Foamed Gravel Backfill for Piles in Permafrost

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ABSTRACT
Bored adfreeze piles dominate foundation installation in permafrost throughout the Canada Arctic. An ideal frozen soil backfill material will: adequately develop bond with the pile material and surrounding frozen soil mass, be stable during repeated freeze-thaw cycles, fully transmit pile loads into the frozen soil, resist solute migration, be chemical inert, have low thermal impact during installation, and be economic. The following laboratory investigation presents test data on the development of a new backfill consisting of pressure injecting polyurethane foam resins into coarse gravel. The resulting polyurethane concrete is a flexible and economical alternative to the use of freeze back cohesionless backfill and/or cold setting cementitious grouts.

RÉSUMÉ
Les tas ennuyés d'annonce-gèle sont devenus la méthode de choix dans le permagel à travers l'Artique canadien. Un remblai de sol gelé idéal volonté matérielle : suffisamment développer la force de lien avec entasser de matériel et la masse de sol gelée environnante, être stable pendant les cycles de gèle-dégel répétés, entièrement transmettre le chargement de tas dans la masse de sol gelée, résister la migration de solute, être chimique inerte, avoir l'impact thermique bas pendant l'installation, et être économiquement compétitif. Les présents suivants d'investigation de laboratoire essaient des données sur le développement d'un nouveau matériel de remblai consistant en de la pression les résines de mousse de polyuréthane injectées dans le gravier grossier remplissent. Le béton résultant de polyuréthane est une alternative flexible et économique à l'usage de gèle le froid de et/ou de remblai de cohesionless arrière réglant les mastics de cementitious satisfaisant tous critères critiques.

1 INTRODUCTION

The use of bored piles, which are pre-bored and backfilled around the installed pile, have become the foundation of choice for use in permafrost. Their use requires a system that can: sufficiently carry loads and be sensitive to both the balance sheet and environment. Pressure injecting polyurethane resin into a coarse gravel backfill is a novel backfill technique that meets these present needs and could meet potential future challenges associated with project emission sensitivities related to climate change and use of portland cement based grouts.

1.1 Grout Backfilled Piles

Cement based grouts in permafrost have become more common since development began with Morris et al. (1971) cementing oil well pipe under freezing conditions. Weaver (1980) highlights some key issues for cold setting grouts: it must cure below 0^{o}C; mix water must not freeze before curing can occur, hydration must not cause excessive thermal impact, grout must be stable during repeated freeze-thaw cycles, and grout must develop adequate internal strength and bond strength between pile material and backfill (friction piles). Both grout and polyurethane concrete must meet these common critical criteria.

A series of laboratory and field tests conducted at the University of Alberta and at the Short Range Radar sites across the western arctic (Sego and Biggar 1990; Biggar and Sego 1990; Biggar et al. 1993) added to the viability of using grout backfilled piles. Model pile tests were able to show ultimate pile failure due to shearing of concentric cylinders within the soil mass (Biggar 1991). Frozen soil around a pile backfill may be thought to shear in this manner (i.e. concentric cylinders) (Ladanyi 1974); therefore a backfill material requires bond and suffiecient shear resistance to push the failure surface into the frozen soil mass (Fedorovich 1987).

1.2 Use of Polyurethane

Polyurethane foams have been used in projects worldwide for their insulating abilities for decades; however, development of novel applications to extend their use is underway. Uretek Inc. began using expanding polyurethane resins (foams) in the early seventies to remediate settlement of concrete slabs and foundations (through deep injection). Biomechanical researchers even use urethane foam to simulate certain types of bone mass (up to 4.2 MPa shear strength) (Thompson et al. 2003). Use of foam to transmit shear is a novel and intriguing technology.

1.3 Polyurethane concrete

Expanded polyurethane foams are created by the reaction of resin with water and a catalyst. The two liquid components (resin and catalyst) are heated to a specific temperature then mixed at the point of injection under pressure. The reaction takes place in two distinct parts: first, the “cream stage” is characterized by a distinct colour change and the rapid production of CO_2 gas bubbles. During the cream stage the foam can easily flow into and fill voids, also the expanding bubbles give the urethane foam its powerful lifting capability. The second stage is a curing phase. The hardened resin encapsulates the CO_2 gas bubbles to form a “closed cell” structure that is largely responsible for the insulating and strength properties. The resulting matrix is a mesh of pressurized gas bubbles that is highly resistant to internal fluid flow.

2 TESTING PROGRAM

The material testing program was divided into two parts. The first phase studied parameters critical to develop adequate shear strength in the foamed gravel mixtures. The second phase was the construction and testing of model piles using a foamed gravel backfill.

2.1 Foam Strength Optimization

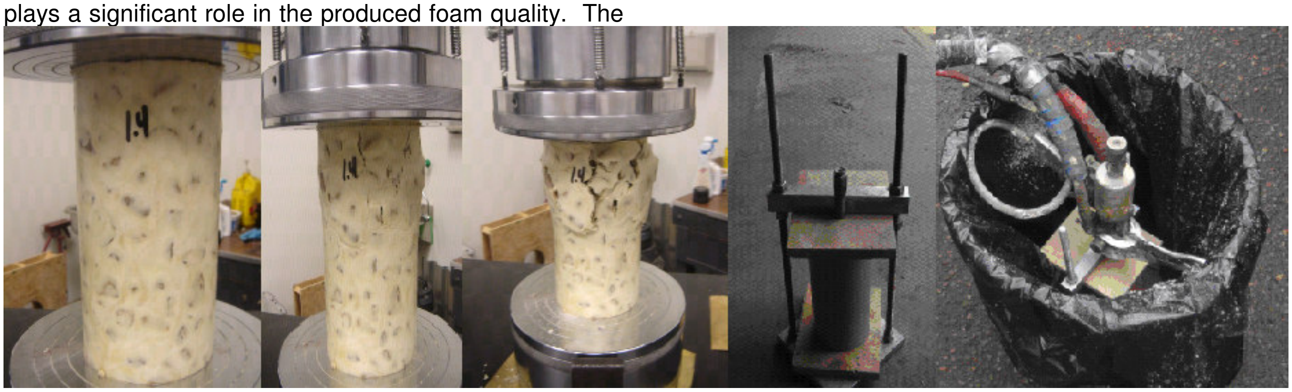
To make the most effective model piles (and future full scale piles) a series of tests designed to optimize the model pile installation procedure was conducted. Foam was injected at 7MPa into plastic 4” x 8” concrete cylinder moulds filled with coarse aggregate. The cylinders can be seen in figure 1. The foamed gravel cylinders were weighed, trimmed using a diamond saw blade, measured, and weighed again. Qualitative data suggested that chemical preheat, void space, and aggregate temperature plays a significant role in the produced foam quality. The test program sought to find the ideal configuration for foam injected into frozen gravel.

The foam used in all tests is Uretek’s 345, which is a 3lb lifting foam (3lb refers to the unconfined expanded density of 3lb/cuft (48kg/m^3). This foam is shipped as a liquid at density of approximately 1150kg/m^3.

For ease of reproduction and simplicity strength tests consist of unconfined compression strength (UCS) tests. The UCS tests were conducted using a Tritest 50 load frame at a constant strain rate of 2mm/min. A V42-5k-10P1 load transducer along with a linear voltage differential transducer (LVDT) was used to record loading data through an Optimum Data Dolphin 400 data acquisition system.

2.1.1 Effect of Chemical Preheat

The first variable tested was the chemical preheat. Qualitative data had suggested that foam curing time and quality depended on the temperature of chemical preheat. The effect of preheat was assessed by injecting sample pairs at 5 to 10^{o}C intervals around normal operating temperatures everything else being equal. For foam injected into room temperature gravel, 30^{o}C was found to be an ideal preheat temperature, while foam injected into -15^{o}C gravel the best quality was obtained with 41^{o}C preheat. Vrignaud et al. (2003) also found application temperature to be a critical consideration during polyurethane installation. A typical distribution of results for this optimization process is summarized in figure 2. The data shows scatter, it is therefore necessary to repeat this process. Section 5 of this paper recommends a future test program to improve our understanding of the resin temperature influence.



(a) (b) (c)

Figure 1: Polyurethane Concrete Cylinders: a) Unconfined Compressive Strength testing of sample 1.4. Frozen cylinder testing not shown. b) Injection frame clamping plastic cylinder filled with coarse aggregate. c) Injection gun clamped to cylinder. Red and Blue hoses contain chemical components with a third air line.

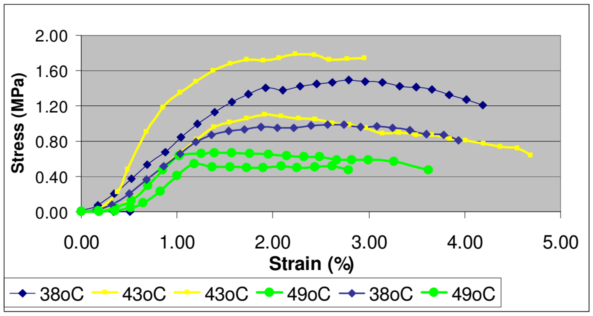


Figure 2: -15°C ¾" aggregate prepared at different chemical preheat temperatures

2.1.2 Void Space Internal Foam Density

The initial series of cylinder tests were prepared using a standard ¾" concrete aggregate. It was clear early into the program that this aggregate size was compatible with future model pile tests because of the size of the annulus; therefore a dried and screened ½" asphalt and crushed ¾" aggregate was used. Model pile tests require an aggregate small enough to fill an annulus of about ¾". Crushed ½" gravel meets this size criterion. Using the specific gravity of the aggregate and measuring both the mass of gravel and foam used to prepare each sample, allows for the calculation of foam density (i.e. foam density within the pore space). Figure 3 presents variation of ultimate unconfined compressive strength versus foam density. The resulting relationship is linear, although some previous work with polyurethane foam only (no gravel) found strength was proportional to the square of the density (Tate and Talal 1999).

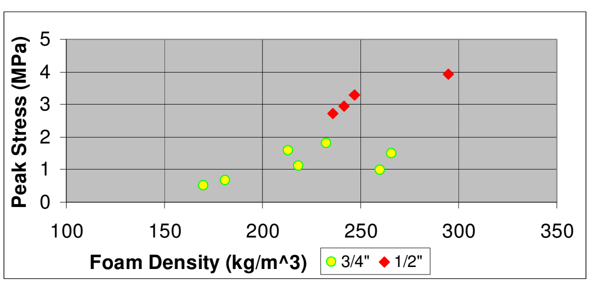


Figure 3: Foam Density vs. Peak Stress for cylinders tested at and installed into gravel at -15°C

2.1.3 Results from Cylinder Tests

The failure during unconfined compression test occurs in two ways: first, the foam matrix can buckles or fold (this is observed in cylinders as linear striations perpendicular to the applied load figure 1a), second, an audible popping sound can be heard accompanying the formation of cracks parallel to the applied load direction. These vertical cracks are characteristic of polyurethane foam failure and grow as the aggregate separates (see figure 1a). Shi and Li (2007) describe similar failure due to formation of vertical cracks while testing urethane foams prepared under a confinement ; however, no gravel was used in their study. Tate and Talal (1999) observed a similar two mechanism process; however samples were not tested to ultimate failure and constant loads were applied over longer time intervals. Post failure behaviour, the cylinder maintains load while barrelling. The mechanics of foamed gravel failure (formation of vertical cracks as the aggregate separates) will be restricted in field applications by confinement of the backfill.

Both failure mechanisms were less evident for frozen samples that appear to behave in a more brittle manner during their study. The ½" frozen aggregate samples routinely resisted 3MPa. As a guide, the shear strength of the polyurethane concrete is one half, which exceeds the expected shear strength of the frozen soil; however, the shear capacity of this material must be more thoroughly investigated.

This test program results in a recommendation to use foam injected into a ½" aggregate and cured at -15°C, while inject chemicals preheat to 41°C.

Outstanding Issues

- What is the ideal chemical preheat for all potential soil temperatures?
- What is the relationship between foam density and ultimate strength for each of the above conditions?
- What is the effect of injection pressure on density, strength, and foam quality?
- The increasing pore air fluid density within the aggregate resulting from the decreasing temperatures may be impeding air flow within the void spaces, and subsequently the polyurethane's ability to flow. Is this effect responsible for the observed increased densities (and consequently strengths) of samples with frozen and smaller aggregate. Can this effect be overcome through a change in injection pressure?

2.2 Use as Bored-Pile Backfill

In the spring of 2006, model foamed gravel piles were prepared using sonotube and pvc pipe to a maximum length of 3m. This work examined various potential installation procedures and foam types. The completed piles were removed from their sonotube and the ultimate unconfined compressive strength of samples were measured. Results from the spring 2006 study showed unconfined compressive strength similar or greater to those reported for this study.

The testing of polyurethane concrete cylinders has increased the confidence that this material could be used to backfill piles. The main determining factor in foam quality is the preheat temperature prior to injection into the aggregate.

2.3 Model Piles Backfilled with Foamed Gravel

Model piles are installed into a 300mm diameter by 300mm in length cylindrical container wherein a frozen soil mass has been previously prepared. The pile is then installed into a central bore hole in the frozen soil.

Soil / Model Permafrost

The native soil used is similar to that reported for previous pile studies (Hutchinson 1989),(Biggar and Sego 1993),and (Hivon and Sego 1995). The grain size distribution is presented in figure 4. The soil consists of equal parts by weight of sand and Devon silt. The soil samples were mixed and allowed to soak for at least 24 hours. After soaking, the soil was placed in a mixer for 30 minutes to achieve a workably stiff consistency, and then spooned into the test cell and rodded to remove air voids.

The borehole was formed by pre-installing a steel pipe with the fill placed outside. The pipe was wrapped in a geotextile to facilitate drainage. The soil was placed to a height of 275mm and was capped with filter paper, then a wire screen, and a well graded sand layer. The sample was consolidated to a vertical stress of 80kPa using an air actuated bellofram that loaded a 25mm thick load cap that fit closely inside the container. Consolidation to 95% dissipation of pore pressure was achieved in less than 24 hours. With consolidation complete the upper sand drainage layer was removed, the soil was trimmed to a height of 240mm (i.e. the height of the steel borehole form), and resistance temperature devices (RTDs) were installed. The unfrozen soil could then be placed on a liquid nitrogen freezing plate and frozen from the bottom up in about 4-5 hours. The frozen sample then had its aluminium base plate, the steel form pipe, and the geotextile removed. The smooth borehole wall was then notched using a chisel and hammer to better simulate the roughed field conditions (Biggar and Sego 1993). The resulting frozen soil “dough-nut” along with the cooling pipe used to maintain the circulation boundary at a constant temperature is now ready for pile installation.

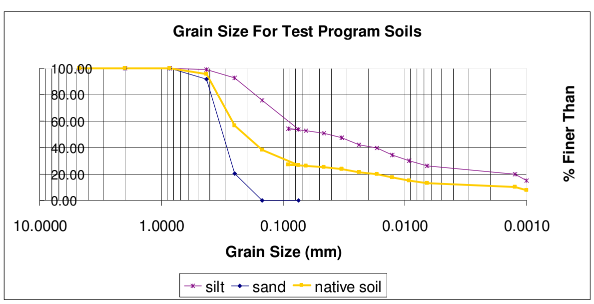


Figure 4: Test soil grain size distribution

Piles

Pile diameters used were 2/3 the borehole diameter, as this is a common pile to borehole ratio used in practice. Initial tests used untreated (i.e. with factory coating) C1020 steel pipe with a 6.3mm wall thickness. Later piles were sandblasted using of either quartz sand or a glass bead medium. The center line roughness was measured using an EGH-1019 Federal Pocketsurf surface profiler. The center line averages for the piles are summarized in table 1. Sandblasted steel pipe adfreeze piles result in a 200% increase in shear capacity over non-surface treated piles (Sego and Smith 1989).

Two piles were also installed with only a short section of steel pipe to act as a loading cap on polyurethane concrete piles.

Table 1: Center Line Average Surface Roughness

Pipe Diameter (mm)	Untreated Pipe (µm)	Quartz Sand (µm)	Glass Beads (µm)
63	2.2	3.8	4.3
102	2.4	2.9	3.6

Pile Installation

The steel pipe pile was centered in the borehole and the gravel backfill was loosely placed. A rigid foam insulation cap was placed on top of the bucket holding the steel pile in place and limiting the deformations in the gravel fill during injection. A plywood top plate was mounted and held in place using a clamping system similar to that used in cylinder preparation. The model pile ready for foam injection is shown in figure 5.

Figure 5: A pile ready for foam injection

The temperature of the soil and foam was recorded prior to and during pile installation to determine the level of thermal disturbance. All piles were installed with gravel at -15°C. Foam was injected into the gravel through a copper tube protruding from the plywood top plate. The foam was injected until foam could be seen exiting the test bucket.

2.4 Model Pile Load Tests

Load tests were performed in a custom built high capacity load frame constructed from C-channel. The load was supplied using a LC-5000 syringe pump attached to a hydraulic jack used to transfer the load.

A LVDT measured the movement of the pile head, while a 22kN load cell powered by an Agilent 34970A Data Acquisition/Switch unit connected to the Benchlink Data Logger 3 recorded the data.

The syringe pump displaced a constant flow rate of 18ml/hr to provide a constant displacement rate of 2mm/hr. The tests were typically run until the pile head had displaced between 8 to 10mm. A hole in the PVC base plate (slightly larger than the borehole diameter) ensured the backfill carried the load and not the base plate.

Table 2: Pile Load Test Results

Test#	Surface Treatment	Borehole Diameter (mm)	Approx. Temp. (^{o}C)	Failure Surface	Max Load (kN)	Time (min)	Displacement (mm)	Max Stress (kPa)		
								Pile to Fill	Fill to Soil	
1	none	152	-10	pile	10.1	887	1.8	132	88	
2	none	152	-10	pile	13.3	641	1.4	174	116	
3	SB-q	152	-10	pile	13.2	42	1.6	173	115	
4	SB-q	152	-10	pile	8.4	82	1.3	110	74	
5	SB-g	101	-5	ns	10.1	88	5.9	398	265	*
6	SB-g	101	-5	ns	38.2	1101	8.1	752	502	**
7	Foamed Gravel Only	152	-10	ns	24.0	170	2.0	628	419	***
8	Foamed Gravel Only	152	-10	ns	70.3	500	7.1	919	613	***

Failure Surface: pile – pile failed at pile backfill interface
ns - Failure occurred at or just outside backfill into the frozen soil mass
SB-q – Sandblast quartz sand; SB-g –Sandblast glass bead

* Foam was in contact with less than half of the pile surface

** Pile held sustained load of 34 kN over a period of about 11 hours

*** Foam only pile with shorter embedment length

Thermal Effects of Installation

Because of the clamping system used, it was difficult to obtain complete test temperature data. Figure 7 illustrates a typical temperature distribution measured halfway along the embedded length (about 120mm) at radial distances from the borehole wall. The foam reaches a maximum recorded temperature of 20^{o}C. The backfill to soil interface experiences a 5^{o}C temperature increase while, the soil 25mm away from the borehole increases only a few degrees. The entire system returns to equilibrium after 2 ½ hours.

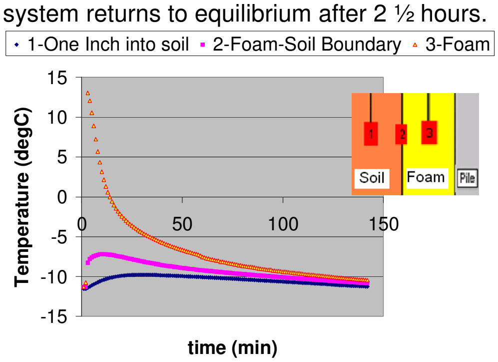


Figure 7: Thermal Effects of Pile Installation

3 RESULTS

The two areas for potential backfill failure scrutiny for this testing program are mobilized and ultimate shear stress and thermal effects of installation. Shear strength results are reported using a concentric shear plane at either the nominal steel pipe diameter or borehole diameter over the average embedment length.

Pile Loads

The goal of a pile system is to transfer the structural load into the soil mass. For a backfilled pile in permafrost, this requires the following: adequate bonding between backfill and pile, the ability of the backfill material to transfer shear load without internal failure, and to develop adequate bond strength between backfill and the frozen soil at the outer surface of the borehole. The resulting failure plane in the frozen soil mass should not be affected by the type or specific strength of the backfill.

In order to achieve adequate bonding between the pile surface and the backfill material some surface treatment may be required. Pile tests 1 and 2 were conducted using untreated pipe to less than desirable results. Initial rounds of pile load tests show encouraging results; however surface treatment appears to be a critical concern to ensure adequate foam to pile adhesion (table 2). With appropriate surface treatment (or for foamed gravel only piles), maximum resistance approaches, equal, or exceed results found in previous slurry and grout model pile studies tested under similar conditions (Biggar and

Sego 1993). A summary of previous model pile load results can be seen in table 3.

When evaluating the results of any model pile test, it is important to remember that (especially for ice-rich permafrost) it is the settlement that influences foundation design (Weaver and Morgenstern 1981), also long-term field load tests show a substantial decrease in ultimate pile capacity over time (Biggar and Kong 2001). Nixon (1988) found that “significant and persistent” creep settlements occurred at loads above 50 kPa in saline permafrost. Combined with the potential to see increased creep arising from climate change, designers must consider using significantly less stress on each pile (Nixon 1990). As a worst case scenario, even the untreated pipe was able to resist a potential design load; however, clearly the use of untreated pipe is not recommended for field use.

Piles 6 – 8 were observed to fail outside of the backfill material. The loading character for these piles can be seen in figures 8-10. Pile 6 reached the set limit pressure output for the syringe pump; therefore, the load would not increase, and the pile was allowed to creep overnight. The final loading of pile 6 resumed 11 hours later. The loading of pile 7 did not record the ultimate failure stress; however the load was applied post failure to find the mobilized shear stress only. Future work should evaluate model piles at lower displacement rates. Polyurethane is known to be (in some applications) a strain rate dependant material (Strawder 2007).

Table 3: Load Test Results from Previous Work

Authors	Backfill	Pile Diameter (mm)	time to failure	Displacement at Failure (mm)	Load Rate (mm/min)	Max Shear Stress (@N.S) (kPa)
Sego and Smith (1989)	Sand	33	378	2.48	0.008	733
Biggar (1991)	Grout	63	N/A	5.9	0.008	925
Biggar (1991)	Sand	33	215	0.7	0.008	583

Drawbacks or Polyurethane Backfill

- There has been limited use of this material as a structural resisting component in a foundation system.
- Effects of injection pressure, temperature, and density on strength must be carried out.
- It is difficult to control the amount of product placed and mixed in each pile.
- Requires gravel to be shipped to or crushed on site.
- A pipe (or any piling material) requires some surface treatment (such as: spiral welds, welded collars, corrugations, welded lugs, sandblasting etc.) to fully engage the strength of the backfill material.
- The model pile load tests to date have not reached the highest capacities measured for grouted piles.

Benefits of Polyurethane Backfill

- For samples that did not fail at the pile surface, there is little evidence of failure in the backfill.
- The foamed backfill will cure and stabilize temperature within hours rather than weeks (grouts) or months (adfreeze); the piles can be loaded rapidly during the same deployment window as installation.
- Project managers have the option to take advantage of optimal short term load capacity for installation and construction (i.e. coldest ground temperatures are not a problem during the foam curing process) (Phukan and Ladanyi 1992).
- The product expands roughly 5:1 (i.e. 1/5th the shipping volume). To achieve adequate strength, an in place foam density would have to be about 250kg/m^3.
- Decreased thermal impact and mass may lead to the development of large base (belled) end bearing piles and foamed gravel only piles (similar to piles 7 and 8). This added end-bearing capacity may allow for higher capacity using less material in settlement prone ice-rich permafrost (Sego et al. 2003).
- Injection equipment has been deployed and used successful in remote and arctic projects in the past and can easily be air lifted to these sites.

4 CONCLUSIONS

Foamed gravel backfilled piles are a new and innovative technique that shows great promise. Model pile load tests have revealed little evidence of backfill failure, and early results are encouraging enough to warrant further testing and development.

5 RECOMMENDATION/FUTURE CONSIDERATIONS

Foam Properties

Future laboratory investigation must better identify the specific parameters that ensure good foam quality. This could be accomplished by sample testing rounds (approximately 50 cylinders each) directed to the follow concerns:

Round 1: Effect of chemical preheat

Samples injected as pairs with five pairs at five different temperature intervals. Testing of each set of different temperature pairs could be carried out over time to identifying foam curing over time.

Round 2: Effect of injection pressure

Again samples would be injected in a similar manner using the optimized chemical preheat and tested over time.

Round 3: Relationship between density and strength

All sample pairs are created using optimized chemical preheat and injection pressure, and again tested over time to asses curing time more clearly.

This procedure could be done for different aggregate temperatures to establish a guide for field installation under a variety of thermal conditions, and provide guidance for quality control and best practice.

Model Piles

Future model pile tests should: create greater borehole surface irregularities to more fully engage the backfill material strength, use a lower displacement rate to evaluate rate effects, and use new surface treatment including a deeper look into foam only piles. For relevant field comparison with grouted pile, the limits of foamed gravel must be reached. Also, model piles should test the foam's thermal effects and strength on warmer and saline permafrost.

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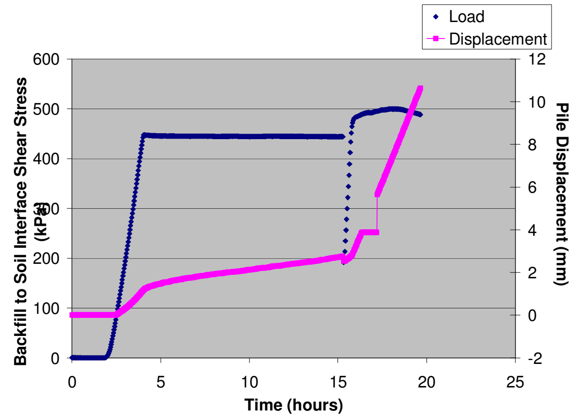

Figure 8: Pile Load 6 (sustained load)

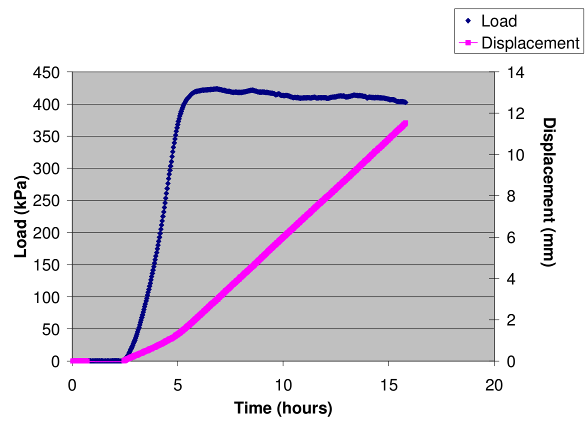

Figure 9: Pile Load 7 (mobilized stress only)

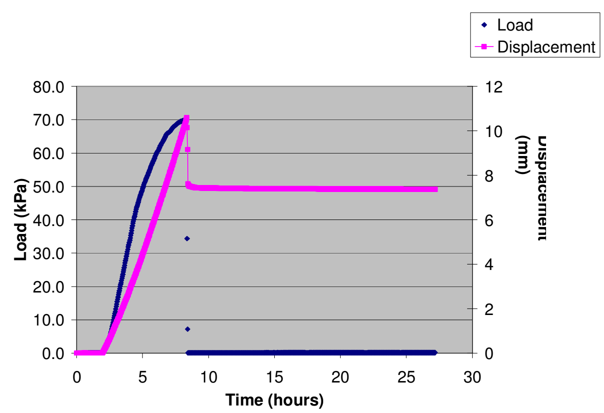

Figure 10: Pile Load 8 (with load removed)