occur. Groundwater problems are common due to the difficulty to predict its movement; there are a lot of uncertainties. However, a good field exploration may reduce the risk perceptibly.

8.3 Ground movement considerations

We are concerned with frost-heave or thaw-consolidation related movements rather than the previously discussed creep movements for the frozen structure as a result of applied loads. Though most of ground movement is predictable with the actual knowledge, the models are so complex, there are always uncertainties and it can occur something not predicted. The reported movements at the moment are in a range of 5-10cm. However, when organic silts have been frozen or when confined soils were frozen without provisions for pressure generated by the change of volume associated to the conversion from water to ice, the movement can be much higher. Despite our ability to reliably predict frost related ground movements, it seems that the occurrence of this problem is not a major problem. This is probably, because AGF has not been employed to sensitive structures founded on frost susceptible soils.

8.4 Construction considerations

Refrigeration pipes:

The number of piper needed will turn out to be higher than the number anticipated, as well as the depth. This is because we always try to reduce to the absolute minimum the drilling and the costs. Relative spacing (pipe spacing / pipe diameter) ratio is a major element in determining the rate at which freezing occurs and the rate of temperature in the structure. Refrigeration capacity has to be controlled. In many cases, due to the high costs and the sophisticate equipment needed, there is insufficient capacity to handle the added heat gained from warm humid ambient. This makes that extra refrigeration pipes were needed, increasing costs and load on the ground. So, it is better to consider them properly since the beginning.

Coolant loss:

The accidental lost of it causes several delays in the works. If there is an small leakage, it is harder to detect and it can cause bigger problems. However, if it is a big lost it should be detected fast. Nowadays the equipment has pressure detectors that indicate if there is any coolant lost.

Premature excavation:

It should be waited to the end of the frozen period. After the intense period of activity during which the AGF system is installed, there is a period of several weeks during which there is very little activity while the ground freezes and the constructors try to reduce it. But it is really important to wait, otherwise you will have to refreezing and re-excavating.

Geotechnical Data:

As we mentioned before the major problem for FG is the groundwater. And the better way to define its gradient and its movement is with large field data. Besides, it is well-known the heterogeneities that the geology uses to present. Good field data are needed again. Therefore, despite the long time required for it., it should be collected as much field data as possible.

9 Case studies

In this chapter we present a number of case studies in which freezing techniques have been used.

9.1 MOL No.2 Freeze shaft (Belgium)

The shaft was sunk between 1980 and 1984 to provide access to an underground laboratory for testing the feasibility of storing radioactive waste material in the Boom Clay bed. The freezing method was successfully used to sink through the clay bed and an underground laboratory was constructed. It was developed to a depth of 167m ., the ground consists of loose, auriferous quaternary sands. The Eigenbilzen sand is in the top and dry Boom Clay bed of around 100 meters beneath, over consolidated clay material only bearing pore water.

Shaft data:

The shaft was designed with 3m inside diameter and 213.5m depth. Two insets were driven above the bottom of the shaft at a depth of 222.45m , in order to connect it in a future with a horizontal gallery from the northern inset. The foundation of this shaft was arranged in a depth of 199.7m. For sinking No.1 shaft the freezing method was used in the loose quaternary sands as well as in the firm Boom Clay form. Having in mind that in the underground laboratory drivage has been done successfully without freezing, it was decided to freeze at Mol No.2 shaft only to loose and water-bearing quaternary sands and a part of the transition zone. It is decided to sink the Boom clay formation itself without freezing.

Freezing:

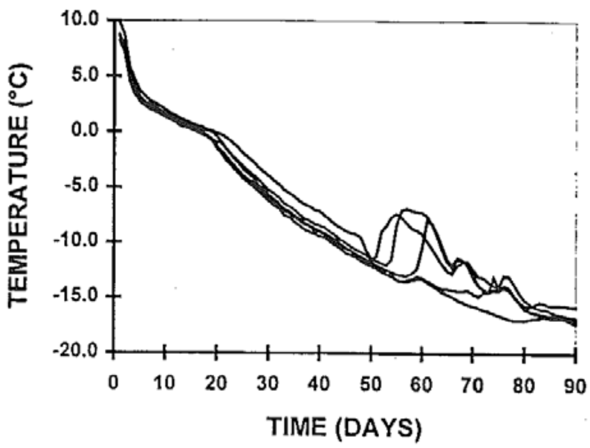

Figure 14; Influence of heat of hydration from shotcrete lining on the inner temperature monitoring pipe (Ground Freezing; Edited by Jean-Francois Thiums)

There were drilled 16 refrigeration holes on a refrigeration circle of 7m diameter to 194m, just below the base of the sand beds, 5m into the tra nsition zone. Fresh water with additives was used as flushing fluid. No directional dril ling techniques were applied. The holes were preliminary lined with PVC-pipes. Two outer holes were drilled inside the shaft perimeter. Two freeze plants were installed to provi de a capacity of 2x250kW or 440000 kcal/h at temperatures down to -33ºC.

Mohr-Coulomb calculations were developed concer ning the stress and strain behavior of the frozen ground into consideration. T he interaction between the different evaluation steps was done using the specific line m ethod. The progre ss of the form ation of the freeze wall was carefully monitored by autom atically recorded temperature data. Figure 14 Taking into account the sinking velo city, the evaluations reg arding stress-strain of the freeze wall were fitted to th e increase of fr eeze wall thickne ss with tim e. Where necessary the primary shotcrete lining which works tog ether with the freeze wall as a com posite system was modified. Figure 15

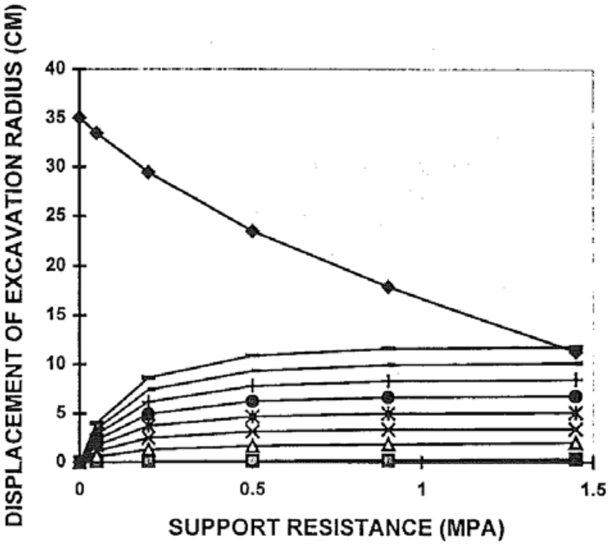

Figure 15; Specific Lines of frozen transition zones and shotcrete lining (variation from rigid lining plates to a yielding lining with 7 Heraklith plates per shotcrete segement) Ground Freezing edited by Jean-Francois Thiums

Sinking through the unfrozen boom clay:

After completing the works in the frozen shaft, deepening through the unfrozen clay bed was undertaken, excavation was undertaken carefully in order to avoid problem s with weak clay and support was done by yielding rings. Two adits were driven above the bottom of the shaft, southwards for 7m and north wards for 6 m from the shaft center line. The north adit is to be connected with the base of shaft 1 and to provide access to the testing laboratory.

9.2 ***Thermal Analysis of Artificial Ground Freezing at the McArthur River Uranium Mine***

The McArthur River uranium mine is located in the Athabasca sandstone region in the northern part of the province of Saskatchewan, Canada. It is the world's largest, high-grade uranium deposit with proven and probable reserves of more than 473 million pounds U_3O_8. It is majority owned and operated by the Cameco Corporation. This case study is about the artificial freezing of an underground ore body at the mine to it prior being mined. The ore body itself is located 550 meters to 620 meters underground where the groundwater pressure is approximately 5500 kPa. Due to the presence of a hanging wall fault structure, the ore body is surrounded on three sides by fairly dry, competent ground. The other three sides are comprised of highly fractured sandstone with significant amounts of rumble, flowing sand and clay regions. In order to mine the ore, it was necessary to create a frozen wall barrier around the three poor sides of the ore body. The frozen wall barrier was designed to permit drainage of water in the ore and consequently reduce water pressures prior to mining. The wall was also required to provide structural support of weak, clay/ore ground near to mining cavities. In Figure 16 a cross-section of the ore body and neighbouring geology is shown.

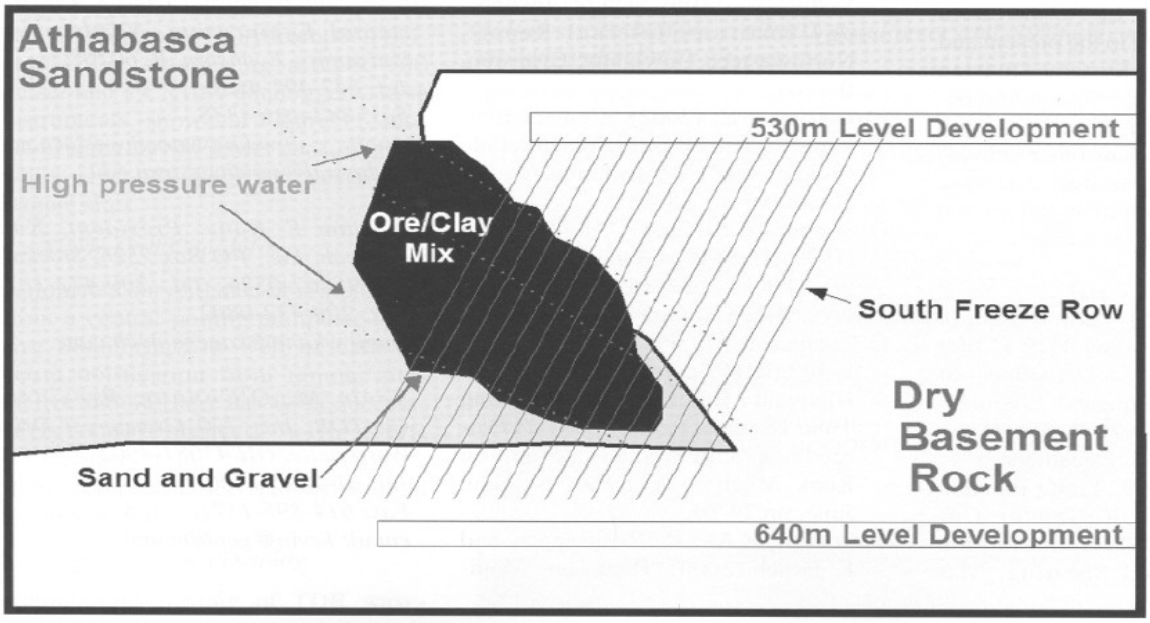

Figure 16; Cross-section of the ore body and neighbouring geology (after Newman and Maishman 2000)

A mechanical freezing system is comprised of a brine cooling and distribution network plus a series of brine freeze pipes installed in the ground to be frozen. Typical ground freezing applications have involved drilling freeze holes from surface or near surface and these activities have been well documented. In addition, the brine cooling and distribution network has typically included an ammonia compressor with ammonia to brine heat exchangers. The process of installing a "typical" freezing system at McArthur River was made more difficult due to the location of the freeze pipe chamber underground. The freezing chamber is located 530 meters below ground, which means that the brine pressures within the freeze pipes and associated brine distribution network would equal 5000 kPa if connected directly to the surface refrigeration plant. This is not practical from a design or operations perspective. In order to minimize the brine fluid pressures, the underground brine distribution system was isolated from the surface brine system using shell and tube brine-brine heat exchangers.

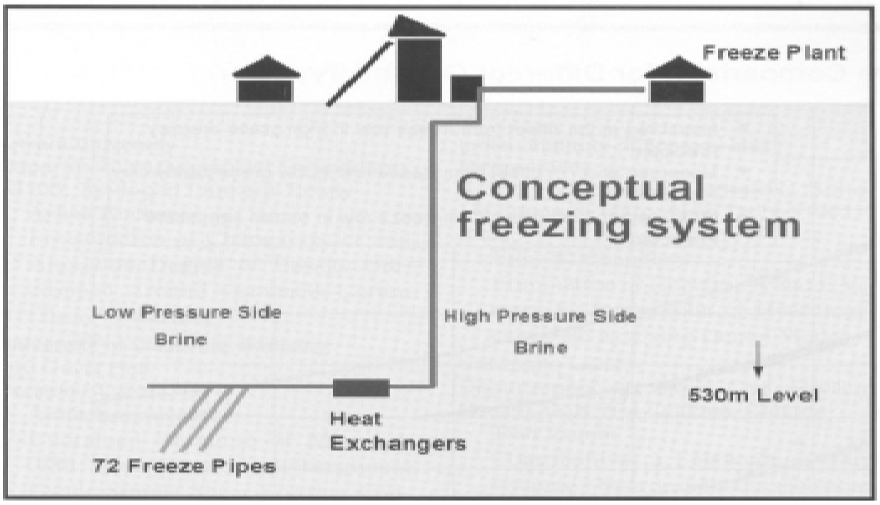

Figure 17; Illustration of the high and low pressure brine distribution networks (after Newamn and Maishman, 2000)

The illustration in Figure 17 shows the relative position of the 800 Ton refrigeration capacity freeze plant on surface, the 12"ID brine supply and return lines installed in the shaft, and one of four shell and tube heat exchangers on the 530 m level. The low-pressure brine network on the 530 m level operates within a 150 kPa to 600 kPa pressure range at flow rates ranging between 130 m^3/hr and 550 m^3/hr. The design brine temperature was -40 degrees Celsius. In order to determine the actual growth of the freeze wall it was necessary to install thermocouple strings at several locations around the freezing region. The thermocouples were lowered into a cased hole containing a fine grout mix prior to the grout setting. Each string was comprised of twelve sensors located at five-meter intervals down any given temperature monitoring hole. This enabled the temperature decay to be monitored offset from the freeze pipes in various types of ground (see Figure 16 for comparison of ground types). Ground temperatures were recorded every second day.

9.3 *Large scale application of large scale soil freezing*

By

van Dijk, P. and Bouwmeester-van den Bos, J.

Introduction

In 2000 the Central Artery/Tunnel project in Boston was with it s 13 years construction tim e (ending in 2004) and estimated total cost of $ 12,2 billion the largest infrastructure project in the USA. The goal of t he project was to repl ace Boston's central hi ghway system, running through the central part of the city, with an underground expressw ay in order to increase the traffic capacity. A major element was the rebuilding of the interchange fo r Insterstate Routes I-90 and I-93 and included the extension of the existing I-90 under an existing railway track system leading to the Boston's South station. The project required the installation of 3 jacked tunnels under the ex isting rail track network: I-90 Eastbound (EB), I-90 W estbound (WB) and an exit ramp for I-90 WB, referred to as ramp D (Figure 18). Large scale ground freezing was used as a soil stabilization method.

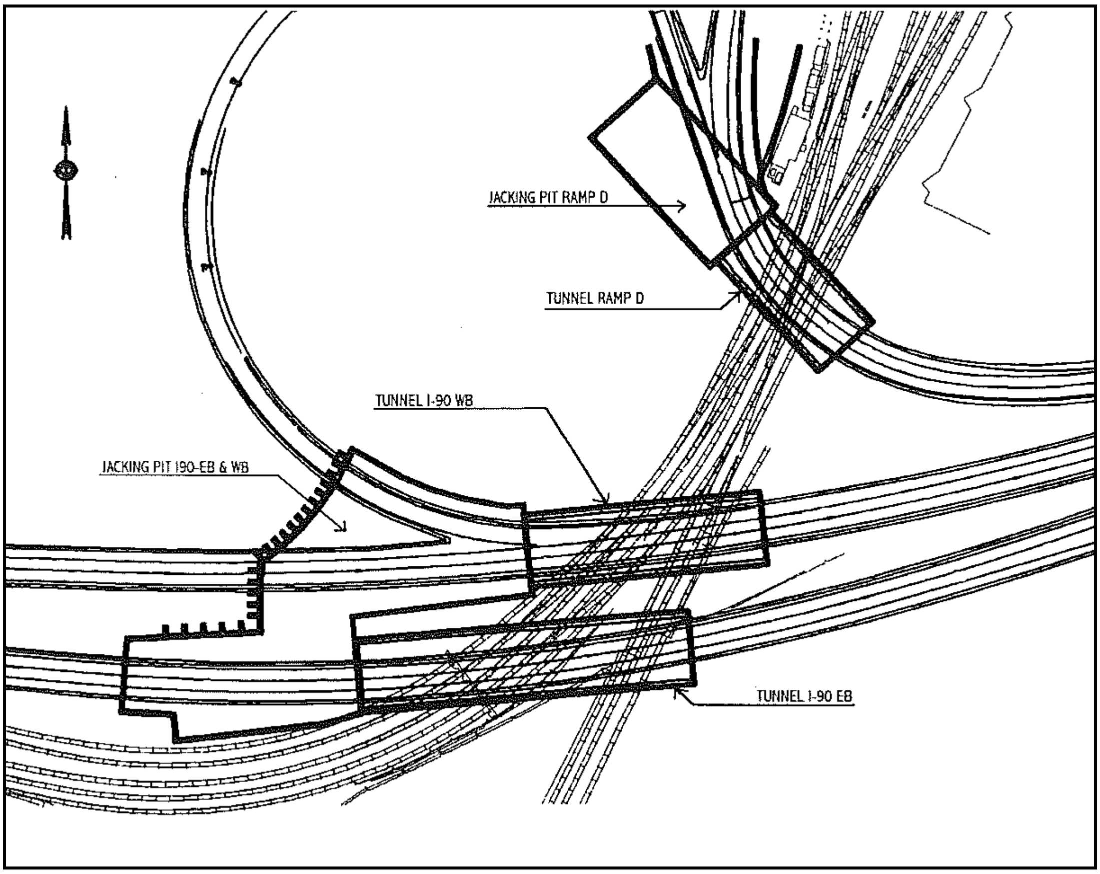

Figure 18; Site layout with location of jacking pits and tunnels (van Dijk, P & Bouwmesster van den Bos, J 2000)

Site's subsurface conditions

The first 6-8m of the site 's geological profile consisted of miscellaneous fill material with possible large obstructions (cobbles, boulders, concrete fragments, steel, wood, bricks and granite blocks and abandoned, depressed track way). Groundwater levels were situated at -2m to -3m. Below, there were continuous, 3-5m thick, organic deposits which consisted of organic silt with fine sand a nd some peat. Underneath these extensive deposits, there were locally lenses of relatively dense sand and inorganic silt. Th eir thickness never exceeded 1,5m. Below, there were thick deposits of m arine clay mixed with silt. The f irst 5m of this marine clay layer was signifi cant stronger and less com pressible compared to the lower sections.

Tunnel Jacking Method

The tunnel construction method was chosen in function of the fact that the railroad operations on top could not be interrupted. Finally, one chose to construct each tunnel section as a series of full cross-section, reinforced concrete boxes and jacking them into place (Rice et al., 1999) (Figure 19). This technique can be used in so ft grounds for relatively short tunnel sections (here: 50-100m) and can be applied underneath surface areas with critical uses, without disrupting them.

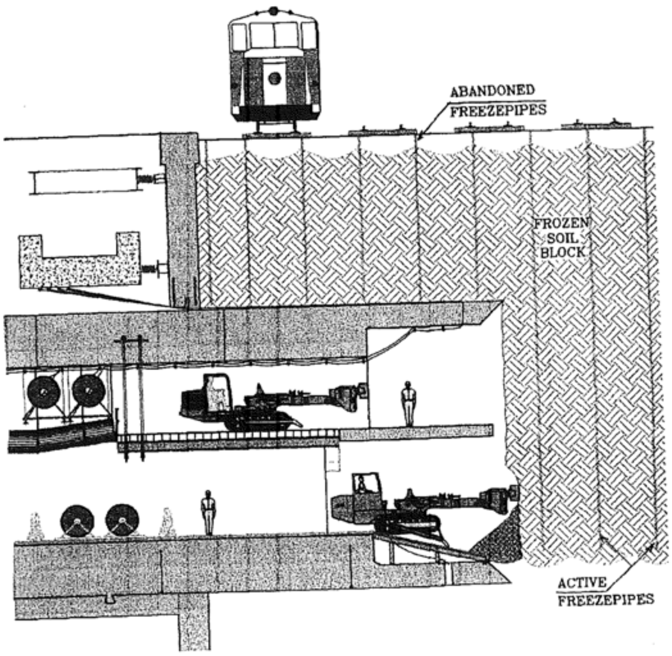

Figure 19; Vertica section of tunnel during the tunneling operation (van Dijk, P & Bouwmeester-van den Bos, J 2000)

Selection of the soil freezing method

When applying this method it is important to control the loss of ground into the face during tunnel installation. Here, one first intended to stabilize the soft soils to be encountered by using a combination of chemical grouting and dewatering the fill materials, horizontal jet grouting in the organic deposits and soil nailing in the marine clay. However, the contractor proposed to replace this combination of ground treatment methods by soil freezing. Eventually, it turned out that ground freezing had several advantages, including complete treatment of the soil mass prior to the start of tunneling, improved face stability and encapsulation of obstructions and a lower risk of ground losses.

Designing aspects of the soil freezing

- *System requirements*

The soil freezing in this project was used to freeze the soil around the tunnel, but also to ensure a stable excavation face during the tunnel jacking (Deming et al., 2000). Therefore, the complete soil mass in the footprint of the future tunnel location of the tunnel was frozen. There were two parts: a ground water cut-off at the edges of the freeze mass and the central part of the mass. Two sides of the future location of the tunnel already had a groundwater cut-off. The first one was the headwall of the jacking pit and the other end was located in an area of improved soil, that was made as part of an adjacent contract. In between, groundwater cut-off wals needed to be designed. These cut-off wals were constructed by installing one perimeter row of freeze pipes at a smaller distance than the freeze pipes in the central area. A closer spacing results in a more rapid closure. Once the outer walls were frozen, water flow from the outside to the inner part was not possible anymore. In this inner part, the spacing of the freezing pipes was larger. The freeze mass had to be larger than the cross-section of the tunnel. The cut-off walls, located at the side of the tunnel, were ± 2m thick. The frozen soil did not reach the surface because the ballast underneath the railway network needed to remain unfrozen in order to allow track maintenance at any time. The freeze mass also did not reach the bottom of the tunnel. This ensured that no thaw settlement occured because the bottom was all the time in unfrozen soil.

- *Freezing method*

For this project, brine freezing was used. The freeze plant, with three to four freezing units, cooled the brine to -25 to -27°C. Each tunnel had an independent freezing circuit. This guaranteed an independent freezing process for each tunnel. Each circuit consisted of a header supply pipe, connected to different freeze sub-circuits. A freeze sub-circuit consisted of 4 to 7 freeze pipes. After 4-7 times passing through the freeze pipes, the brine returned to the freezing plant to be cooled again.

- *Freeze mass design*

The ground froze radially from outside of each freeze pipe. The freeze speed is dependent on the soil characteristics and the pipe spacing. Soil characteristics are fixed, but spacing can be adjusted. The selected pipe spacing is a trade of between the available time for freezing and the cost for installation. There was less time available for ramp D. This resulted in a spacing of 2,1m. For the EB and WB tunnels, spacing was 2,4m . These different spacings resulted evidently in a different freezing time. For ramp D this was approximately 3 months, for the EB and WB tunnels approximately 4 months.

Execution aspects of soil freezing

- *Installation of ground freezing systems*

The designed grid of planned freezing pipes interfered in many locations with obstacles: rails, switches, timber rail ties and other infrastructure. In cooperation with the Railroad, adjustments were made in order to avoid these areas and areas that would be disturbed by ballast tamping required for track maintenance. This resulted in locating the pipes along the centerline of track and outside the edges of the timber ties. At some places, pipe spacing became too big and additional freeze pipes needed to be installed in order to maintain the required overall energy removal capacity.

Because excavation in the heavily used track structure was not feasible and there was a big risk of encountering obstructions and buried railroad utilities when using pipe jacking, the header pipes were installed at the surface between the ties. An advantage was that they were visible for maintenance crews and this reduced chances of damaging them significantly.

Another problem was choosing the right drilling method. Conventional drilling equipment would require unacceptable amounts of track outage time and lead to extensive provisions to contain the drilling fluids. Finally, one chose for the sonic drilling method. This is a vibratory drilling system where the entire drill string is vibrated at a frequency range of 50-150 Hz. This is a dry drilling process which allows to fracture obstructions and displace loose fill and clay. The drill was mounted on a raised rotating platform on a rig equipped with rail track wheels. With this arrangement, pipes could be drilled within tie footprint and for some distance beyond.

In total, 1740 freezing pipes were installed. Drilling took place during nights and weekend. Most of the track area was available from 9 PM to 5 AM, but the center of the track network was only available between 2 AM and 5 AM. On average, 3 freezing pipes were installed each day.

- *Freezing process*

The construction schedule resulted in a separate freeze for ramp D, followed by the EB freeze and the WB freeze taking place concurrently. After six weeks of freezing for ramp D, leaks started to occur in the freeze pipes. It turned out that the threads in the screw joints could not stand the extra loads and they failed. This required a total shutdown of the system and replacement of all the threads. Six weeks after the restart, a leak in the cooling system caused an ammonia release and another total shutdown for 2 weeks. After the completion of the soil freezing, soil temperatures were in the range of -8 to -22°C, depending on the total freezing duration in a particular area. This was well within the specified design (-10°C).
A large number of temperature sensors were located in the freeze masses, at different depths, in order to monitor the temperature development in function of time (Lacy et al., 1999). The effect of the interruptions in the freeze on the temperatures, for pipe DT-129-10 in the ramp D area, can be clearly distinguished in the graph : interruptions occurred after approximately 40 and 135 days (Figure 20).

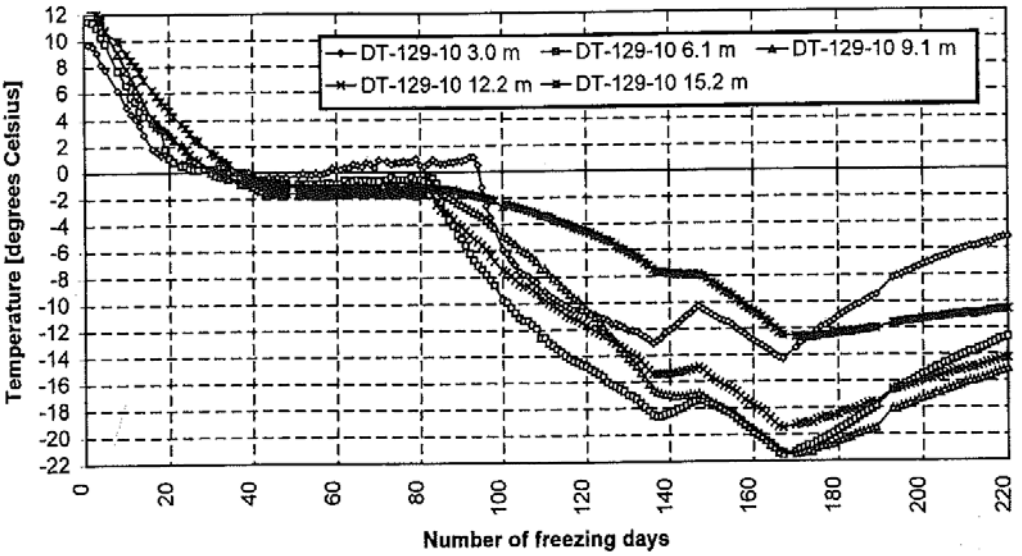

Figure 20; Soil temperature develpment in location 129-10 in the ramp D area (van Dijk, P & Bouwmeester-van den Bos, J 2000)

- *Development of track heave*

If the heave due to the soil freezing were to exceed 180 mm, the railroad operations could be seriously affected. Heave in the center part of each freeze block was estimated between 90 mm at the WB tunnel and 130 mm at ramp D. Initially the heave matched the predictions, but after the several interruptions at the ram p D site, heave reached, for still unknown reasons, approximately 210 mm in a sm all area (Figure 21) . An extensive daily survey program was executed to monitor rail alignm ent and profiles (Peterson et al., 2000). The results were used to take measures (e.g. temporarily shut down of freeze circuits) in order to limit the impact on the track structure.

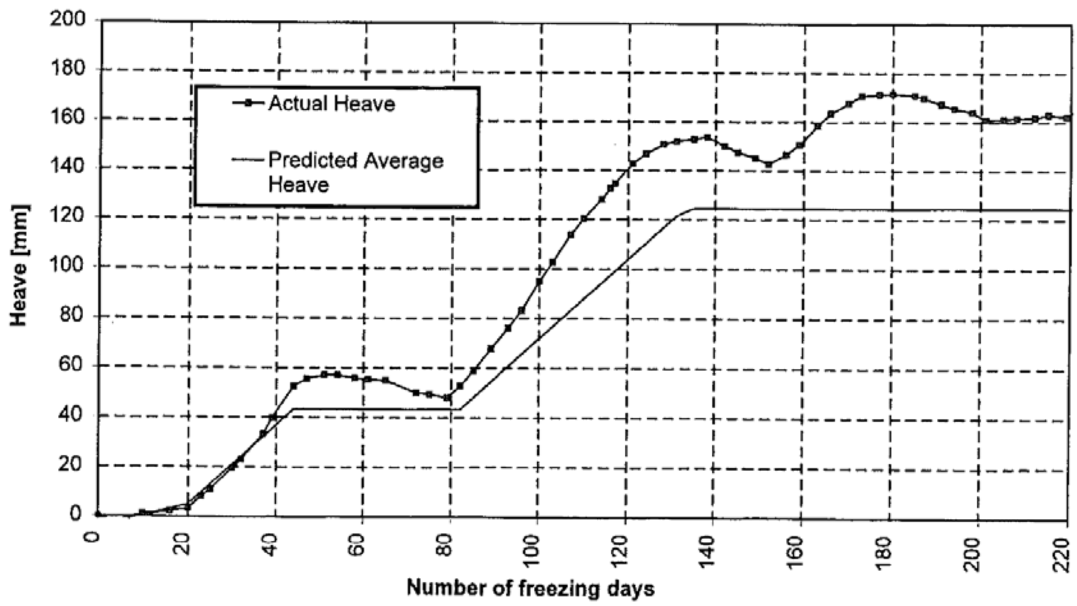

Figure 21 Vertical heave development at ramp D survey station 17 (van Dijk, P & Bouwmeester-van den Bos, J 2000)

Conclusion

Ground freezing in this project was used as an alternative method to reduce the risks involved in mining in difficult ground under live railroad tracks. The advantages were:

- Obtain a stable, full height, self supporting mining face
- Eliminate the risk of running water
- Lock in obstructions in the frozen ground for controlled and easy removal

The frozen ground served as a save support for the train loads and faci litates excavation for the tunnel jacking. Surf ace heave and settlem ent occurred slowly and rail alignm ent can be maintained with scheduled maintenance instead of expensive emergency stand-by crews.

10 Literature and reverences

- Al-Nouri, I. 1969. Time-dependent strenght behavior of two soil types at lowered temperatures. Ph.D. diss., Michigan State Univ., East Lansing.
- Andersland, B. and Ladanyi, B., 2005. Frozen Ground Engineering, 2nd edition. John Wiley & Sons. xii + 363 p, illustrated, hard cover. ISBN 0-471-61549-8.
- Andersland O.B., B.Ladanyi, Frozen Ground Engineering, 2nd Edition, 2004.
- Bakulin, F.G., B.A. Savel'yev, and V.F. Zhukov. (1972) "Physical Processes in Thawing Ground". Draft Translation 325, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.
- Braun, Shuster and Burnham 1979, Ground freezing for support of open excavations. In: int. symp. Ground Freezing 1st Bochum 1978, eng. Geol. 13(1979), pp 429-453
- Deming, P.W., Lacy, H.C. and Chang, D.K., 2000. Ground freezing for tunnel face stabilization. NAT 2000 conference, Bonston, Ma.
- Dijk van, P. and Bouwmeester-van den Bos, J., (2001), Large Scale Application of Artificial Ground Freezing, Soft Ground Technology, ASCE Geo-Institute Geotechnical Special Publication Number 112, Hanson, J. L. and Termaat, R. J., Eds., pp. 170-181.
- Harris J.S., Ground Freezing in Practice, London, 1995
- Jean-François Thimus. GROUND FREEZING, Frost Action in Soils.
- Jessberger, H.L. State-of-the-art-report, ground freezing: mechanical properties, processes and design,"Proceedings of the Second International Symposium on Ground Freezing, Trondheim, Norway"(1980), pp. 1–33.
- Kersten, M.S. (1949). "Laboratory Research for the Determination of the Thermal Properties of the Soils". *Technical Report 23*, Arctic Construction and Frost Effects Laboratory, U.S. Army Engineer Division, New England, Waltham, Mass.
- Lacy, S.L., Rice, P.M., Deming, P.W. and P. Schmall Jr., 1999. Groundwater Cut-off for Jacked Tunnel with Ground Freezing. Rapid Excavation and Tunneling Conference, Orlando, June 21-23, 1999.
- Linell, K.A., and E.F. Lobacz, Design and Construction of Foundations in Areas of Deep Seasonal Frost and Permafrost. U.S. Army Cold Regions Research and Engineering Laboratory Special Report 80-34, 1980.
- Murphy, D.W., 1965. An experimental investigation of geysering in vertical tubes. In advances in Cryogenic Engineering, ed. K.D. Timmerhaus, Proc. 1964 Cryogenic Engineering Conf., Univ. of Pennsylvania, Philadelphia. New York: Plenum Press, vol. 10A, pp. 359-59.
- Newman, Greg and Derek Maishman. Artificial Ground Freezing of the McArthur River Uranium Ore Deposit. Proceedings: International Conference on Ground Freezing and Frost Action in Soils.Belgium.September, 2000
- Osterkamp, T.E. (1964). "Temperature Measurements in Permafrost," State of Alaska, Department of Transportation and Public Facilities Research Report, Fairbanks, Alaska
- Peterson, J., Sailor, J., Bobrow, D., Vaghar, S. and Priestley, R., 2000. Use of Web Technology in Monitoring Tunneling-induced Deformation in Railroads. Boston BSCE Journal, Spring/Summer 2000, pp. 39-50.
- Rice, P.M., Mainville, P.A., Taylor, S. and Powderham, A.J, 1999. Development of Design & Construction Concepts for Jacked Tunnel Sections of I-93 / I-90

Interchange, Central Artery/Tunnel Project, Boston, Ma. ASCE Geotechnical Special Publication Number 90, June 1990.

- Shuster, J.A., 1972. Controlled freezing for temporary ground support. Chap. 49 in Proc. First North American Rapid Excavation and Tunneling Conf., Chicago, e.d. K.S. Lande and L.A. Garfield. Baltimore: ASCE-AIME, vol. 2, pp. 863-95.
- Shuster, J.A., GEOFREEZE Incorporated, Lorton, Va., USA.
- Skaven-Haug, S.V. (1963). "Control of Frost Penetration in Norway". *Proceedings of the First International Conference on Permafrost*, National Academy of Sciences National Research Council, Washington, D.C., 268-272.
- Ting, J.M., Martin, R.T., and Ladd C.C. 1983 Mechanisms of strength for frozen sand. ASCE Journal of Geotechnical Engineering, 109(10): 1286-1302.
- Tsytovich, N.A., et al. (1959). "Physical Phenomena and Processes in Freezing, Frozen and Thawing Soils". *Principles of Geocryology* (Permafrost Studies), Part I, General Geocryology, Chapter V., Academy of Sciences of the USSR, Moscow, 108-152, (Technical Translation 1164, National Research Council of Canada, Ottawa, Canada, 1964).