PILE SETTLEMENT IN SALINE PERMAFROST: A CASE HISTORY

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Abstract

A three-story office building was constructed in Barrow, Alaska, on steel pipe piles with a sand-water slurry for adfreeze support in cold permafrost. During the final stages of construction in early 1986, unacceptable settlement of the building became obvious. Settlement and ground temperature data have been collected since then, and a subsurface investigation revealed that the piles were embedded in cold permafrost soils with salt contents of up to 35 ppt. Settlement rates were determined from periodic level surveys of the piles and were correlated with pile loads which range from 58 to 404 kN and with ground temperature variations.

The survey data shows that the settlement rates are strongly related to ground temperatures. The settlement was effectively stopped by placing a layer of insulation at the ground surface. The insulation reduced the amplitude of the seasonal ground temperatures, and provided colder temperatures at the end of the summer which appear to have stopped the settlement. The measured rates during the rapid settlements in 1986 appear to be larger than predicted from the previously published data and methods. Results of the investigation, settlement patterns and ground temperatures are presented.

Résumé

Un édifice à bureaux de trois étages à Barrow, en Alaska, a été construit sur du pergélisol froid et installé sur des pieux en tuyau d'acier avec, pour assurer l'adhérence au gel, un coulis composé de sable et d'eau. Durant les étapes finales de la construction au début de 1986, il devint évident que l'édifice connaisait un affaissement excessif. Le tassement et la température du sol ont été mesurés depuis lors et une investigation du substrat a révelé que les pieux étaient enfoncés dans du pergélisol froid avec une teneur en sels allant jusqu'à 35 ppt. Les taux du tassement furent déterminés par le nivellement périodique des pieux et furent mis en corrélation avec la charge des pieux, variable de 58 à 404 kN, et avec les variations thermiques du sol.

Les taux de tassement sont liés de près aux températures du sol. Le tassement a pu être efficacement stoppé grâce à l'installation d'une couche d'isolant à la surface du sol. L'isolation a réduit l'amplitude thermique saisonnière du sol et a assuré des températures plus froides du pergélisol à la fin de l'été ce qui, de toute apparence, a mis fin au tassement. Les taux mesurés durant le tassement rapide de 1986 sont supérieurs à ce qu'on trouve dans la littérature spécialisée. Les résultats de l'investigation géotechnique, les patrons de tassements et les températures du sol sont présentées.

Introduction

The three-story office building that would house the State Courthouse in Barrow, Alaska, was designed in 1984, and construction was started that fall. Settlement of the structure was obvious by March 1986. The ceramic tile on the entry lobby floor was cracked, the floor was visually unlevel, sheetrock was cracking, and several doors were jammed. Furthermore, the distress to the building appeared to be getting worse with time. The cause of the movements had to be identified and the movements stopped.

The pile foundation system had been designed using criteria that had been successfully applied to many other projects in Barrow and at other sites on Alaska's North Slope. The permafrost was cold and visually appeared to be well frozen. The piles had been installed under the full time inspection of an experienced engineer who verified that the design criteria had been satisfied. Ground temperature measurements showed that the elevated structure and space beneath the building were keeping the permafrost in a cold, frozen condition as assumed in the design.

Brine pockets are common in the permafrost beneath Barrow at depths of 3 to 5 m. The brine layers are observed as water flowing or weeping from the side walls of auger holes where high salt contents depress the freezing point of the pore fluid. However, no brine zones were observed in the permafrost during either the investigation or pile installation. The initial investigation for design had included only one salinity test. The test of a sample from a depth of 5 m showed a freezing point depression of 1.5°C. This was not considered to be significant because it was well above the temperature of the ground. Shallow piles designed to gain support from the bonded soils above possible brine layers had been used before in Barrow and appeared to be performing satisfactorily.

Figure 1. Courthouse building in Barrow.

Theory

The design and construction of the foundation system was performed without the knowledge of the precedent setting work by Nixon and Lem (1984) and Nixon and Neukirchner (1984) which provided some of the first creep rate properties for saline permafrost and placed the design of piling in such soils on a rational basis. The data collected during the investigation of the foundation settlement failure at the State Courthouse building provides general confirmation of the data and design procedures presented in those two papers.

As discussed by Nixon and Neukirchner, the theory for creep settlement of piles as derived from the non-linear creep law can be expressed using the following equation

$$\dot{u}_a = \frac{3^{(n+1)/2} a B \tau_a^n}{n-1}$$

where $\dot{u}_a$ = pile displacement rate,
a = pile radius,
τ_a = the applied stress on the pile shaft,
n = creep exponent, and
B = creep coefficient

The literature suggests that the creep exponent, n, is normally between 3 and 7 depending on stress levels, soil type and salinity; a value of 3 is commonly used. The parameter B depends on soil type, ice content, salinity and temperature. The laboratory data for saline soils by Nixon and Lem (1984) shows that B has a wide range of values for slight changes in salinity and temperature.

The site, the design and the construction

Barrow, at a latitude of 71°18', is the most northern community on the North American continent. The village is located on the coast of the Arctic Ocean at the boundary between the Chukchi and Beaufort Seas. The climate is arctic with an average air temperature of -12.7°C. and average freezing and thawing indices of about 4800°C-days and 300°C-days. The village serves as the commercial and governmental center for the North Slope region of Alaska and has a population of about 4000.

Barrow is underlain by unconsolidated sediments of the Gubic Formation which consist of lenses and mixtures of sand, gravel, silt and clay. Although mainly of marine origin, the formation has also been modified by alluvial, lacustrine, eolian, and freezing processes. Permafrost underlies the area and is as deep as 400 m below Barrow. Typical ground temperatures at depth in the area are -9.5°C.

The site for the office building is located about 100 m southeast of the Chukchi Sea beach line in the central commercial area of Barrow. The site slopes gently towards the beach and is well drained. The site had been covered with fill many years before the construction of the office building. The soil investigation for the building found the silty sand fill layer to average about 1.5 m thick and overlying a 1 m thick layer of ice and ice-rich silt. Below the icy soils were silt and sand mixtures with moderate ice content.

The office building is three stories high plus a mechanical-room penthouse and has plan dimensions of 31 m by 27 m. The entry corner is cutoff at a 45° diagonal. The structure is wood frame with the subfloor of the bottom level consisting of four rows of glulam beams with web trusses spanning between the glulams. The four main rows of glulams are spaced 10.4 m apart and are supported by the pile foundation. The design loads on the piles under the main lines of glulams varies from about 133 kN to 787 kN. The sustained live loads were estimated to be about one-third of the code live load, so the actual sustained total loads on the piles, dead plus sustained live load, were estimated to be from 58 kN to 404 kN per pile.

The piles are all steel pipe except for the lightly loaded entry grate area which is supported on three timber piles. The pipe piles are all 457 mm in diameter, and their tips are closed with a steel plate. The piles were installed to depths of 4.0 m to 5.9 m below finish grade with the average depth being about 4.7 m. The pile lengths were designed to prevent long term adfreeze failure and included a factor of safety of 3. The deeper embedments were to compensate for massive ice encountered in the upper part of the pile hole. The top 0.61 m of each pile was greased and wrapped with plastic sheeting to provide a bond break with the active layer and to avoid frost jacking.

The contractor installed the piles in the first half of September 1984. The piles were placed in 0.61 m diameter holes that had been drilled using a Highway auger. The annulus around the pile was backfilled in lifts with a sand-water slurry, and each lift was rodded thoroughly to achieve a dense, saturated backfill. The slurry was made using potable water and a slightly silty, gravelly sand. A few days after installation, the piles were cut off to the design grades, a one-inch thick steel cap was welded to their top, and construction of the superstructure was started with the placement of the glulams.

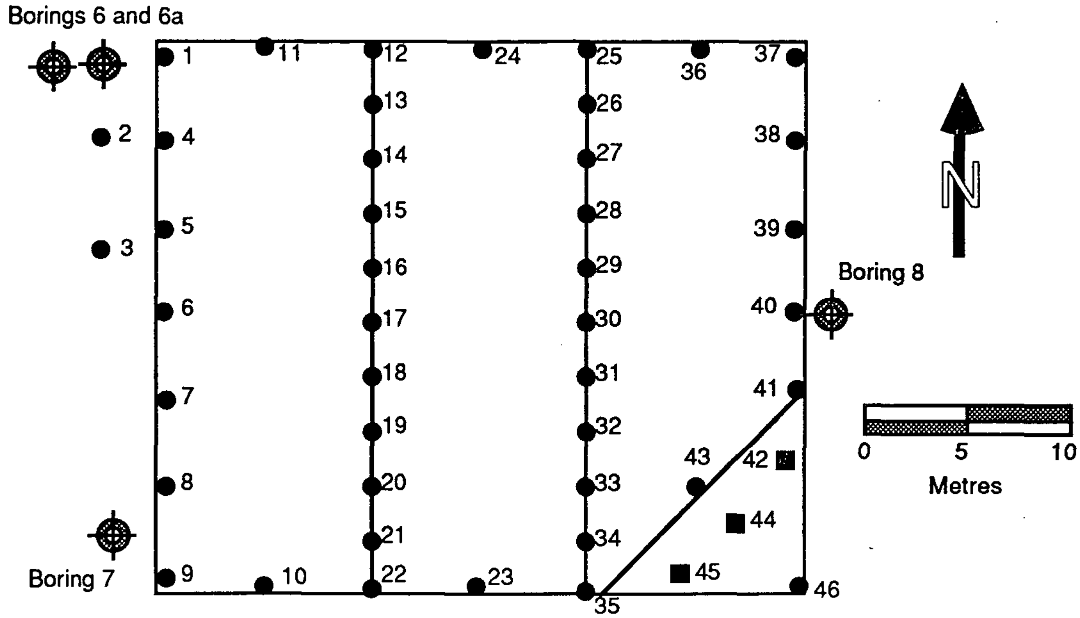

Figure 2. Pile plan and boring locations.

The investigation

When the distress to the building was noticed and brought to the attention of the design team in April 1986, a program of ground temperature measurements and level surveys was immediately started. Four piles had been instrumented for temperature measurements when the foundation was constructed, and the multi-point thermistor strings at these piles were used for the initial ground temperature measurements. In December 1986, five additional thermistor strings were installed by suspending the strings inside the pipe piles. The thermistor strings were constructed to provide an accuracy of ±0.1 °C.

An initial level survey was performed of all of the piles on April 30, 1986, using a self-leveling level and short level rod to determine the relative elevations of the pile caps. The initial level surveys allowed direct measurements to 3 mm with an estimated reading to 0.3 mm. This technique was continued until May 1987 when Invar rod was permanently fixed to each pile. All the level surveys performed from May 1987 were performed using a geodetic level which allows a direct reading of the Invar rod to a precision of 0.03 mm. This data collection program with some refinements has been continued to date.

To provide more detailed information on ice content and salinity, three additional borings were drilled and sampled around the perimeter of the building in late November and early December 1986. The borings were drilled to depths of 9.1 m to 15.2 m with a drill rig equipped with hollow stem augers. The borings were sampled by driving a 63 mm inside

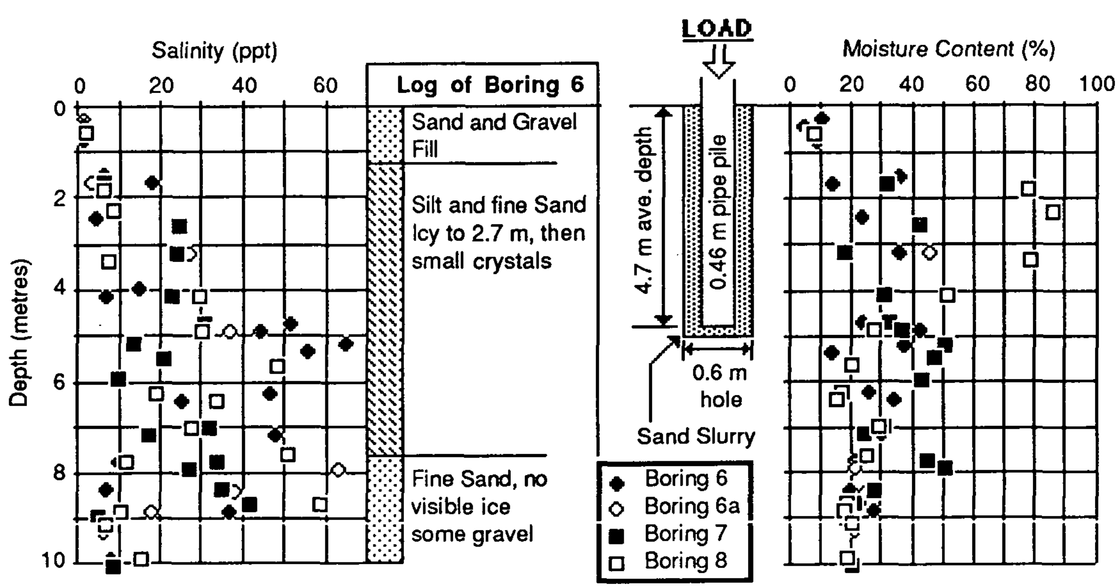

Figure 3. Soil types, salinity, moisture content and pile design versus depth.

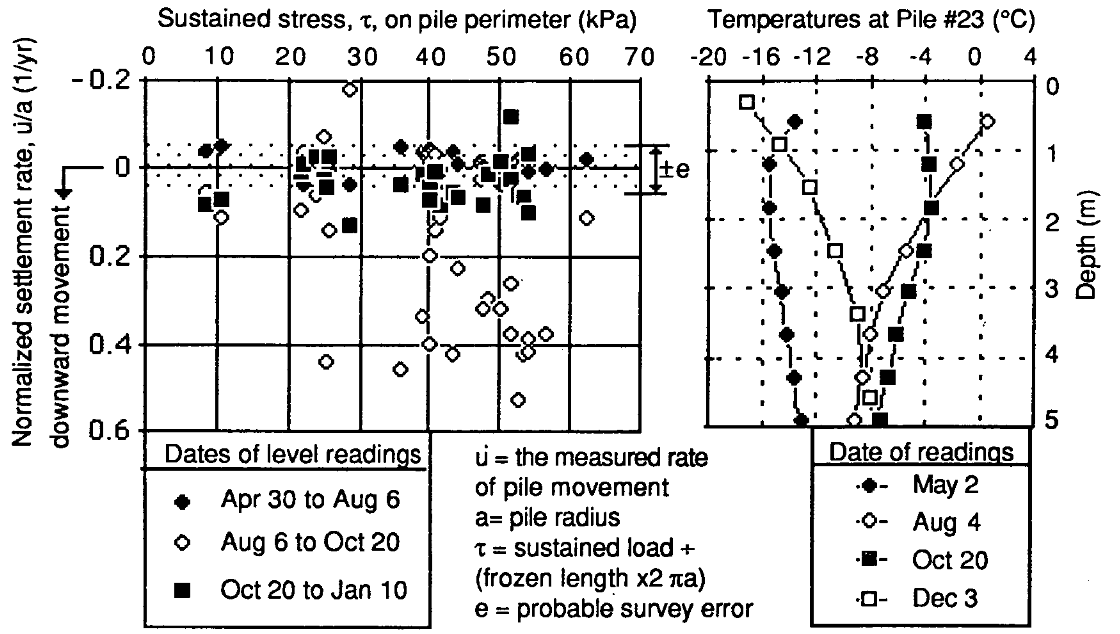

Figure 4. 1986 Settlement rates and temperatures.

diameter, split barrel sampler into the permafrost using a drop hammer. The samples were tested in the laboratory for moisture content, salinity of the pore fluid, and classification. Salinities were determined by measuring the electrical conductivity of the thawed pore fluid and calculating the salinity using the relationships for seawater presented in the Handbook of Chemistry and Physics. As shown in Figure 3, the salinity at the site increases with depth and reaches values equal or greater than 25 parts per thousand (ppt) below depths of about 2.5 m to 3 m. At depths of 5 m the pore fluid salinity is as high as 65 ppt, about twice the value of seawater.

The settlement pattern and the solution

At first the results of the level survey were inconclusive. The data from April to August showed no significant movement over the 98 days. Then the October measurements were made, and almost all of the piles showed a significant settlement. The average pile settlement in the preceding 75 days showed an annual rate of movement normalized to the pile radius ($\dot{u}_a/a$) of 0.22 yr^{-1} with many piles moving as fast as 0.4 yr^{-1}. The level readings were checked two weeks later, and the rates were significantly lower. The average rate of movement from October to January dropped to 0.06 yr^{-1}, as shown on Figure 4.

Several options were considered for stopping or slowing the settlement of the building. Since the creep rate of the piles in the saline soils appeared to be very sensitive to ground temperature, various schemes were evaluated to cool the ground. These included conversion of the pipe piles to passively or actively refrigerated systems or installation of horizontal cooling systems in the soil. Since all of these cooling options involved surface insulation to reduce the heat gain in the summer months, surface insulation alone was tried as the first step in slowing the pile settlement. Computer modeling showed that a surface layer of insulation would reduce the amplitude of the ground temperature variation so that the creep rates might be reduced to an acceptable level.

A 100-mm thick layer of rigid, board insulation was placed on the ground surface beneath the building in May 1987 to lock in the cold ground temperatures from the preceding winter. The surface of the ground was smoothed with a thin sand layer, and two layers of 50-mm thick insulation were placed with their joints offset. Because of the limited height of the blow-through space under the building, a protective layer of fill could not be placed on the insulation. Instead the boards are held in place by the weight of steel straps. A protective membrane is to be placed over the insulation to protect it from ultraviolet radiation. At the exterior of the building, the insulation was covered with sand fill and the insulation was extended down into a ditch cut into the permafrost.

The ground temperature measurements and level surveys taken to date show that the surface insulation has reduced the pile settlements to an acceptable rate. The ground temperatures have matched the predictions from the computer model. As shown in Figure 5, the presence of the insulation has reduced the September and October temperatures at the tip of the pile by about 2 °C below the temperatures measured in 1986.

Figure 6 shows the settlement patterns for interior and exterior piles with various loadings. These plots are for average movements of piles grouped by location and load. The large settlements observed at the end of the 1986 summer season have not been repeated in 1987 through

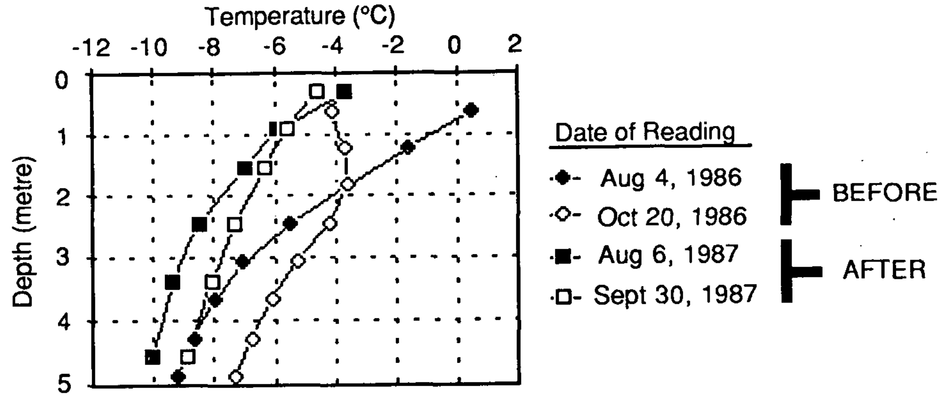

Figure 5. Temperatures for Pile #23 before and after insulation was placed in May 1987.

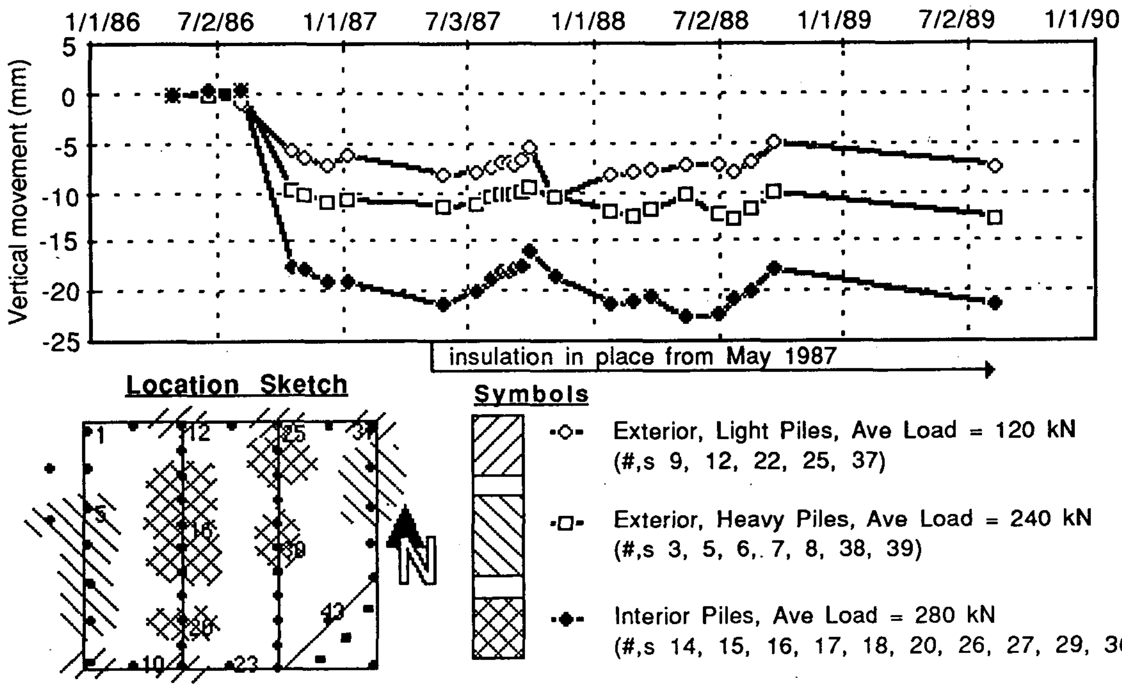

Figure 6. Averages of measured pile movement vs. time and load.

1989. The annual settlement now appears to be between 1 mm/yr and 1.5 mm/yr for the more heavily loaded piles. The amount of annual settlement is difficult to estimate precisely since it appears to be superimposed on a larger cyclic movement of 5 to 6 mm that occurs each year. This does not appear to be a survey error since the two bench marks that were used to reference the level surveys showed less than 1 mm of difference throughout the year.

Discussion

The data from the Courthouse building show that the laboratory data and procedures proposed in the 1984 papers by Nixon and Lem, and Nixon and Neukirchner provide a good basis for estimating the general rates of creep movement of piles and the sensitivity of those rates to small variations in temperature.

The settlement patterns observed in 1986 are as expected from the ground temperature changes during that period of observation. The upper half of the pile is in soil with a lower salt content than the bottom of the pile. The lower portion of the pile is in highly saline soil, but during most of the summer the deeper ground is still cold from the chilling of the previous winter, and the creep movements are small. However, when the summer warming finally reaches the lower portion of the pile, the higher supporting capacity expected from the colder ground is not available, and the overstress causes high creep rates to occur. With the onset of winter, the upper portion of the pile becomes cold again and the creep movement stops.

The pile capacity has been calculated for both layered and uniform conditions as shown in Figure 7. The layered analysis attempts to duplicate the salt profiles measured from the borings and uses the end of summer temperatures

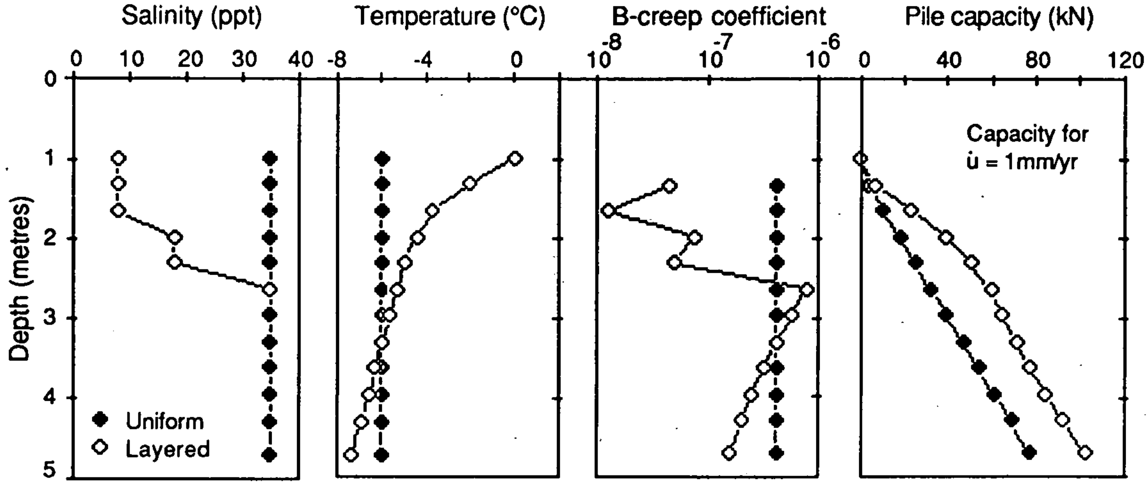

Figure 7. Comparison of pile analysis using uniform or layered conditions.

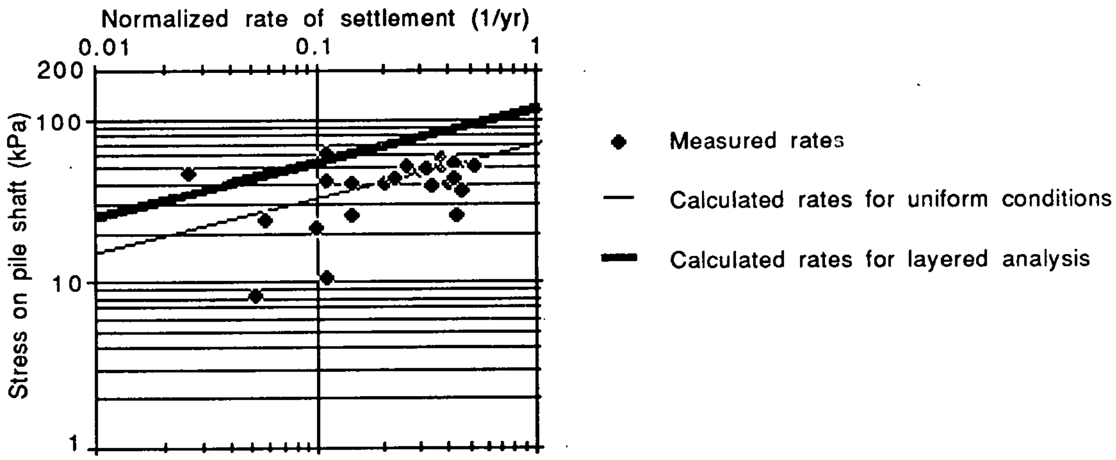

Figure 8. Normalized annual settlement rates vs pile shaft stress.

measured at Pile #23, a warmer than average condition. The uniform analysis assumes a temperature of -6°C and a salt content of 35 ppt over the supporting length of the pile. Both the uniform case and layered model were analyzed using the creep coefficients, B-values, interpolated from the laboratory data by Nixon and Lem.

Figure 8 shows the rates of movement measured between the August and October 1986 surveys and compares the measured data with predictions calculated for the uniform and layered cases. The 1986 level surveys indicate that the piles were moving at rates faster than predicted by the layered analysis. The analysis for the uniform condition fits the measured rates reasonably well.

As shown in Figure 9, the 5 to 6 mm of upward and downward movement that appears to be occurring each year under the building tends to follow approximately the temperature cycles for the 4.6 meter depth. The movement is suspected to be related to thermal expansion and contraction of the frozen ground with seasonal variations in temperature. Thermal expansion of the above grade portion of the steel piles only accounts for about 10% of this movement. As previously shown in Figure 6, the cyclic movement also appears in the data for the exterior piles but with a smaller amplitude than for the interior piles. The difference in amplitude is suspected to be temperature-related rather than associated with the applied load.

Conclusions

Salt contents must be considered in the design of pile foundations in permafrost. The creep properties of the frozen soils are markedly affected by the salinity of the pore fluid and by subtle differences in temperature. In permafrost investigations, the testing for pore water salinity must become as routine as moisture content determinations.

Depending on the method of analysis, the field data may show a faster rate of settlement than that predicted by analysis using the laboratory data reported by Nixon and Lem for saline soil. As discussed in their paper, further laboratory testing is needed "to improve the level of confidence in the data base". The data from the Courthouse confirms the sensitivity of the creep rates to small changes in temperatures.

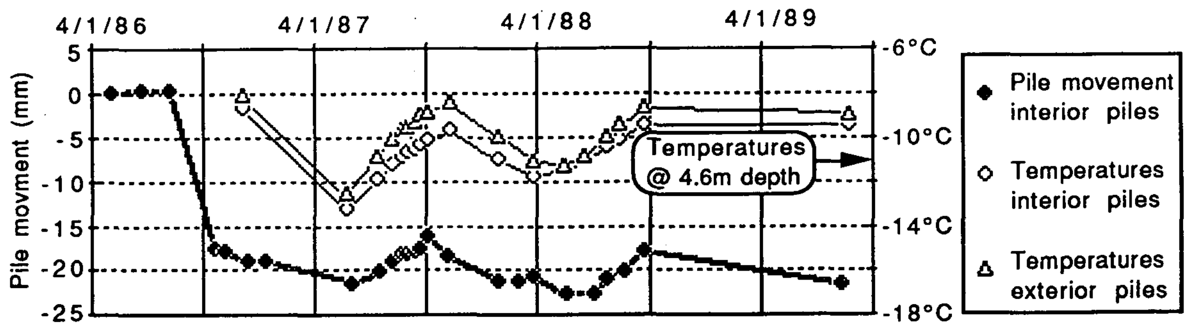

Figure 9. Movement of interior piles compared with ground temperatures.

A considerable amount of scatter is present in the settlement data. The large rates of movement seen in lightly loaded piles is possibly due to unknown load transfers through the superstructure. Alternatively, these piles might be at locations with salinities much higher than those at other piles. Large variations in rates between similarly loaded, nearby piles also suggest a variation in salinity.

Future research needs

To date, the laboratory testing has been limited to samples with salt contents of up to 35 ppt, approximately equal to that of seawater. Natural soils frequently have much higher concentrations of salt, and further research is needed to establish estimates of creep parameters for these higher

Tablel. Summary of pile loads and measured movements.
normalized to radius per year (+ = downward)

Pile #	Location	Sustained Depth	4/30/86 to Load	8/6/86 to 8/6/86	10/20/86 to 10/20/86	1/10/87
3	Exterior W	4.6m	191-kN	-0.050	0.455	0.042
5	Exterior W	4.6m	258-kN	0.010	0.299	0.012
6	Exterior W	4.6m	222-kN	0.005	0.110	0.083
7	Exterior W	4.6m	218-kN	-0.005	0.143	0.000
8	Exterior W	4.6m	218-kN	0.045	-0.032	0.006
9	Corner SW	4.0m	111-kN	-0.010	-0.071	-0.006
12	Exterior N	4.5m	129-kN	0.015	0.442	0.042
13	Interior	4.9m	249-kN	-0.035	0.422	0.053
14	Interior	4.6m	276-kN	-0.005	0.377	0.083
15	Interior	4.6m	302-kN	0.005	0.377	0.805
16	Interior	4.6m	289-kN	0.010	0.416	0.101
17	Interior	4.6m	289-kN	-0.010	0.390	-0.030
18	Interior	4.9m	276-kN	-0.005	0.318	0.083
19	Interior	4.7m	240-kN	-0.010	0.227	0.071
20	Interior	4.7m	258-kN	-0.015	0.026	0.065
21	Interior	4.7m	156-kN	0.040	-0.182	0.131
22	Exterior S	4.7m	120-kN	0.035	-0.039	0.012
25	Exterior N	4.6m	138-kN	0.005	0.143	-0.024
26	Interior	4.6m	276-kN	0.000	0.260	-0.012
27	Interior	4.6m	280-kN	-0.020	0.526	-0.119
28	Interior	4.6m	285-kN	-0.015	0.422	0.024
29	Interior	4.9m	289-kN	0.040	0.318	0.065
30	Interior	5.9m	289-kN	-0.045	0.403	0.059
32	Interior	4.7m	58-kN	-0.050	0.110	0.071
33	Interior	5.7m	58-kN	-0.040	0.052	0.083
34	Interior	4.9m	360-kN	-0.020	0.110	0.065
35	Exterior S	4.8m	120-kN	-0.020	0.097	0.036
37	Corner NE	4.0m	107-kN	-0.005	0.058	0.006
38	Exterior E	4.6m	214-kN	-0.015	0.201	0.024
39	Exterior E	4.7m	214-kN	-0.035	0.338	-0.024
	Average =	4.7m	216-kN	-0.007	0.224	0.060
	Std Dev =	0.4m	80-kN	0.025	0.186	0.149

salinities. Until this extension of the data base is performed, foundations that rely on saline soils with salt contents greater than 35 ppt should be designed with caution.

The comparison of creep parameters between the Courthouse piles and the published laboratory data assumes that the salinity adjacent to the pile is similar to that sampled in the borings. This assumption rests on several questions that should be investigated, particularly methods of pile installation, the rate and process of the diffusion of salt in permafrost, and the possibility of sampling errors in determining the salt content of natural soils.

Samples taken in this investigation within a 150 mm vertical spacing showed variations in salt content of up to 400%. Are these large variations in salinity in the natural soils due to a slow diffusion process, variations in soil types (not visually obvious in the samples), or sampling or testing errors?

The freezeback process around slurried piles is suspected of influencing the salinity near the surface of the pile. During the construction of the piles, the annulus of the pile is backfilled with a fresh water slurry. The usual analysis of pile creep settlement assumes, as was assumed for the cases in this paper, that the critical stress level is at the outside surface of the piling, which presumes that the salt concentration in the slurry is the same as that in the natural ground. For this to occur, the salt from the natural ground has to contaminate the slurry. This probably occurs when the unfrozen slurry is placed in the annulus, and the process of diffusion and dilution should result in a saline level in the slurry that is less than that of the natural ground.

However, higher salt concentrations could occur if the salt moves by exclusion in front of the freezing front. Freezing of samples in the laboratory has shown that this process occurs in the vertical direction (see Stuckert, B.J., et al (1985) and Baker, G.C. and T.E. Osterkamp (1989)), but is it significant in the horizontal direction without the effect of gravity? If salt exclusion does occur with a horizontal direction of freezing, natural freezeback of the slurry inward towards the pile could result in salt concentrations near the pile. Possibly this could be reversed using thermal syphon piles or artificial freezeback systems to freeze the slurry.

The Courthouse building in Barrow is near several buildings that are multi-story and pile-supported. Although survey data is not available for these structures, they do not appear to be experiencing the severe movements seen at the Courthouse. The obvious difference between these structures and the Courthouse is that all of the other buildings are supported on timber piles rather than steel piles. If salt redistribution occurs as the slurry freezes, the steel pile might act as an impermeable barrier that results in a higher salt concentration. Timber piles which have a much higher permeability would not develop the high salt concentration at their surface.

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