FREEZE-THAW DEWATERING AND STRUCTURAL ENHANCEMENT OF FINE COAL TAILS

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Abstract

An 18.2 hectare coal tailings impoundment which reached full capacity in 1989, has since been undergoing reclamation activities. The impoundment is sectioned into coarse, intermediate, and fine tails regions. The fine tails region, which consists of saturated silt and clay size soil and coal particles of high void ratio and negligible shear strength, offers unique problems in terms of reclamation to a dry surface landscape condition.

Freeze-thaw consolidation and dewatering is an effective process for transforming these fine coal tails to a condition of a weak soil with measurable shear strength. Consolidation of the fine tails is found to occur both within and below the frost front. Within the frozen zone, localized moisture migration results in the development of a three dimensional consolidated soil ped and ice lense structure. Upon thaw, the consolidated peds settle by gravity with the water escaping to the surface through the fissured soil ped structure. Thermal induced suction gradients developed at the advancing frost front result in moisture migration and dewatering of saturated fine tails below the frost front.

These two freeze-thaw consolidation and dewatering processes are described, along with models for predicting potential volumes of freeze-thaw treated material for given climatic conditions. Field results showing the significance of these processes on the dewatering and strength enhancement of fine coal tails are also presented. This dewatering and strength development provides the opportunity to implement dry rather than wet landscape reclamation procedures during reclamation of these waste storage facilities.

Key words: reclamation, dry landscape, freeze-thaw, volume reduction, strength

INTRODUCTION

The Coal Valley mine, owned and operated by Luscar Sterco (1977) Ltd. is located approximately 96 km south of Edson, Alberta in the foothills of the Rocky Mountains. Yearly production of 1.8 million clean tons of coal results in generation of two waste streams, a coarse dry crushed rock and a fine saturated slurried tails (Figure 1). During one stage of mineral extraction and waste stream deposition, an 18.2 hectare impervious impoundment was constructed to contain the fine saturated slurried tails as shown in Figure 2a. This impoundment reached its capacity in 1989 and has since been undergoing reclamation.

During deposition of the slurried tails stream into the impoundment, segregation occurred as coarse particles settled more readily while the finer particles were transported to the pond. Segregation resulted in the development of three distinct zones which potentially require different reclamation schemes. These zones are the coarse, intermediate, and fine tails regions and are approximately defined in Figure 2b. The grain size distribution of the fine tails region of the impoundment is shown in Figure 1.

Previous reclamation practices to achieve dry landscape conditions at the Coal Valley mine have included capping the tails with 3 to 6 m of waste rock to satisfy operational requirements. These thicknesses were in excess of the 1.2 m initially required by regulation. Greater capping thicknesses were required for the softer saturated fine tails as material squeezed under the loads imposed during placement of cap rock. Placement of thick capping layers directly affect the production costs and profits at the mine. Incorporation of freeze-thaw consolidation processes is viewed as a viable method of reducing or eliminating these excessive material capping requirements.

FREEZE-THAW

One of the central mechanisms surrounding the proposed dry landscape reclamation of fine saturated tails involves freeze-thaw consolidation. The process of consolidation of fine, high void ratio saturated tails through freeze-thaw has been known for several years. Johnson *et al.* (1989) reports that the concept of freeze-thaw to consolidate saturated materials was initially developed in temperate climates where biological sludges were concentrated from 3-5 % to greater than 30 % solids. Although the use of freeze-thaw to consolidate high void ratio saturated materials may have originated with biological sludges, its effects have been known previously as reported by Andersland and Anderson (1978).

Following the freeze-thaw consolidation of biological sludges, research and development into the dewatering of sludges from municipal wastes sources and dredging operations also developed. Recently, the freeze-thaw consolidation process has developed interest in the mining and mineral extraction industries. In particular, the Oil Sands operations in Northern Alberta are presently evaluating the effects of freeze-thaw consolidation on the dewatering and structural enhancement of their fine tails derived from the hot water bitumen extraction processes. As discussed by Sego *et al.* (1993 and 1994), large scale field tests are presently being conducted on Oil Sands fine tails incorporating thin layered freeze-thaw disposal of chemically treated fine tails.

Freezing of a soil-water system involves two process defined as *closed* and *open* system freezing. Both processes occur in nature and several examples are described by MacKay (1972). The effects of closed and open system freezing on the dewatering and structural enhancement were observed with the Coal Valley fine tails, located within the fine tails region of the impoundment, and are described in this paper.

Open System Freezing

Open system freezing involves the freezing of *insitu* and additional moisture which migrates to the freezing front within the frozen soil. A mechanistic theory of this process is described by Konrad and Morgenstern (1980). The physical process initiates with the downward freezing of *insitu* pore fluid near the surface. As the frost front progresses, ice nucleates in the water-filled pores with some of the water remaining as unfrozen adsorbed water film around the soil particles. Water from the unfrozen soil, below the frost front, migrates to the front and through the unfrozen water films into the frozen zone under the action of temperature induced suction gradients. The partially frozen zone with pore ice, adsorbed water, and soil particles in a non-equilibrium state is defined as the "Frozen Fringe". Water from below the frost front gradually migrates through the frozen fringe and freezes at the freezing front, feeding a growing ice lense. The latent heat released during freezing of the attracted water retards the advance of the frost front (0^{0}C isotherm). Gradually, as the temperature of the frozen soil decreases, so does the thickness of adsorbed water film around the soil particles. Continued shrinkage of the absorbed water film layer results in very low permeabilities, eventually stopping the upward flow of attracted water. With the flow of water stopped, the 0^{0}C isotherm continues to advance into the soil until equilibrium conditions are once again reestablished. This ice lense building action results in the development of multiple ice lenses within a frozen soil, potentially causing high uplift stress on overlying structures (Penner, 1974).

Observation of the open system freezing process described above, and considering continuity, it is evident that the migration of moisture towards the growing of ice lenses results in a loss of moisture from within the underlying soils. Depending on several factors including the permeability of the underlying soil and the spatial moisture "reservoir" conditions, this process can result in dewatering and consolidation of the unfrozen soil beneath the frost front as illustrated in Figure 3. Laboratory and field results on Coal Valley fine tails indicate that this dewatering of unfrozen saturated tails occurs and results in significant structural enhancement of tailings found below the frost front.

Closed System Freezing

Open system freezing was described as the development of horizontal ice lenses through the migration and freezing of moisture drawn from the underlying soil. Open system freezing includes the presence of an unfrozen soil moisture reservoir. Conversely, close system freezing may be characterized as freezing of only *insitu* water without the presence of a moisture reservoir. Impermeable boundary conditions, reduced permeabilities, or relative quick freezing rates preclude the migration of moisture from outside the advancing frost front.

Although moisture migration is reduced or eliminated on a macro scale in closed system freezing, migration or redistribution of *insitu* moisture on a micro scale occurs. As described in the open system freezing process, a matrix of pore ice develops which surrounds soil particles and their associated absorbed water layers. The water within these layers is stationary on a macro scale.

Temperature gradients and the associated suction pressures within the partially frozen structure cause the absorbed moisture around the soil particles to migrate towards the ice lense within the closed freezing system. The action of this localized pore fluid flow results in the development of a three-dimensional ice lense matrix. Continued localized moisture migration results in a reduction of the thickness of the absorbed water layers and consolidation of the soil mineral matrix.

For fine grained soils, closed system freezing results in the consolidation of the soil to an overconsolidated "ped" structure. The ped structure is surrounded by a three-dimensional system of ice lenses composed of virtually pure ice with few mineral impurities. This closed system freezing process may also be considered as *undrained freezing* since no change in total moisture content occurs.

The consolidation process during freezing and subsequent thaw of saturated fine tails subjected to closed system or undrained freezing may be illustrated using the conventional soil mechanics void ratio *versus* effective stress plot shown in Figure 4 (Nixon and Morgenstern 1973). The homogenous fine saturated tails in their *insitu* state prior to freezing is shown in this figure at location A with a void ratio of e_A under a vertical effective stress (self weight) of σ_A'. Considering the entire sample, upon undrained freezing, the sample expands due to a 9 % volume expansion of the voids as the pore fluid changes phase. The entire sample moves to location B' with a void ratio e_B'. With expansion of the entire sample, the freezing results in the development of a three dimensional segregated structure of consolidated soil peds housed within an ice matrix. Within the soil peds, freezing over consolidates the soil matrix to a void ratio of e_B at location B, under an effective stress of σ_B'.

Upon thaw, water is released as the ice lenses melt and the entire sample returns to location A. The sample at location A after freezing is no longer homogeneous. Rather, a segregated profile exists with the moisture from the thawed ice matrix at the surface, and the consolidated peds formed during the freezing process settled at the bottom (due to density differences). Decanting of the "pure" water from the top of the thawed sample results in the average void ratio decreasing to e_C under an effective stress σ_A'. The void ratio at C includes some moisture reabsorbed during the thawing and ped settling process. This reabsorbed moisture is illustrated as the consolidated peds at location B, swell upon thaw to location C.

The path A-B-C describes the freezing and thawing process within the consolidated peds, whereas path A-B'-C illustrates the freezing, thawing, and decanting of the total sample. The void ratio reduction from A to C is directly related to the volume reduction or thaw strain of the total fine tails.

Research at the University of Alberta indicates that the magnitude of thaw strain and overconsolidation of the soil matrix depend on several factors including initial solids contents, mineral composition, grain size distribution, pore fluid composition, freezing rate and temperature boundary conditions imposed during closed system freezing.

The material at C has under gone both a physical and mechanical transformation. Included with the volume reduction (thaw strain) and increased solids content at the lower void ratio, the material has in general an increased permeability, reduced compressibility, and increased shear strength compared to the unfrozen material at A. These post freeze-thaw mechanical changes have been discussed by several authors on various materials (Stancyzyk *et.al.* 1971), (Nixon and Morgenstern 1973 and 1974), (Chamberlain and Blouin 1978), (Chamberlain and Gow 1979), (Chamberlain 1980), (Johnson *et al.* 1989), (Vahaaho 1991), (Sego and Dawson 1992), (Stahl 1993), (Sego *et al.* 1993), and will not be discussed further.

DESIGN PROCESS

The first step in considering whether freeze-thaw consolidation can be utilized for dewatering of fine tails is to evaluate the available energy for freezing and thawing. Stanczyk *et al.* (1971) calculated the energy requirements in terms of calories per gram or kilowatt-hours per ton to cool and freeze phosphate rock slime at varying initial solids contents. Stanczyk points out that theoretical energy computations and cost estimates can be developed assuming idealized freezing cycles utilizing reversible heat exchange processes.

Although freezing and thawing systems may be designed and implemented on a large scale, their costs would be considerable. With this in mind, perhaps the most economical process and energy source for freeze-thaw is to utilize the natural seasonal temperature fluctuations associated with the climate. Fortunately in most parts of Canada, natural seasonal temperature variations result in alternate freezing and thawing cycles. The subzero temperatures during the Fall and Winter months may be used to freeze the fine tails, with the warmer temperatures recorded during the Spring and Summer facilitating thaw.

Freezing and Thawing Indices

Prediction of the natural freezing and thawing energy begins with an analysis of the climatic data at the tails disposal or storage area. Using 30 year monthly temperature averages from 1951 to 1980 (from Environment Canada), the seasonal temperature variation near the Coal Valley site may be approximated as shown in Figure 5. For this 30 year period, the average Air Freezing Index (AFI) and Air Thawing Index (ATI) are 1316 ^{0}C - days and 1864 ^{0}C - days respectively.

The mean yearly temperature is approximately +1.5 ^{0}C with an average seasonal amplitude of 13.6 ^{0}C. The equation describing the seasonal temperature variation approximated for the Coal Valley site is shown in this figure. With the available natural energy sources for freezing and thawing defined, prediction of the potential volumes of freeze-thaw treated material is desired.

Freezing Model

Martel (1988) has developed a mathematical model for freezing of sewage sludge which gives the time to freeze a layer of sludge. The model is based on the boundary conditions shown in Figure 6, and assumes that the sludge is initially at 0 ^{0}C when freezing begins.

The freezing model considers both convective and conductive heat transfer processes to the surface and is given as:

$$t_f = \frac{\rho_f L \varepsilon}{T_f - T_{ac}} \left(\frac{1}{h_c} + \frac{\varepsilon}{2K_{fs}} \right) \qquad (1)$$

where

t_f	=	time to freeze
ρ_f	=	density of frozen fine tails
L	=	latent heat of fusion of fine tails
ε	=	thickness of frozen fine tails
h_c	=	conductive heat transfer coefficient
K_{fs}	=	thermal conductivity of frozen fine tails
T_f	=	freezing temperature of fine tails
T_{ac}	=	ambient air temperature

The first and second terms in the brackets of equation (1) account for convective and conductive heat transfer processes respectively. Equation (1) was used to predict the depth of freezing of fine coal tails in terms of the AFI and is presented in Figure 7. The input values used to predict the depth of frost are presented in Table 1. These values are based on typical values reported by Martel (1988), adjusted for the characteristics and composition of fine coal tails. Figure 7 shows the relative contribution of conduction and convection to the total energy requirements for freezing of a single layer. The energy requirement (ie. the AFI) increases significantly for thicker layers due to the retarding effect of conduction through the frozen tails as the layer thickness increases. This figure illustrates that an AFI of 1316 ^{0}C - days results in a predicted frost penetration of approximately 1.1 m. This prediction is supported by depth of frozen material measurements reported on the fine coal tails at the Coal Valley mine.

Thawing Model

The benefits of freeze-thaw such as increased shear strength, increased permeability, and reduced volume and liberation of moisture are realized if the fine tails frozen during the fall and winter, thaw during the next spring and summer. Thus, in evaluating optimal freezing thicknesses, one must also consider the predicted thaw depth based on the climatic conditions in the area.

The model illustrating the thawing process of frozen fine tails is shown in Figure 8 (after Martel, 1988). The mathematical representation for this model is shown as:

$$t_{th} = \frac{\rho_f L Y}{T_{at} - T_f + \frac{\alpha \tau I}{h_c}} \left(\frac{1}{h_c} + \frac{\theta Y}{2K_{ss}} \right) \qquad (2)$$

where

t_{th}	=	time to thaw
ρ_f	=	density of frozen fine tails
Y	=	depth of thawed fine tails
L	=	latent heat of fusion of fine tails
h_c	=	conductive heat transfer coefficient
K_{ss}	=	thermal conductivity of settled fine tails
T_f	=	freezing temperature of fine tails
T_{at}	=	ambient air temperature
I	=	insolation (rate of solar radiation)
θ	=	thickness of frozen fine tails
α	=	solar energy absorptance ratio
τ	=	transmittance factor

Similar to the freezing model, this equation represents the time to thaw a thick frozen layer. The model assumes that the supernatant water released upon thaw is decanted quickly and the settled thawed tails do not desiccate.

Once again, the first and second terms in the brackets are to account for the convective and conductive heat transfer processes respectively. The parameters shown in equation (2) are defined in Table 2 with the values adjusted for the properties of fine coal tails. The thawing model was used to predict the depth of thaw of frozen fine coal tails in terms of the ATI as shown in Figure 9. Considering the ATI of 1864 ^{0}C - days at the Coal Valley site, a maximum predicted thaw depth of 1.5 m is predicted.

The maximum possible predicted thaw depth of 1.5 m assumes heat transfer only occurs from the tailings surface towards the atmosphere. Detailed design would warrant accounting for heat transfer processes from the base of the frozen tails downwards into the unfrozen tails and foundation (geothermal effects).

Freeze-Thaw Optimization

With the maximum assumed thaw thickness of 1.5 m (neglecting geothermal effects), it is desirable to optimize the placement layer thickness for freezing. As discussed above and shown in Figure 7, the predicted frozen thickness at the Coal Valley Impoundment, assuming one layer, is approximately 1.1 m. Considering this model, the freezing process may be optimized by freezing the fine tails in thin layers. Freezing in multiple thinner layers reduces the retardation effect of heat conduction through the frozen tails which predominates with thicker layers. Figure 10 shows the total frozen layer thickness *versus* placement thickness of individual layers for the air freezing index of 1316 ^{0}C - days and 658 ^{0}C - days. The latter AFI assumes that 1/2 of the freezing season is required for layer placement and provides a suitable lower bound. The actual "usable" AFI would likely lie between this upper and lower bound and depend on the specific season's temperature profile, placement geometry, depositional rate and methodology, and efficiency.

Based on a maximum previously assumed thaw depth of 1.5 m, the optimal multiple placement layer thickness is between 0.31 m and 0.75 m. Greater thicknesses would likely result in non-optimization of the freezing process with respect to the available thaw thickness. Conversely, thicknesses less than the lower bound may result in freezing great thicknesses and development of a remnant frozen fine tails layers within the stratigraphy following completion of thaw.

As a comparison, if one assumes that an additional 1 m of thaw occurs through geothermal effects (resulting in a total thaw thickness of 2.5 m), the optimal placement layer thickness is between 0.15 m and 0.31 m.

Optimization of the freeze and thaw processes with respect to the available energy sources, placement conditions and variables, results in maximization of the volumes of freeze-thaw enhanced materials. This reduces the time required and costs associated with structurally enhancing saturated fine grained tails through freeze-thaw

FIELD RESULTS

Shear Strength Data

As discussed previously, the tailings impoundment reached full capacity in 1989, at which time reclamation activities were initiated. During the winter months from 1989 through 1993, shear strength profiles of the unfrozen tails were measured in the fine tails region of the impoundment. Holes were drilled through the ice and frozen fine tails using a standard ice auger or a core barrel. The shear strengths were determined using a *Genor* hand held field vane. Due to the expected weak strengths of the saturated fine tails and the shear strength resolution desired, larger non-standard vanes were required and fabricated at the University of Alberta.

The average undrained shear strength profiles from November 1989 to February, 1993 are presented in Figure 11. This period represents four freeze-thaw seasons. The profiles are based on the average results determined from three sites, except November, 1989 and November, 1990 which only include profiles from two and one site(s) respectively. The three sites are shown in plan in Figure 2a.

The shear strength profiles determined on two separate occasions in the winter of 1989/1990 are virtually identical. The profiles represent that of a normally consolidated soil with increasing shear strength with depth due to increasing effective stress. The shear strength increases linearly from approximately 0.2 kPa at 0.5 m below the ice surface to 1 kPa at a depth of 2 m.

The shear strengths recorded following the initial 1989/1990 profiles show significant gains with time. In terms of relative shear strength increases, the shear strength in February, 1993 is approximately 9 times greater at a depth of 1 m, and 5 times greater at a depth of 2 m than the initial 1989/1990 profile. Beyond a depth of 2 m, the strength appears to increase linearly with depth.

Similarities between the profile for a normally consolidated clay with a desiccated crust, and the February, 1993 profile are evident. For a desiccated normally consolidated clay, the higher shear strength near the surface is due to drying and matrix suctions which consolidate the material and increase the shear strength. Although the surface of the fine coal tails has always been capped with water and has never been exposed to desiccation processes, it has likely been dewatered through the suctions developed during the freezing process. The suction pressures developed within the frozen fringe cause pore water at depth to migrate towards the frost front. Migration of moisture from the unfrozen tails below the frost front results in dewatering and consolidation.

Space limitations preclude discussion of the laboratory results on the fine coal tails. However, laboratory experiments have also shown that dewatering and structural enhancement of fine coal tails occurs both within and beyond the frost front (Stahl, 1993).

Normally Consolidated Shear Strengths

To provide a relative index for the strength increase due to freeze-thaw and moisture migration processes, conventional concepts of undrained shear strength for normally consolidated fine grained materials are used for comparison. As discussed by Schiffman et al. (1988), for hydraulic fill with significant plasticity, undrained shear strength can be evaluated using normalized soil properties approaches developed for natural clays. The undrained shear strength of natural clays is conveniently expressed according to the ratio of s_u/σ_c' where s_u is the undrained shear strength and σ_c' is the effective consolidation pressure. This relationship allows the changes in the undrained strength to be monitored over time with changes in consolidation (induced pore water pressure dissipation).

Several undrained shear strength relationships (s_u/σ_c') for various materials are cited by Schiffman and are presented in Table 3. The s_u/σ_c' ratios for fine tails from various sources range between 0.2 and 0.3. Considering that normal consolidation conditions apply for most hydraulic fills, the undrained shear strength relationship for natural soils proposed by Bishop and Henkel and discussed by Schiffman may be considered to help refine the s_u/σ_c' ratio estimate. The undrained shear strength ratio was shown to correlate with the plasticity index (PI) and is presented as:

$$s_u/\sigma_c' = 0.11 + 0.0037\ (PI) \qquad (3)$$

Based on the Atterberg Limits conducted on the Coal Valley fine tails, (L_L = 70 %, P_L = 35 %, PI = 35 %) equation (3) results in an s_u/σ_c' = 0.24. This value is within the range reported in Table 3 and will be used to compare with the field shear strengths.

The theoretical shear strength profile is not complete without account for selfweight consolidation processes resulting in a void ratio reduction and density increase with depth. Considering a bulk unit weight of the tails measured at the surface of 13.3 kN/m^3 and compression indices, C_c , in the range of 0.3 to 0.54 to 1.0 (Stahl, 1993), the theoretical shear strength profiles may be compared with the actual profiles as shown in Figure 12.

The theoretical shear strength profiles compare well with the shear strengths measured during the winter of 1989/1990. Furthermore, the slopes of the actual and theoretical strength profiles are similar, supporting the s_u/σ_c' ratio of 0.24 chosen and the range of C_c values selected. Comparison of the theoretical strength profile with the measured profile above a depth of 2 m for the March 1991 profile, and the entire February 1993 profile indicate the freezing process has overconsolidated and strengthened the upper regions of the saturated fine tails.

The depth of dewatering and consolidation encountered in February, 1993 could not be determined due to equipment limitations. It is expected, however, that with increasing depth, the measured shear strength profile would eventually coincide with the calculated profile. It is noted that this calculated profile was based largely on empirical correlations. A detail theoretical profile would require investigations including laboratory consolidometer tests with shear strength measurements, and a detailed knowledge of the stratigraphy within the fine tails at this location.

FREEZE-THAW CONCEPT FOR EXISTING IMPOUNDMENT

Freeze thaw consolidation is a powerful structural enhancement process for fine saturated high void ratio tails. Specifications enforced by reclamation regulatory authorities, the Development and Reclamation Review Committee (DRRC) in Alberta, occasionally require that fine saturated tailings areas be returned to dry landscape conditions for wildlife or perhaps productive farm land purposes. Freeze-thaw consolidation is viewed as a viable process to assist the consolidation (dewatering) of fine tails zones enabling the development of a dry landscape scenario.

An illustration of a possible freeze-thaw consolidation disposal operation at the Coal Valley mine at their abandoned tailings impoundment is illustrated in Figure 13. The freeze-thaw operations would incorporate natural freezing to freeze the top layer of fine tails to a depth of approximately 0.3 m. This thickness should provide sufficient stability for relatively light human and equipment traffic. In order to reduce the freezing retardation effects of conduction and to optimize the volume of freeze-thaw treated material, holes would be drilled through the frozen fine tails with the underlying unfrozen fine tails pumped to the surface in thin layers and exposed to the atmospheric thermal conditions. The pumped placement layer thickness could be optimized as discussed previously and this process repeated throughout the freezing season.

The warmer temperatures during the spring and summer would thaw the frozen tails and unlock the benefits developed during freezing including increased shear strength and permeability. This freeze thaw enhancement process could be continued for several seasons until the consistency of the fine tails changes from that of a slurry to a weak soil. Evaporation coupled with evapotranspiration through introduction of stable, high moisture demand vegetation grown on the thawed tails results in further dewatering and strengthening. This enhancement is in addition to the fibre reinforcing effects of the vegetative root system. As discussed in Stahl and Sego (1992), evaporation, evapotranspiration, and fibre reinforcement can significantly contribute to bearing capacity and surface stability of fine coal tails. These surface enhancement processes following treatment by freeze-thaw can provide sufficient surface stability alone, or through the addition of thin capping layers, to support revegetation and other dry landscape reclamation activities. The goal of which to provide an acceptable, stable reclaimed environment commensurate with the post-mine land use philosophy.

CONCLUSIONS

The Coal Valley tailings impoundment reached full capacity in 1989 and has been undergoing reclamation activities. Freeze-thaw dewatering and consolidation processes have structurally enhanced the fine coal tails both within the frost front and at depth due to moisture migration. Four freeze-thaw cycles representing four winters have resulted in a shear strength increase in the fine tails between 5 and 9 fold. The shear strength has increased from a negligible value to near

5 kPa at the surface. Continued freeze-thaw consolidation processes coupled with evaporation, evapotranspiration, and fibre reinforcement of vegetative root systems may support dry landscape reclamation practices of these problematic soft, weak soils.

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TABLE 1 Input Variables for Depth of Frost Predictions for Fine Coal Tails

VARIABLE	DEFINITION	VALUE
t_f	Time to freeze	varies
ρ_f	Density of the solidified fine tails	1130 kg/m^3
ε	Thickness of fine tails layer	varies
L	Latent heat of fusion of fine tails	93 W·h/kg
h_c	Average convective heat transfer coefficient	30 W/m$^2\cdot{}^0$C
K_{fs}	Thermal conductivity of the frozen fine tails	2.22 W/m·^{0}C
T_f	Freezing temperature of fine tails	0^{0}C
T_{ac}	Ambient air temperature during freezing	varies

TABLE 2. Input Variables for Depth of Thaw Predictions for Fine Coal Tails

VARIABLE	DEFINITION	VALUE
t_{th}	Time to thaw	varies
ρ_f	Density of the solidified fine tails	1130 kg/m^3
Y	Total depth of thawed fine tails	varies
L	Latent heat of fusion of fine tails	93 W·h/kg
h_c	Average convective heat transfer coefficient	30 $W/m^2 \cdot {}^0C$
K_{ss}	Thermal conductivity of the settled solids	0.87 $W/m \cdot {}^0C$
T_f	Freezing temperature of fine tails	0^0C
T_{at}	Ambient air temperature during thaw	varies
I	Insolation (rate of direct solar radiation)	197 $J/s \cdot m^2$
θ	Approximate thaw strain	50 %
α	Solar energy absorptance ratio	0.9
τ	Transmittance factor	1.0

Table 3. Shear Strength Ratios for Mine Tails (after Schiffman et al. 1988)

DESCRIPTION	SHEAR STRENGTH RATIO
Cycloned Copper Slimes Tailings:	
Field Vane Data	$s_u/s_{vo}' = 0.26$
CIU* Triaxial Test Data	$s_u/s_{1c}' = 0.30$ to 0.33
CAU* Triaxial Test Data	$s_u/s_{1c}' = 0.32$ to 0.34
Normally Consolidated Phosphate Clay Hydraulic Fills	$s_u/s_c' = 0.22$
Cycloned Non-plastic Lead-Zinc Slimes	$s_u/s_c' = 0.20$ to 0.22

*Note: CIU and CAU indicated "Isotropic Consolidation Undrained Triaxial" and "Anisotropic Consolidation Undrained Triaxial" respectively.

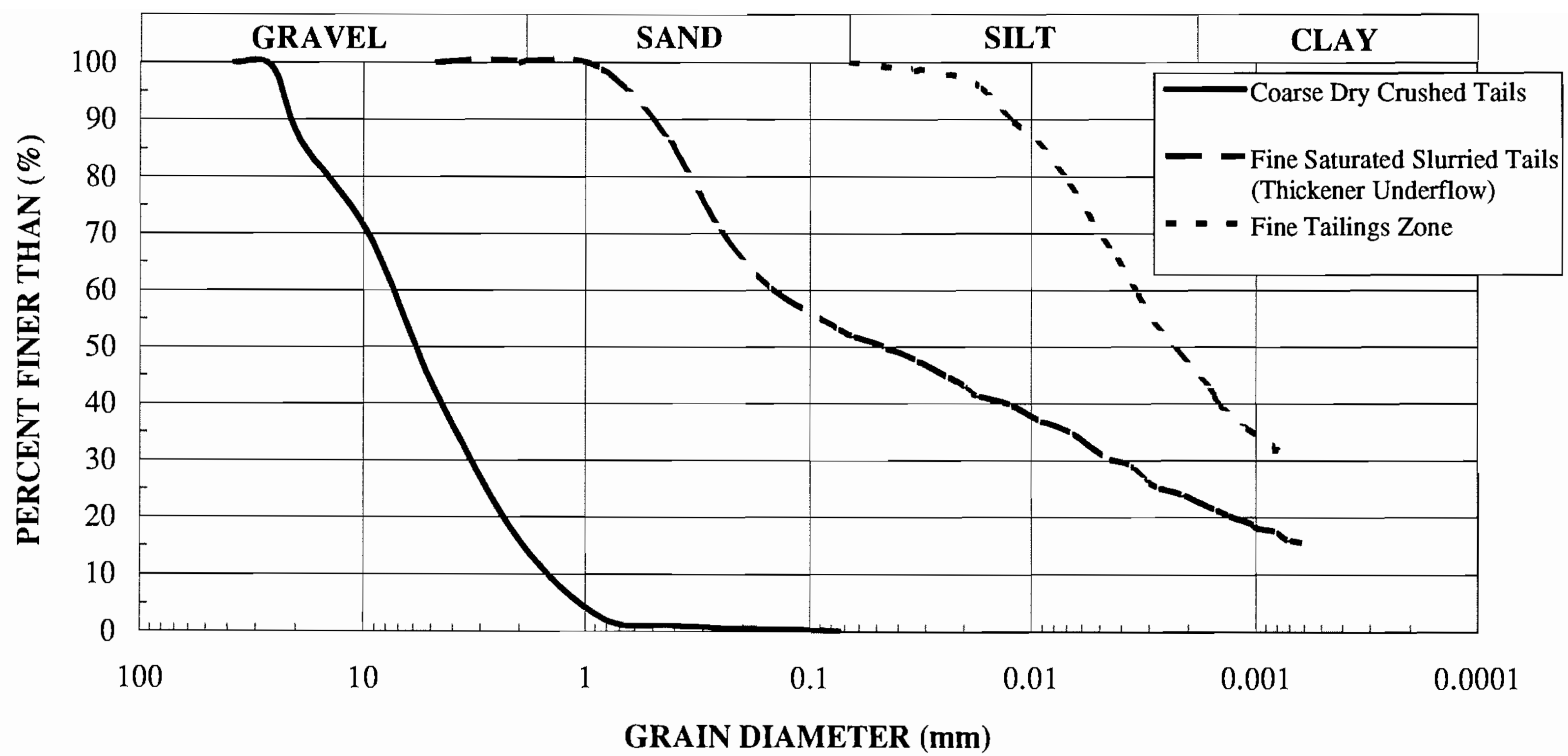
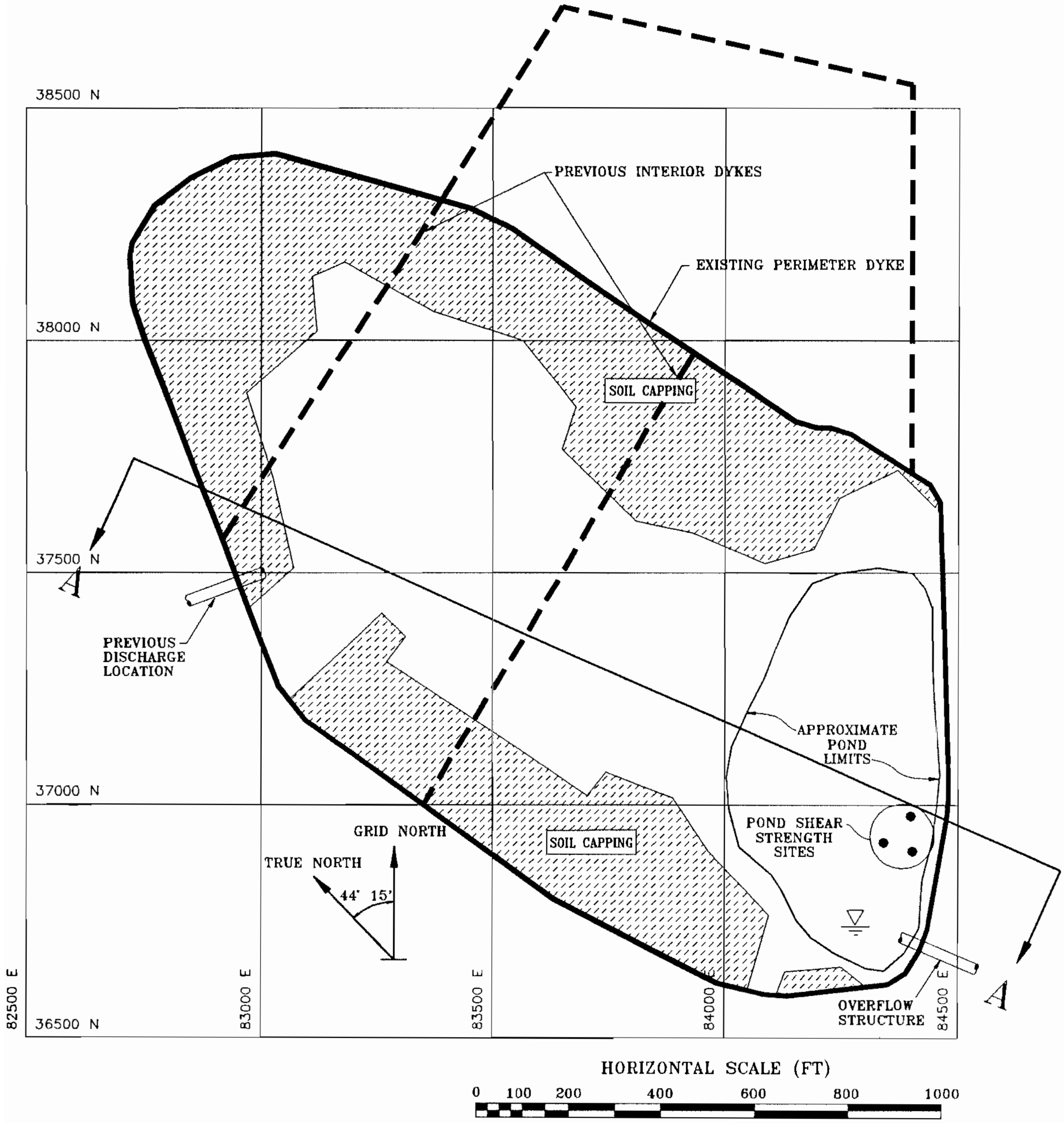
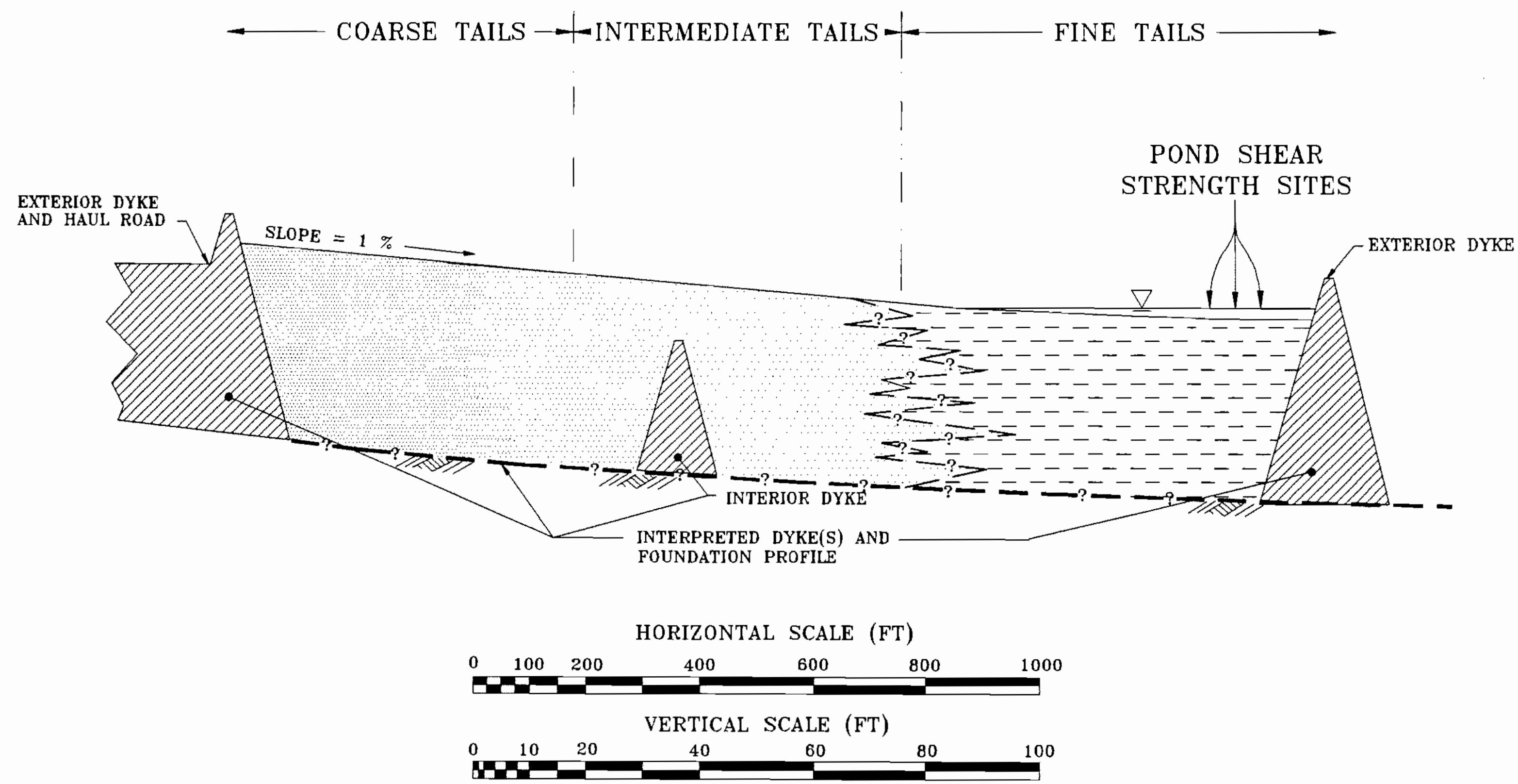

GRAVEL
SAND
SILT
CLAY
PERCENT FINER THAN (%)
100
90
80
70
60
50
40
30
20
10
0
100
10
1
0.1
0.01
0.001
0.0001
GRAIN DIAMETER (mm)
Coarse Dry Crushed Tails
Fine Saturated Slurried Tails
(Thickener Underflow)
Fine Tailings Zone

FIGURE 1



38500 N
38000 N
37500 N
37000 N
36500 N
82500 E
83000 E
83500 E
84000
84500 E
PREVIOUS INTERIOR DYKES
EXISTING PERIMETER DYKE
SOIL CAPPING
SOIL CAPPING
A
A
PREVIOUS DISCHARGE LOCATION
APPROXIMATE POND LIMITS
POND SHEAR STRENGTH SITES
OVERFLOW STRUCTURE
GRID NORTH
TRUE NORTH
44° 15'
HORIZONTAL SCALE (FT)
0 100 200 400 600 800 1000

FIGURE 2a



SECTION A – A

FIGURE 2b

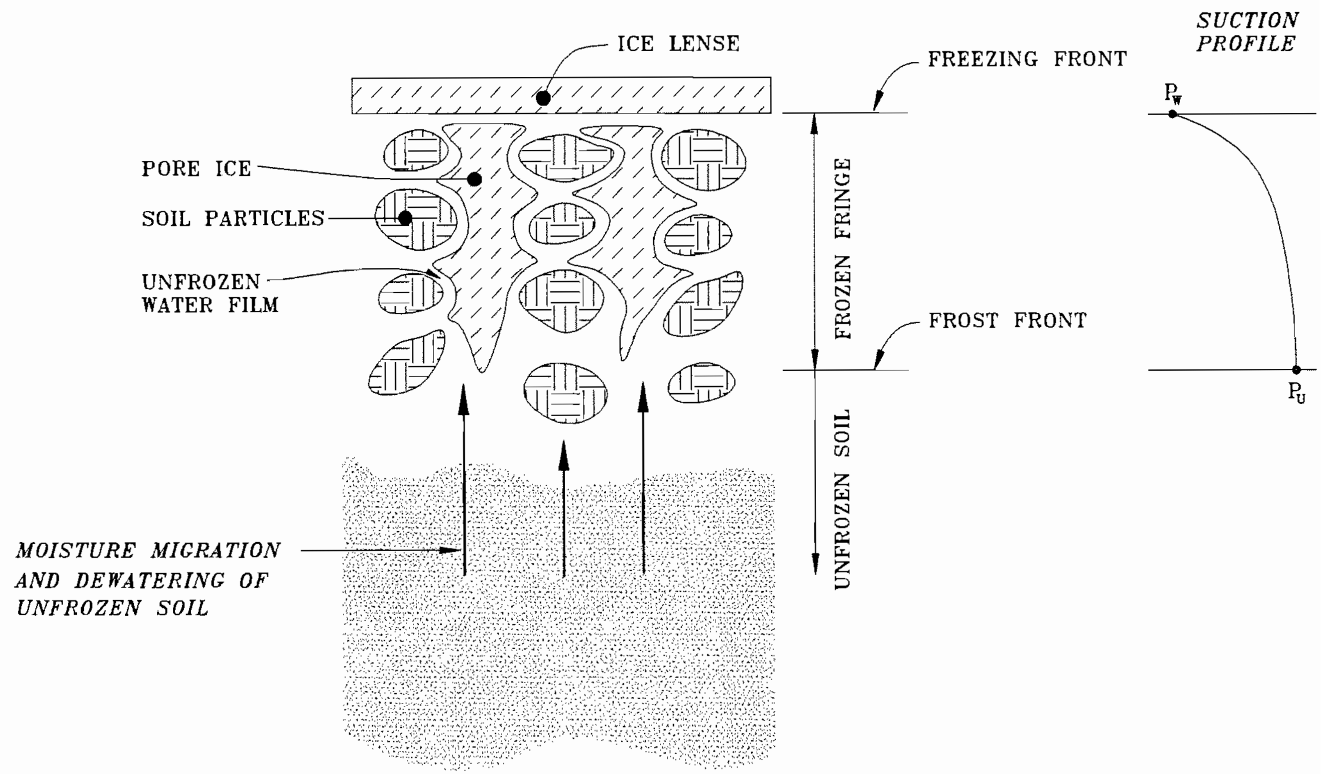
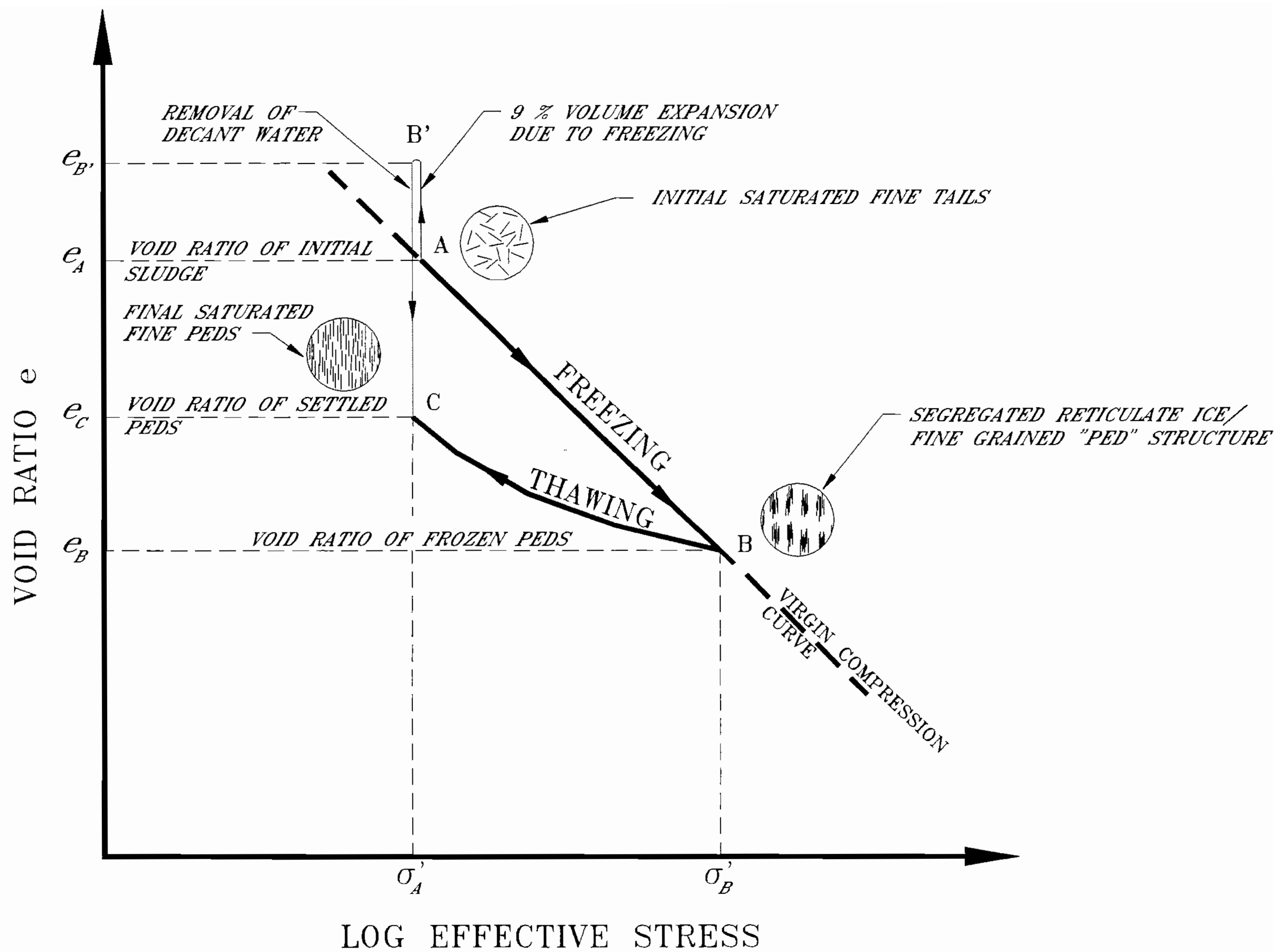
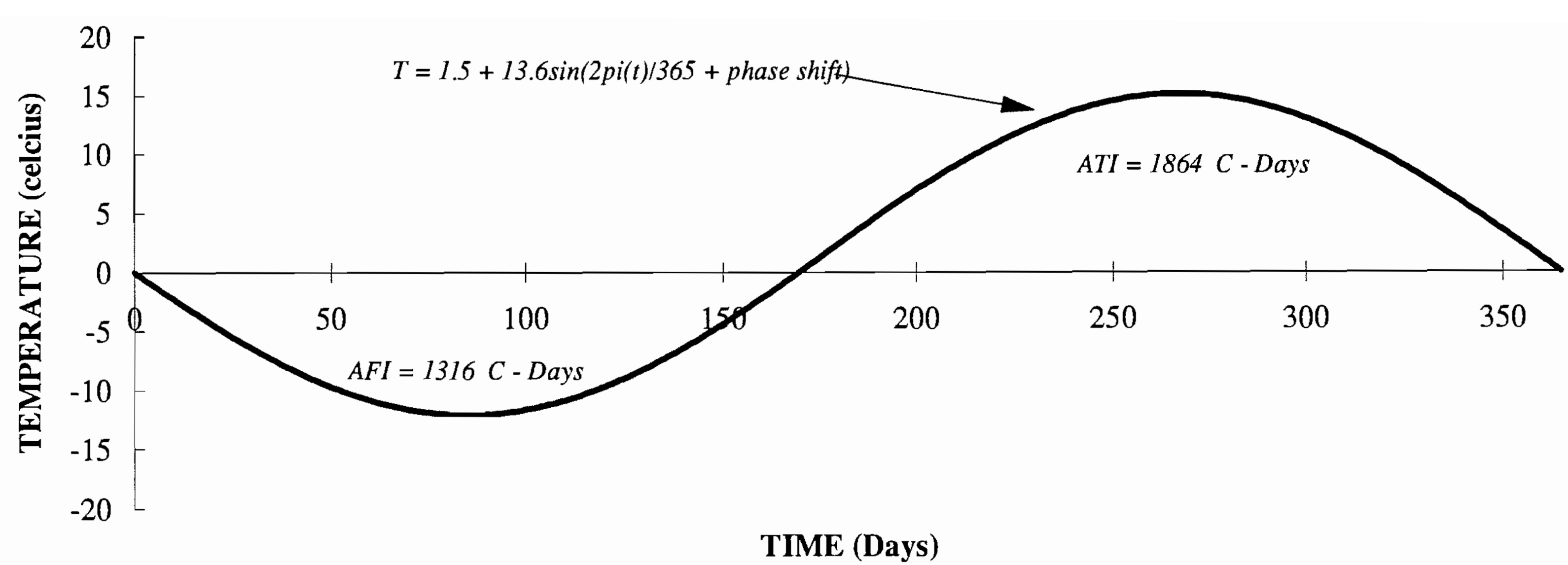

ICE LENSE
PORE ICE
SOIL PARTICLES
UNFROZEN
WATER FILM
MOISTURE MIGRATION
AND DEWATERING OF
UNFROZEN SOIL
FREEZING FRONT
FROST FRONT
FROZEN FRINGE
UNFROZEN SOIL
SUCTION
PROFILE
P_w
P_U

FIGURE 3



REMOVAL OF DECANT WATER
9 % VOLUME EXPANSION DUE TO FREEZING
B'
$e_{B'}$
INITIAL SATURATED FINE TAILS
e_A
VOID RATIO OF INITIAL SLUDGE
A
FINAL SATURATED FINE PEDS
e_C
VOID RATIO OF SETTLED PEDS
C
FREEZING
THAWING
SEGREGATED RETICULATE ICE/ FINE GRAINED "PED" STRUCTURE
e_B
VOID RATIO OF FROZEN PEDS
B
VIRGIN COMPRESSION CURVE
VOID RATIO e
σ'_A
σ'_B
LOG EFFECTIVE STRESS

FIGURE 4



T = 1.5 + 13.6sin(2pi(t)/365 + phase shift)
ATI = 1864 C - Days
AFI = 1316 C - Days
TEMPERATURE (celcius)
20
15
10
5
0
-5
-10
-15
-20
0
50
100
150
200
250
300
350
TIME (Days)

FIGURE 5

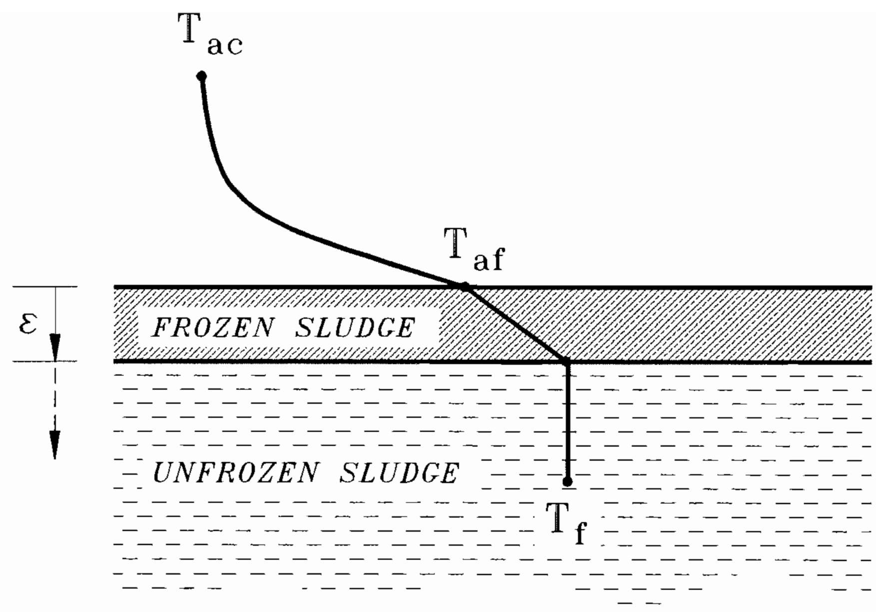


FIGURE 6

FIGURE6

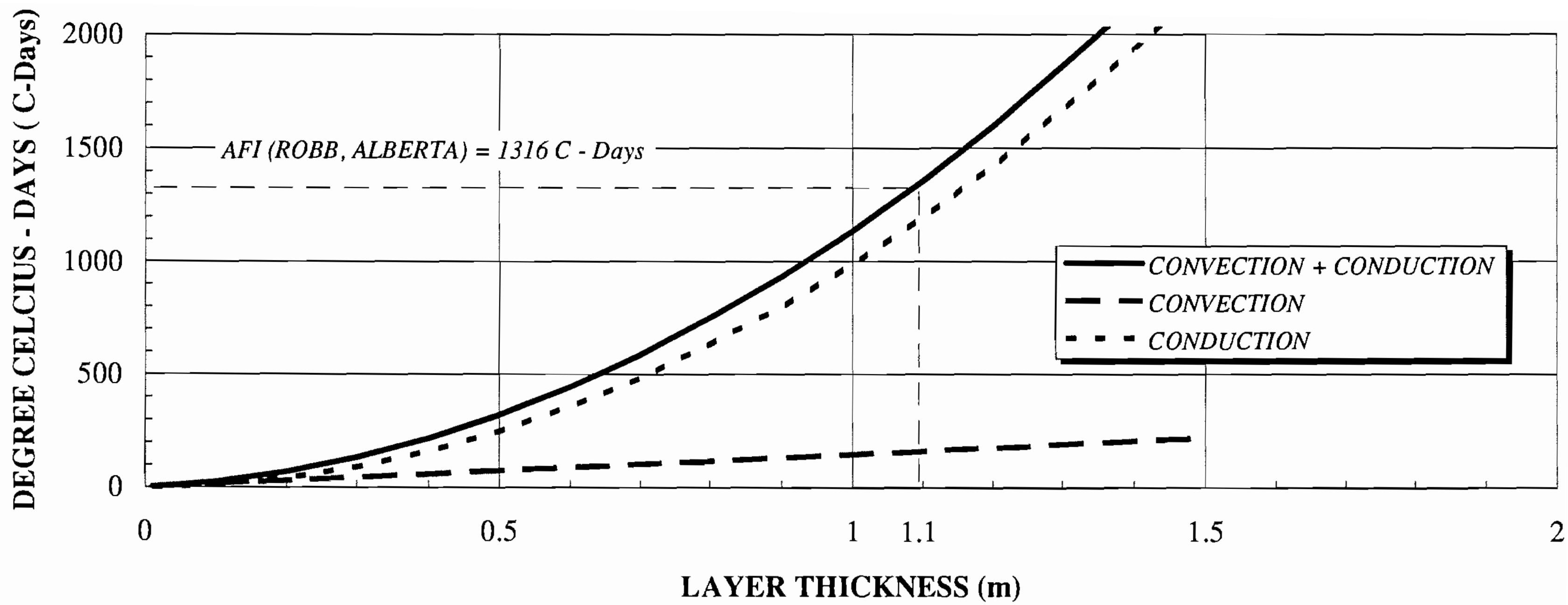
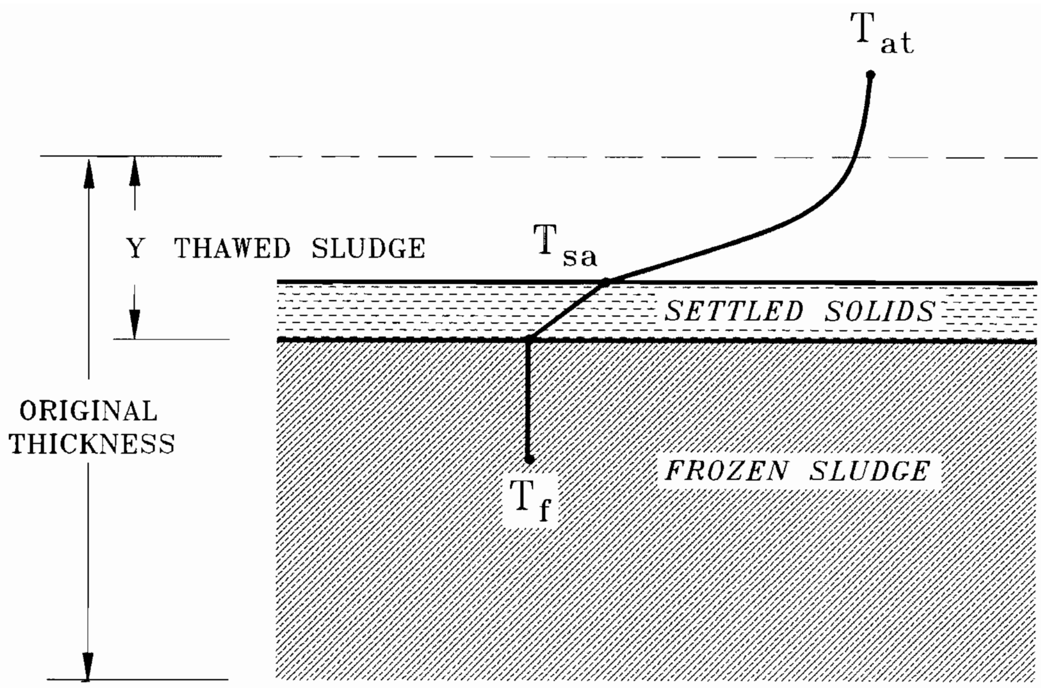
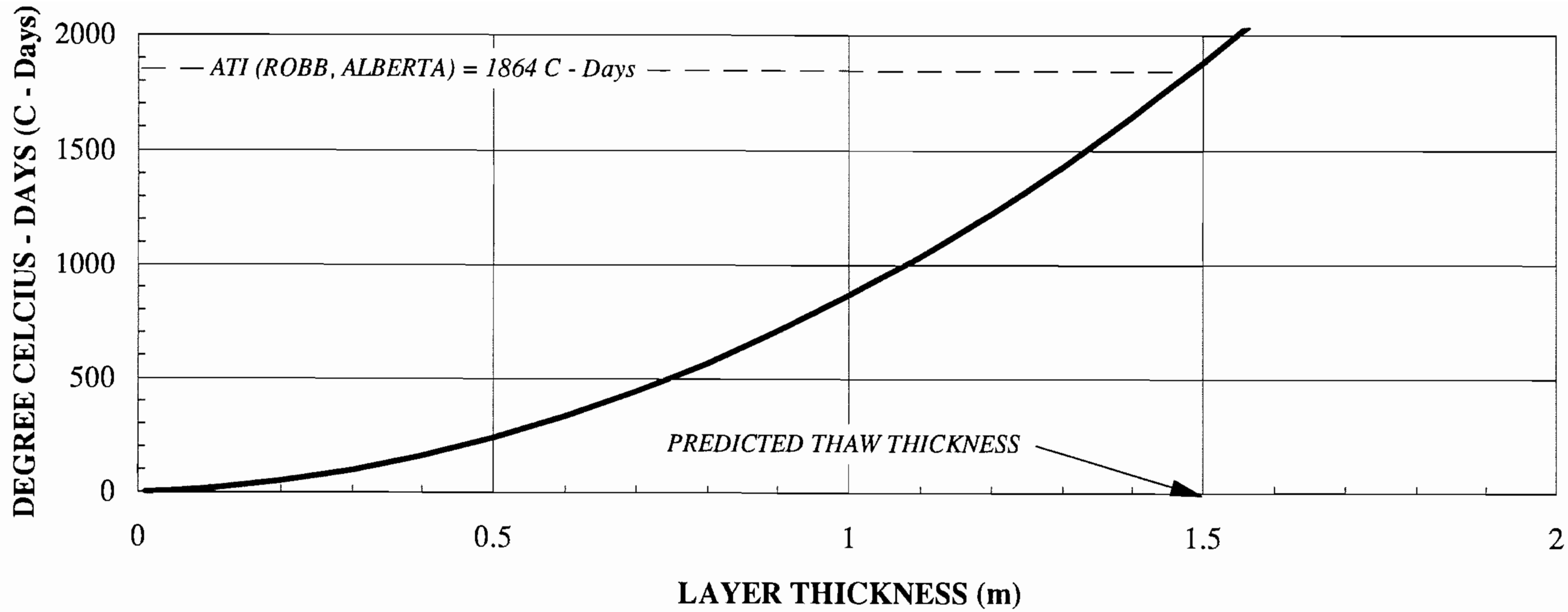

DEGREE CELCIUS - DAYS (C-Days)
2000
1500
1000
500
0
AFI (ROBB, ALBERTA) = 1316 C - Days
CONVECTION + CONDUCTION
CONVECTION
CONDUCTION
0
0.5
1
1.1
1.5
2
LAYER THICKNESS (m)

FIGURE 7



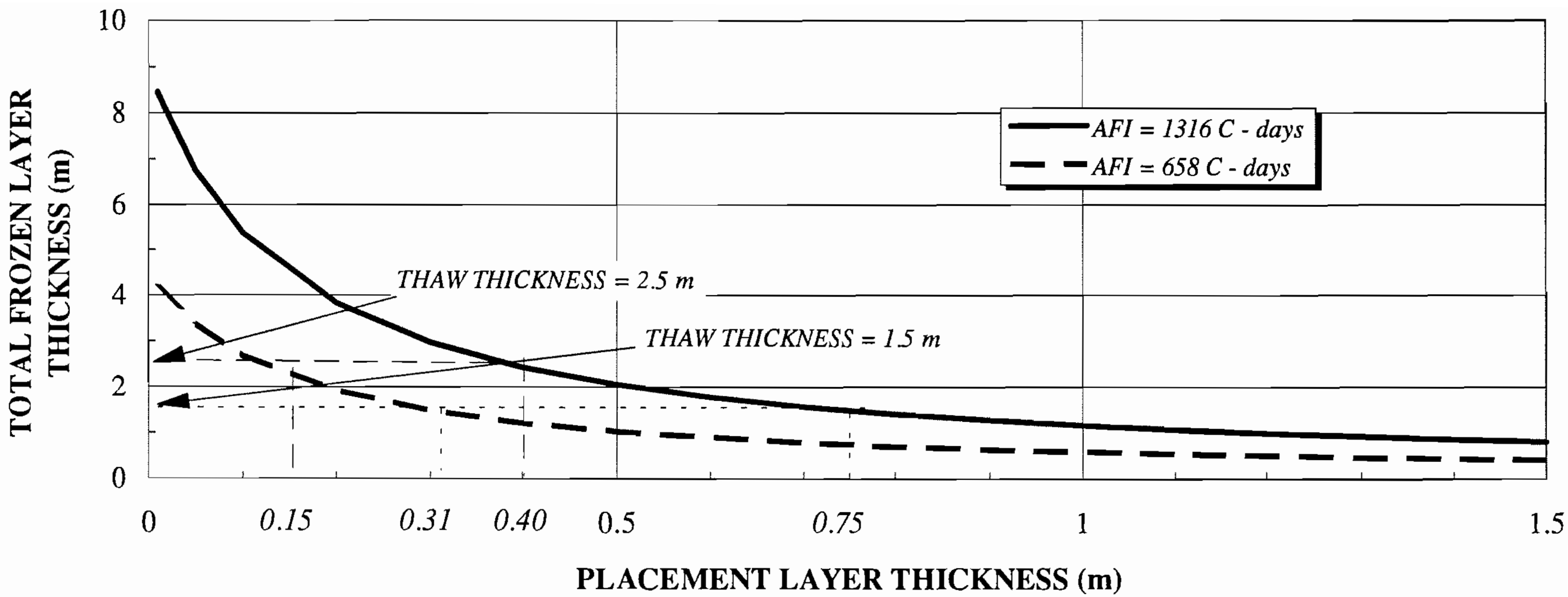
T at
Y THAWED SLUDGE
T sa
SETTLED SOLIDS
ORIGINAL THICKNESS
T f
FROZEN SLUDGE

FIGURE 8



DEGREE CELCIUS - DAYS (C - Days)
2000
1500
1000
500
0
ATI (ROBB, ALBERTA) = 1864 C - Days
PREDICTED THAW THICKNESS
0
0.5
1
1.5
2
LAYER THICKNESS (m)

FIGURE 9



TOTAL FROZEN LAYER THICKNESS (m)
10
8
6
4
2
0
AFI = 1316 C - days
AFI = 658 C - days
THAW THICKNESS = 2.5 m
THAW THICKNESS = 1.5 m
0
0.15
0.31
0.40
0.5
0.75
1
1.5
PLACEMENT LAYER THICKNESS (m)

FIGURE 10

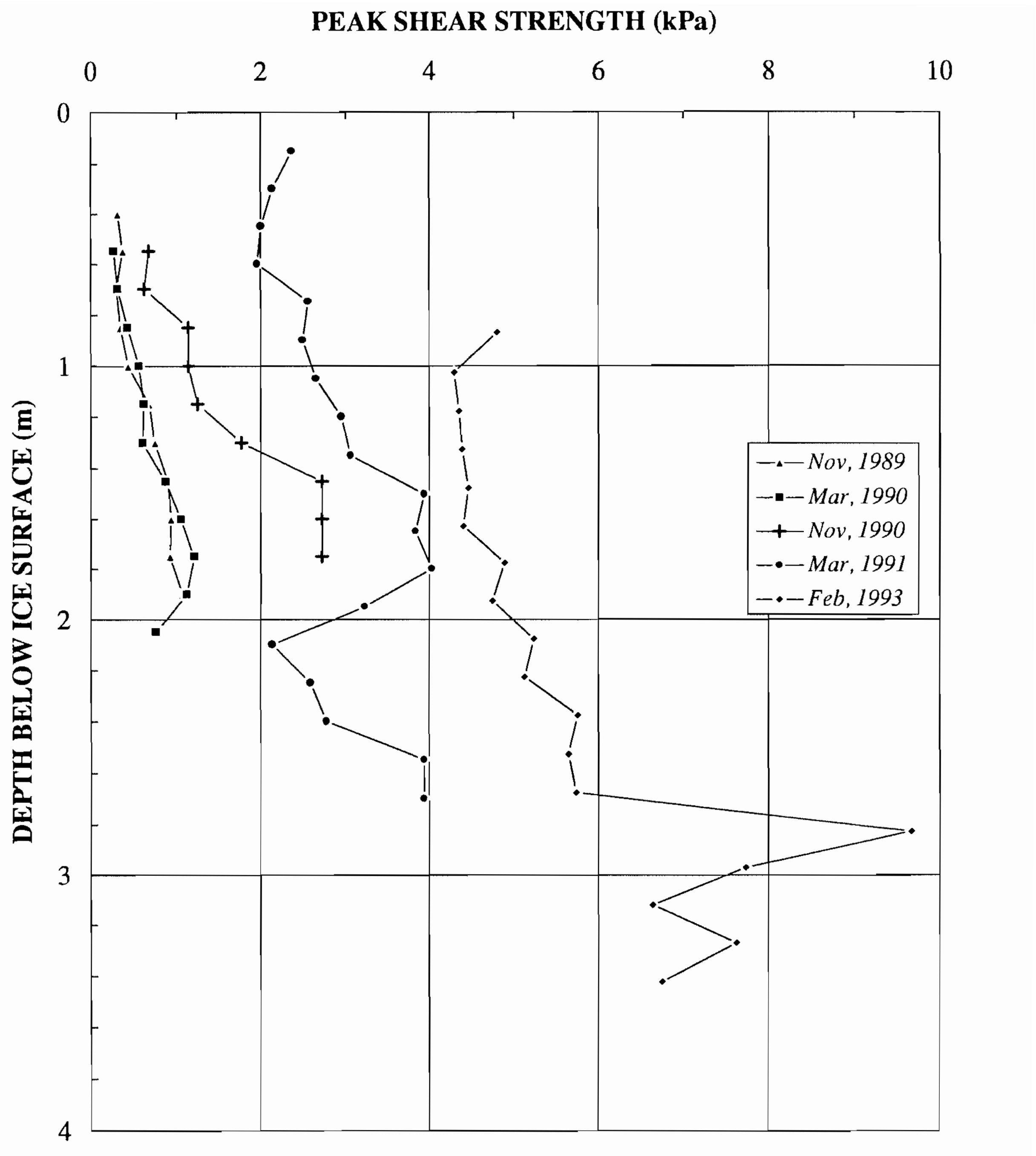

PEAK SHEAR STRENGTH (kPa)
0
2
4
6
8
10
0
1
2
3
4
DEPTH BELOW ICE SURFACE (m)
Nov, 1989
Mar, 1990
Nov, 1990
Mar, 1991
Feb, 1993

FIGURE 11

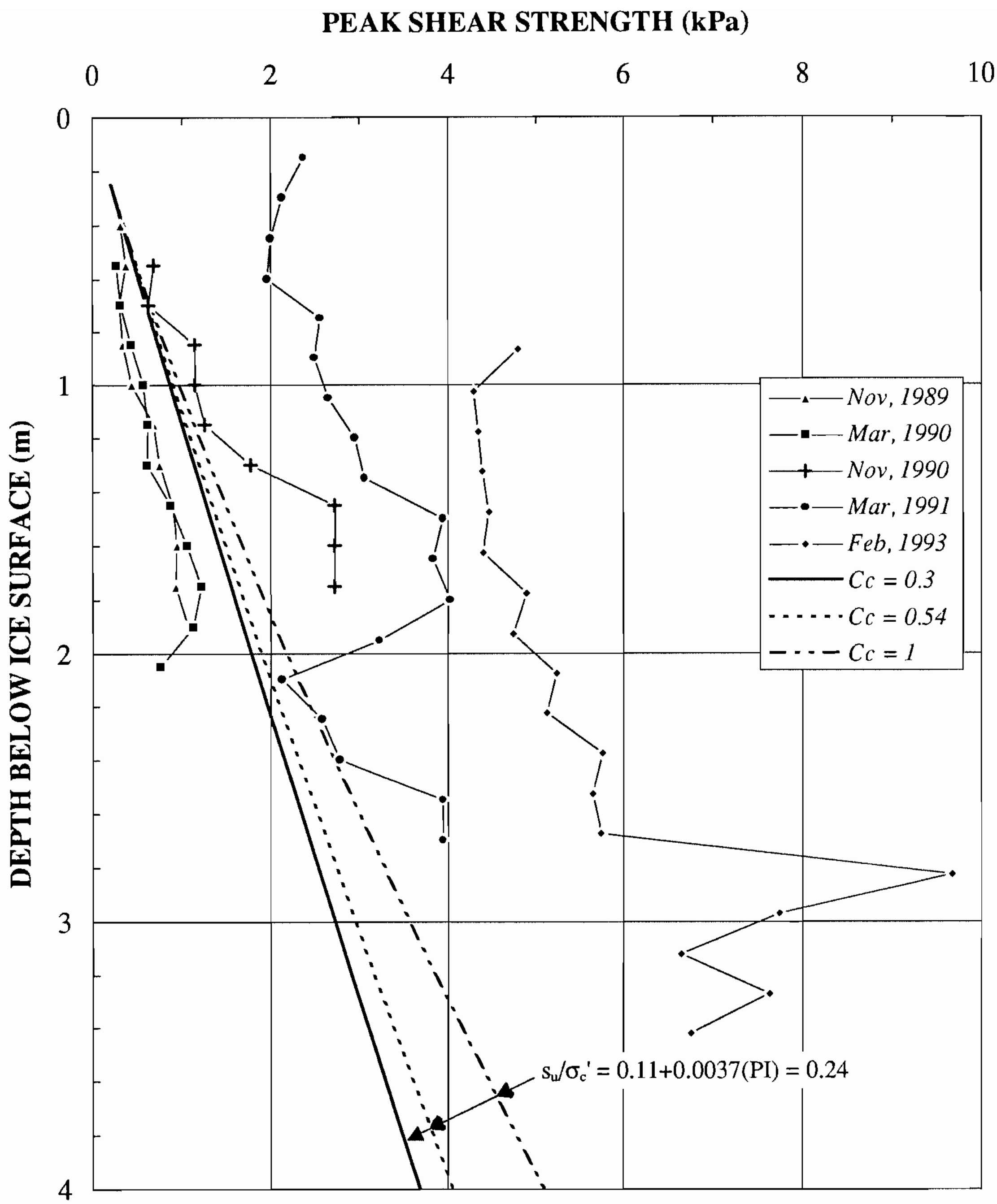


FIGURE 12

FIGURE 12

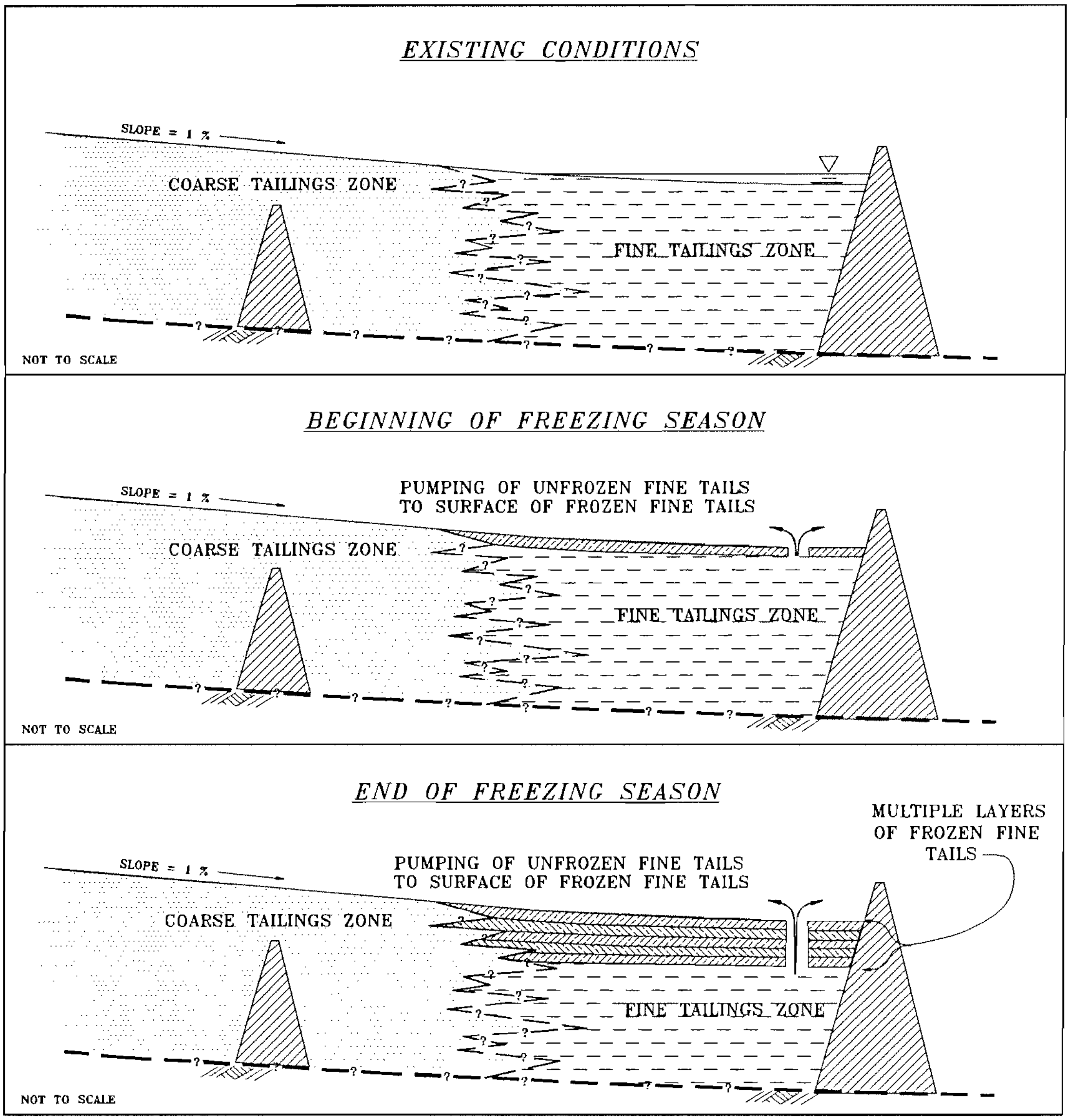


FIGURE 13

FIGURE 13