SEASONAL AND CLIMATIC WARMING EFFECTS ON PILE CREEP IN PERMAFROST

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Abstract

A one-dimensional geothermal model for predicting the temperature distribution in the ground has been modified to (a) simply simulate a climatic warming trend by adding 0.1 °C/year to the applied surface temperatures, and (b) to calculate the creep rate of a cylindrical pile embedded in the upper permafrost strata. The analysis shows that permafrost has considerable thermal inertia in the upper 6-9m, and warming at depth due to climatic warming takes place at a reduced rate when compared with the ground surface. Seasonal pile creep effects are explored, and the increase in pile settlement rate that occurs in late summer is very much more pronounced for saline permafrost sites. Climatic warming effects on pile creep settlement are also predicted to be more pronounced for saline permafrost areas.

Résumé

Un modèle géothermique unidimensionnel de prévision de la distribution de température dans le sol a été modifié pour a) simuler simplement une tendance au réchauffement du climat en haussant de 0,1 °C/an les températures superficielles appliquées et b) calculer le taux de fluage d'un pilier cylindrique enfoui dans les couches supérieures du pergélisol. L'analyse montre que le pergélisol a une inertie thermique considérable dans les premiers 6 à 9 m et que le réchauffement en profondeur dû au réchauffement du climat est moins rapide qu'en surface. Les effets saisonniers de fluage des piliers sont explorés, et l'augmentation de la vitesse de tassement des piliers à la fin de l'été est beaucoup plus marquée dans les pergélisols salins. Les effets du réchauffement du climat sur le fluage des piliers sont plus marqués, comme prévu, dans les régions à pergélisol salin.

Introduction

There is considerable debate at the present whether a gradual warming trend in air temperatures is taking place. Undoubtedly, an increase in reflective gases in the atmosphere is occurring, but no clear link to ambient air warming trends has been established. Climatic trends that would cause warming in permafrost (if a permanent trend exists) might be modelled in several ways. These would include increasing ambient air temperatures, increasing greenhouse factor (i,e, fraction of back-reflected long-wave radiation), or alterations in the surface wetness or snow cover.

If a steady warming trend takes place in a permafrost area, the ground temperatures at depth would respond with a damped version of the same warming trend. Many northern communities have buildings supported on pile foundations. Piles in warm icy permafrost creep continuously over their design life, and the normal design approach is to maintain a sufficiently low pile shaft stress to limit creep settlement to a tolerable level (Nixon, 1978). If a warming trend takes place at depth, the pile settlement rate might accelerate with time.

Many northern coastal communities are underlain by saline permafrost (Nixon, 1988; and Biggar & Sego, 1990). This material is known to be even more sensitive to creep and temperature effects, and pile foundations in such materials may also experience acceleration in creep settlements over their design lifetime.

Although future structures may incorporate some consideration of climatic warming in their design, northern structures completed in the recent past do not have any allowance for climatic warming. The stability of the foundations of such structures is therefore of concern, and it is of interest to evaluate the potential effects of a surface warming trend on long term performance of pile foundations in permafrost.

Whether or not a permanent long-term climatic warming trend is in place, this article reviews some of the available ambient air temperature data for some northern communities, and then carries out a preliminary study of the predicted effects of surface warming on the creep of typical pile foundations in warm, discontinuous permafrost, and in a colder saline permafrost environment.

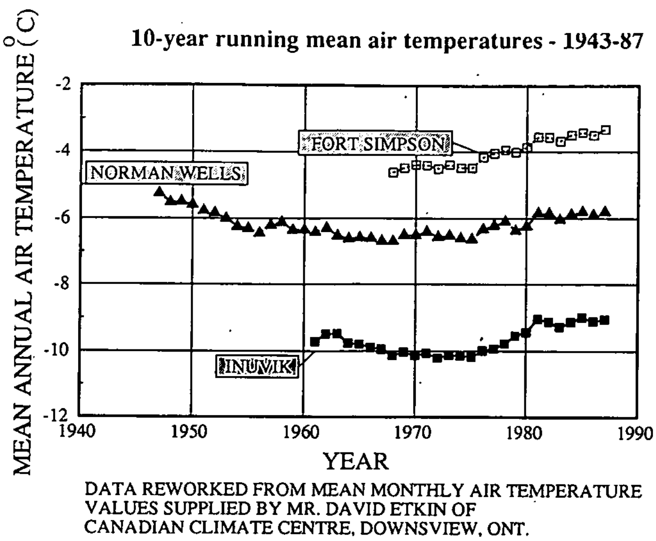


Figure 1. Long-term mean annual temperature variations for Mackenzie Valley.

Trends in air temperatures in the Mackenzie valley

One area of Arctic Canada, i.e. the Mackenzie Valley was selected for a brief review of long term air temperature trends. Mr. D. Etkin of the Canadian Climate Centre, Environment Canada supplied the writer with the digitized mean monthly records for Inuvik, Norman Wells and Fort Simpson, since record-keeping began. These records were averaged to obtain the mean annual temperatures, and are plotted as a running 10-year average as shown on Figure 1. Norman Wells has the longest record period, dating back to the 1940s. The records indicate that a warming of about 1.0 °C has occurred over the 15 last years. The same records indicate, however, that a continuous cooling trend over the previous 20 years of about 1.0 °C also took place. Consequently, the data indicate that the mean air temperatures are at a similar level as they were 35 years ago.

More data of this nature need to be evaluated, however, before any firm conclusions can be drawn. However, bearing in mind that CO_2 and other reflective gases have been steadily increasing over the same 35-year period, no concrete relationships between air temperatures and atmospheric gas build-up is apparent. As the North American climate has been cycling up and down over recorded history, it seems possible that the current warming trend is another fluctuation in an ongoing series of cyclic variations.

The situation is further complicated by the fact that mean snow cover in the Mackenzie Valley area appears to have decreased significantly over the past 20-30 years (Judge, personal communication), although no definitive rates of decrease have been established for different Arctic regions. A combination of diminishing snow cover and slowly increasing ambient air temperatures could easily result in a *cooling* trend in ground temperatures at depth, depending on the relative rates of change of each.

However, if the current warming trend of 0.05-0.1 °C/year continues for another 25 years or more, then structures currently founded on discontinuous permafrost, or soon to be built on icy frozen ground may experience some negative effects, if the thickness and duration of winter snow cover remains much the same.

Geothermal model

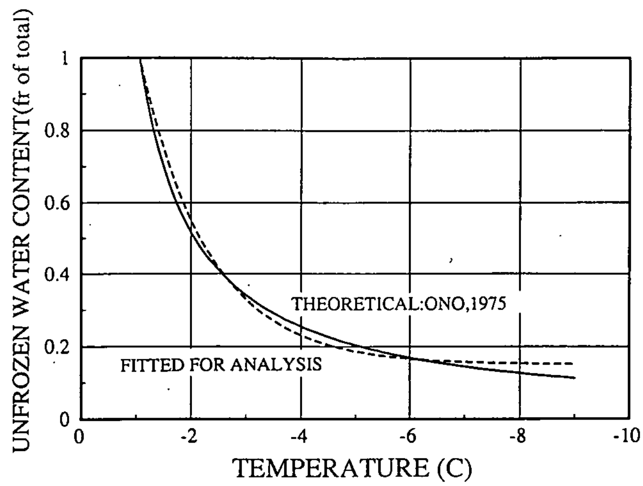
The writer's PC-based 1-D geothermal model was used to predict the temperature profiles over a 25-year period in 2 permafrost situations.

(a) Warm, Fresh water permafrost.

A typical fine-grained soil profile in a discontinuous permafrost area with an average temperature of -1.3 °C was established. The fresh water soil unfrozen water content curve was expressed by:

Table 1
MEAN MONTHLY SURFACE TEMPERATURES AND SNOW COVER

	<—(DISCONTINUOUS)—>		<—(SALINE SITE)—>	
MONTH	SURFACE TEMPERATURE (°C)	SNOW COVER, cm	SURFACE TEMP. (°C)	SNOW COVER
JANUARY	-24.4	43.2	-25.6	13.0
FEBRUARY	-18.0	50.8	-25.9	10.0
MARCH	-12.8	40.6	-22.7	12.0
APRIL	-2.3	7.6	-14.3	10.0
MAY	6.86	0.0	-3.2	5.0
JUNE	14.42	0.0	5.1	0
JULY	17.22	0.0	11.4	0
AUGUST	14.56	0.0	10.4	0
SEPTEMBER	7.14	0.0	3.6	0
OCTOBER	-3.2	10.2	-5.0	5.0
NOVEMBER	-13.4	12.7	-13.0	7.0
DECEMBER	-22.0	33.0	-21.8	8.0



"THEORETICAL" CURVE FROM ONO(1975) FOR 20ppt SALINE ICE
"FITTED" CURVE USED BY GEOTHERMAL PROGRAM
GIVEN BY Wu = 0.15+0.85exp(0.8(T-To)
INITIAL FREEZING POINT, To = -1C

Figure 2. Theoretical and fitted unfrozen water content curves for saline permafrost.

$$W_u = 0.2 + 0.8 \exp(2T) \quad (1)$$

where W_u is the fraction of the total water content remaining unfrozen,
and T is the soil temperature in degrees C.

This was used to model the gradual phase change over a range of negative temperatures. The soil was assumed to have a water content of 25 % by dry weight, with thawed and frozen thermal conductivities of 1.55 and 2.0 W/mK respectively. A surface layer of peat of 200 % water content and 0.3m in thickness was also present.

The mean surface air temperatures were increased by an n-factor of 1.3 in summer, to simply model the summer ground surface temperatures. The winter ambient air temperatures were applied directly to the snow surface. The air temperatures and monthly snow cover values used in the simulation are given in Table 1.

(b) Saline permafrost

A second site in a cooler, continuous permafrost area was also modelled. At this site, the permafrost was assumed to be saline, and characteristic of many northern coastal communities. Ambient temperatures for Iqaliut, Baffin Is., NWT were selected as typical of this class of saline permafrost environment, with a mean ground temperature of -5 °C. For simplicity, the salinity of the fine-grained soil for this case was assumed to be constant with depth at 20 ppt. The unfrozen water content curve for this soil was estimated based on the theoretical relationship for sea ice from Ono (1975), and is shown on Figure 2. The writer's 1-D simulator employs an exponential relationship between unfrozen water content and temperature, and the "fitted" curve for unfrozen water content is also given on Figure 2, and is

$$W_u = 0.15 + 0.85 \exp(0.8(T-T_o))$$

where T_o is the initial freezing point, and is -1 °C for the saline soil.

Mean ground surface temperatures and snow cover used in the geothermal analysis for this case are also given on Table 1.

Pile creep analysis

The method of predicting pile creep in permafrost is detailed in Nixon (1978), and elsewhere. The method is based on the theory adapted by Johnston and Ladanyi (1972), and has been extended by Nixon and Neukirchner (1986) to handle saline permafrost and temperature profiles that vary with depth and time. An element of a cylindrical pile in icy permafrost creeps at a rate given by:

$$u = 4.5\, a\, B\, \tau_a^n \quad (2)$$

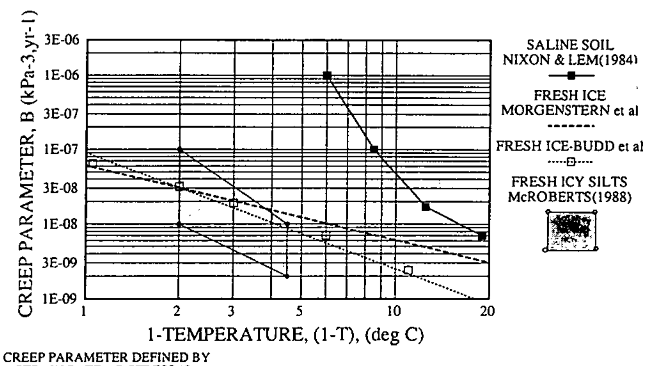
where u is the pile element creep rate
a is the pile radius
τa is the pile shaft stress
B is the secondary creep parameter
and n is the secondary creep exponent.

The parameter, B, can be obtained from Morgenstern *et al* (1980) for ice or icy soils, and from Nixon and Neukirchner (1986) for saline soils. More recently, a good synthesis for the creep behaviour of ice by Budd and Jacka (1989) provides guidance on the relationship between creep rates and temperature. Further, in an extension of some of his earlier work on icy frozen soils, McRoberts (1978) provides an extensive secondary creep data base for icy frozen silts, clays and organic soils at different temperatures in the range of -0.5 to -4.1 °C. These data sources are shown together with earlier data for the secondary creep of ice on Figure 3.

The earlier creep relationship of Morgenstern *et al* (1980) used for fresh water ice or icy soils has been adopted for this study, and is given by:

$$B = 6.1 \times 10^{-8} / (1-T)\ ;\ kPa^{-3}\, yr^{-1} \quad (3)$$
$$\text{and } n = 3.$$

For saline soils, a different relationship with temperature must be sought, due to the large percentage of water changing phase close to the melting point. Based on the data of Nixon & Lem (1984) and others, a tentative correlation for the secondary creep parameter, B, can be established as:



CREEP PARAMETER DEFINED BY
STRAIN RATE = B STRESS ^3
from : Nixon & Neukirchner(1986)
B = 6.1E-8 (1-T)^-1 FOR FRESH WATER SOILS
B = 0.000021(-2-T)^-3 FOR SALINE SOILS

Figure 3. Creep parameter, B, for frozen soils correlated with temperature.

$$B = 2.1 \times 10^{-5} / (-2-T)^3 \quad (4)$$

This relationship is also reviewed on Figure 3, and shows the striking increases in creep rate that can be experienced for saline soils, particularly near the melting temperature.

Assuming that the pile is incompressible, and that u is the same for each pile element, the contribution of each element along the pile can be assessed in terms of the local temperature of the surrounding ground at that depth. Therefore, at each time step, the creep rate of the incompressible pile with a constant total load can be computed for any arbitrary temperature profile. A procedure to calculate the creep parameter, B, was incorporated in the writer's 1-D geothermal program, and a numerical integration was carried out to predict the creep rate of a pile at each time step. The total accumulated creep of the pile was also tracked as time progressed.

The base case pile dimensions for this study were assumed to be:
Pile length below ground = 6.0m, with one run for 9.0m;
Pile radius = 0.1m
Pile load = 200 kN for the fresh water case,
and 100 kN for the saline permafrost case.

When the temperature was predicted to rise above 0°C in the summer active layer, the strength contribution of these soil layers was assumed to be zero. For the saline permafrost case, no strength contribution was assumed once the temperature rose above -2°C.

Geothermal analysis and pile settlement

(a) Fresh water discontinuous permafrost

Figure 4 shows a 25-year simulation of the ground temperature profile for the non-saline discontinuous permafrost site. Only the temperature at the 3m depth has been plotted. The ground temperature amplitude at this depth is 0.5°C, but would of course vary depending on the depth below ground surface.

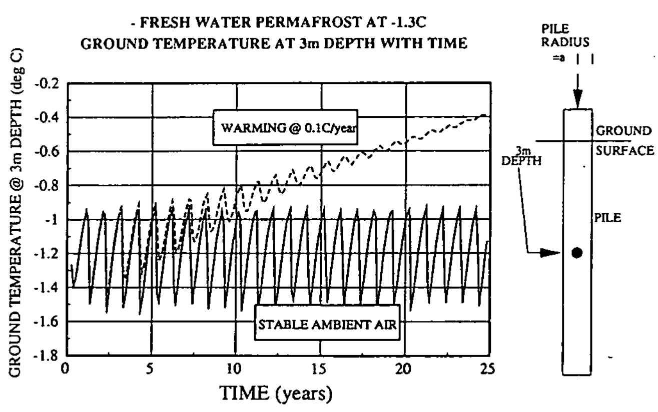


Figure 4. Effect of climatic warming on predicted ground temperatures.

Figure 4 also shows the effects of imposing a "ramp" surface temperature increase to the present-day "stable" surface temperature distribution. The temperature increase equal to 0.1x(time) was simply added directly to the current surface temperature, with no regard for different amounts of warming that could occur in winter or in summer, or possible changes in snow cover that could accompany such ambient temperature changes. The predicted temperature at a depth of 3m rises at an average rate of about 0.033°C/year, or about one-third of the imposed rate of surface warming. The rate of warming in the ground would of course diminish with depth.

This simplified simulation indicates that the effects of a surface warming trend would vary along the shaft of an embedded pile. Therefore, it is necessary to carefully integrate these effects along the full depth of the pile, to obtain the overall effects of climatic warming.

Figure 5 shows the normalized pile settlement rate plotted with time for the 25 year duration of the simulation. The normalized pile settlement rate when presented in this form does not appear to be dependent on the pile radius, provided the average pile shaft stress is maintained the same. The seasonal fluctuations in pile settlement rate are apparent from Figure 5, and the normalized rate varies from 0.012 to 0.037 year^{-1} from winter to summer. The average annual settlement rate is about 2.3 mm/yr, or a normalised settlement rate of 0.023 year-1. It is of interest to compute the average settlement rate if the temperature were constant at -1.3°C. The creep parameter would be 2.65×10^{-8} from the creep data reviewed earlier. Assuming an active layer 1m thick is ignored for load bearing along the pile shaft, an average shaft stress of 53 kPa is calculated. The simple pile creep equation reviewed earlier gives a pile creep rate of 1.77 mm/year, or a normalised creep rate of 0.0177 year^{-1}. This is closer to the lower (winter) rate of pile settlement, and indicates the importance of using the predicted seasonal creep rates, or at least pile creep rates based on some warmer, late summer temperature profile.

When the surface temperature warming effect was superimposed to the surface temperatures used in the

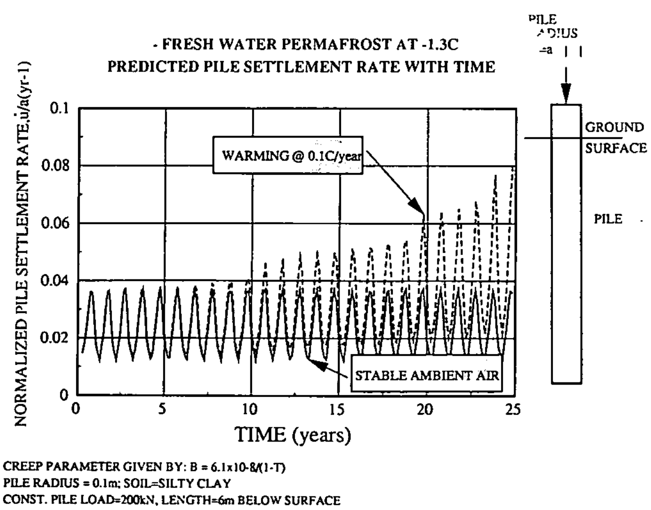


Figure 5. Pile creep rates for fresh water permafrost.

geothermal analysis, the pile settlement rates started to increase at a significant rate after about 10 years after the start of warming. The average settlement rate had reached 0.05 year-1 after 25 years of simulation. Although only one pile length was studied for this article, the depth of pile embedment would be clearly be important in limiting the effects of the surface warming trends.

Finally, Figure 6 shows the predicted pile settlement for a pile radius of 0.1m with time. The "present-day" pile settlement after 25 years was 58 mm, whereas the equivalent pile settlement for the case including climatic warming was 77 mm. This is a 33% increase over the settlement expected if present-day conditions persisted. But Figure 6 clearly indicates the steadily deteriorating conditions if the assumed warming trend were to continue.

(b) Saline continuous permafrost

Figure 7 shows a similar ground temperature history at 3m depth for a pile in saline permafrost, having a mean ground temperature around -5.5°C. When the surface ramp condition due to climatic warming is imposed, the summer peak temperatures rise quite slowly, due to the large amount of water changing phase at colder temperatures in the saline soil. The winter minimum temperatures rise more quickly, however, with a greatly decreasing amplitude as the warming trend continues.

The seasonal rates of pile settlement vary much more widely than for fresh water soils (fig 8). For the 100 kN load studied, the late summer normalised rates are as high as 0.25 year^{-1}, and late winter rates almost zero. The temperature variations at different depths along the pile shaft are such as to result in large increases in late summer pile creep rates, whereas the late winter creep rates are not seriously increased due to cold temperatures along the upper parts of the pile shaft.

The effects of surface warming would appear to result in a doubling of the total accrued pile creep settlement over a 25 year period (fig 9).

Finally, the pile length in the saline soil was increased by 50% to check if the effects of climatic warming could be reduced by increased embedment. The overall settlement rates are considerably reduced, of course. However, the percentage increase in total settlement resulting from climatic warming appears to be much the same (fig 10).

In some cases where the ground temperatures are closer to the melting point, the acceleration in pile settlement might be more severe. Designers may also have to check for conditions where the ultimate adfreeze strength of the soil might be exceeded in the upper soil strata.

Conclusions

Geothermal and pile creep models have been combined to indicate some of the potential effects of climatic warming on pile foundations in permafrost. Depending on the

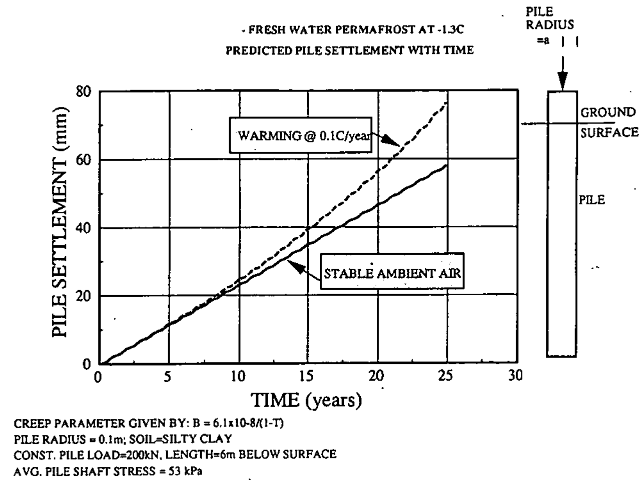


Figure 6. Predicted pile settlement for fresh water permafrost.

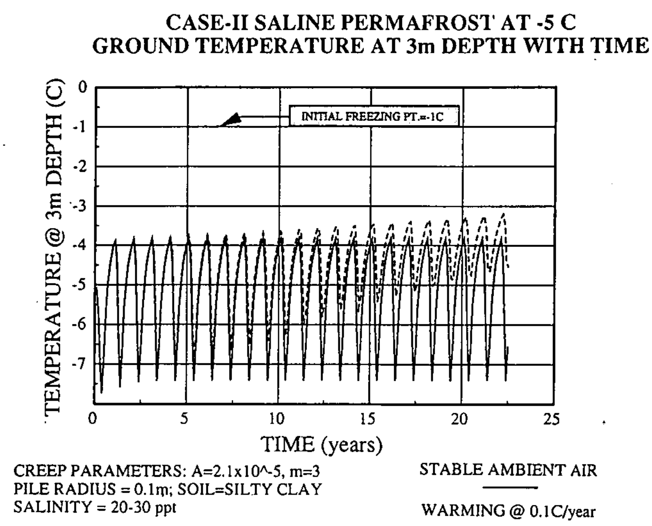


Figure 7. Predicted ground temperatures in saline permafrost.

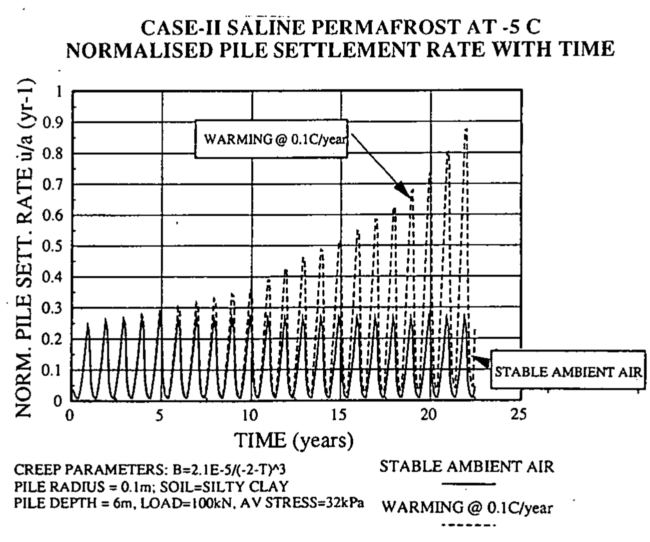


Figure 8. Pile creep rates for saline permafrost.

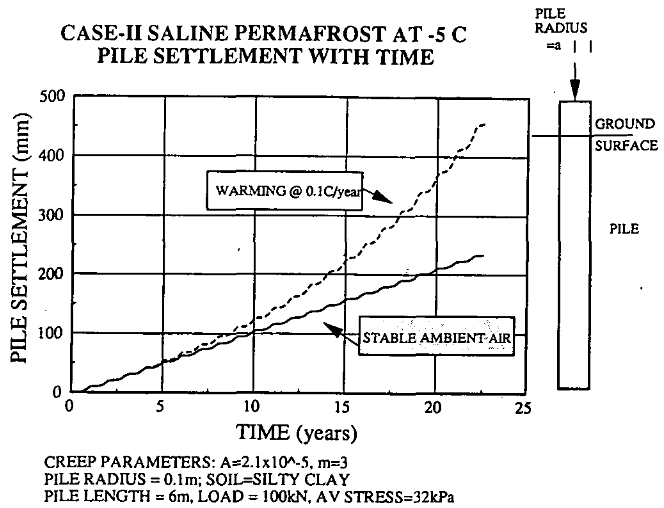


Figure 9. Predicted pile settlement for saline permafrost.

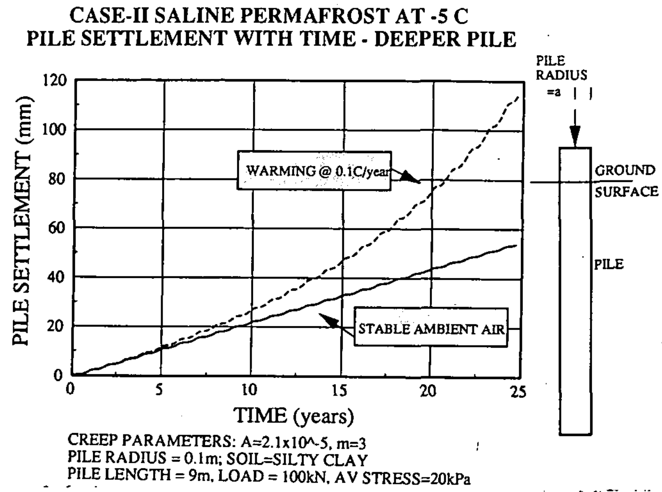


Figure 10. Pile settlement in saline permafrost-deeper pile.

embedment depth of the pile in the permafrost, significant warming and increase in pile settlement rates might be anticipated over the design life of a pile if current warming trends continue. More work is required to evaluate these effects over a wider range of pile, soil and ground temperature conditions. However, it still remains to establish whether increasing amounts of atmospheric gases will result in a long-term continuing warming trend in temperatures in the Arctic. Clearly, long-term ambient temperature warming trends with no decrease in snow cover will bring about significant increases in pile settlement rate. However, these increased rates will not occur for several years after the surface warming trends have been initiated, due to the significant thermal inertia of the soil strata around the pile.

Recommendations for research

As stated above, the brief analysis carried out here should be extended to a wider variety of pile and ground temperature conditions.

Several structures on pile foundations should be selected and monitored in the long term for evidence of increasing rates of pile settlement, that can be related to increasing ground temperature trends. This will not be an easy task, as it may be difficult to isolate the effects of climatic warming from thermal changes resulting from the presence of the building itself, for example.

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