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Article

Field studies of frozen soils composed of alluvial Quaternary deposits

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Abstract. This study examines the behavior of frozen soils at a construction site in Astana, Kazakhstan. Field static load tests (SLT) and dynamic load tests (DLT), were conducted using driven piles embedded in alluvial Quaternary deposits overlying a 2.5 m permafrost layer. SLT results reveal settlements below 20 mm at a maximum load of 1400 kN, supporting a design capacity of 1167 kN after applying a safety factor of 1.2. Notably, creep behavior was observed in the upper soil layers, and lateral displacement patterns indicate complex interactions within the frozen soil. These findings highlight the need for further research into soil creep and lateral deformations in frozen environments.
Keywords: DLT, SLT, pile, frozen soils, soil creep.

1. Introduction

In cold climate construction applications, including Astana, Kazakhstan, pile foundations are crucial in ensuring the stability of buildings and infrastructure [1]. However, frozen soils present a complex geotechnical environment, subject to seasonal temperature fluctuations, frost heave, and permafrost degradation, all of which can significantly impact the bearing capacity (BC) and long-term durability of pile structures [2]. Previous studies [3] have shown that the strength of frozen soils increases as temperature decreases due to the reduction of unfrozen water content and the formation of ice bonds, while pile-soil interaction is governed by cohesion, internal friction, and pile surface roughness. In the context of global warming and permafrost degradation, the risks of excessive settlement [4] and reduced bearing capacity of pile foundations are increasing, as revealed by studies in Arctic regions [5]. This highlights the need for continuing studies on pile behavior in frozen soils.

[6] proposed a method and correction coefficient to determine the bearing capacity of piles in various permafrost soil conditions (i.e., different soil temperatures) based on static loading test (SLT) of piles installed in weak sites. However, the method was verified only in the loamy soils with temperatures ranging between -0.1 and -0.6 °C to a depth of 7 m. Therefore, considering a large possible variation of soil type and temperature ranges the method cannot be scaled widely, highlighting the necessity of continuous studies. [7] proposed a technique to obtain the pile-bearing capacity by testing it in a creep-relaxation regime in laboratory and field conditions on morainic loams. They argue that the technique should work well for permafrost soils if the bearing capacity is defined as the stabilized, relaxed pressure measured after a pile is loaded into the soil at a specific subzero temperature, the soil is then heated to a certain level, and sufficient time is allowed for

pressure relaxation following unloading. Unfortunately, the authors did not provide evidence for their hypothesis, which suggests the need for further tests at various temperature regimes and soil types. [8] conducted a series of accelerated SLTs of steel piles assuming their applicability for permafrost soils. However, the authors themselves experienced the unsuitability of such tests for permafrost soils due to their specific behavior. Because while such soils strengthen rapidly under fast loading, they creep under slow loading.

While many efforts were made to derive unified methods in existing studies, they all agree on the specificity of permafrost soils and their dissimilarity across sites, suggesting the need for continuous studies of their behavior, as well as the impracticality of unified approaches. Therefore, to broaden the knowledge and practice in this direction this study examines the permafrost soils in the case of Astana, Kazakhstan. Hence, the study aims to investigate the behavior of permafrost soils in a specific case and determine their bearing capacity by field tests and numerical analysis of a pile-base system. The field tests included both SLT and dynamic loading tests (DLT).

2. Methods

The study area is represented by the construction site of the Central Mosque of Astana city, Kazakhstan. According to the conducted survey [9], the site is located at the elevations of 348.33-348.74 meters above the sea at a sharply continental climate characterized by long and cold winters reaching -50 °C. The soil freezing depth in the region reaches 2.5 m on average. During the survey, the groundwater was found at a depth of 3-3.6 m. The geological structure of the survey site involves alluvial Quaternary deposits, including clay loams, medium-grained sands, gravelly sands, and gravel soils, as well as eluvial Lower Carboniferous soils, represented by loamy peat, peat soils, and stony soils (Table 1).

Table 1 – Properties of soil under natural/saturated state [9]

No.	Soil type	Occurrence depth, m	Thickness, m	Normative values (n)					Estimated values based on:						
									deformations (II)			bearing capacity (I)			
				ρ_n, g/cm^3	c_n, kPa	φ_n, °	E, MPa	E*, MPa	ρ_{II}, g/cm^3	c_{II}, kPa	φ_I, °	ρ_I, g/cm^3	c_I, kPa	φ_I, °	R_0, kPa
1a	Loams	0-6.7	5.1-6.7	1.94	-/23	-/28	-/6.5	-	1.92	-/15	-/27	1.91	-/11	-/26	-
1b	Loams			1.98	-/42	-/18	-/6	-	1.95	-/29	-/15	1.93	-/21	-/13	-
2	Medium sands	5.7-7.0	0.5-2.6	1.92	2	35	-	17	1.92	1.6	32	1.92	1.33	30	-
3	Gravelly sands	4.5-9.0	1.0-6.5	1.92	1	38	-	35.7	1.92	0.8	35	1.92	0.67	33	-
4	Gravel soils	6.0-9.0	2.0-4.6	2	-	-	23	18	-	-	-	-	-	-	300
5	Loamy peat	10.7-12.0	0.7-16.0	2.06	80/44	22/30	12/9.5	20.9	2.05	64/30	20/27	2.04	53/21	19/25	-
6	Peat soils	11.0-23.5	0.5-14.5	2.2	-	-	-	36.4	-	-	-	-	-	-	400
7	Stony soils	17.0-26.0	1.0-2.0	2.4	-	-	-	36.4	-	-	-	-	-	-	450

*Plate loading test

The field tests were conducted using 0.3×0.3×8 m driven piles on 26 February 2019. The piles were installed with the Junttan PM-25 pile driving machine having a 7-ton hydraulic hammer, simultaneously measuring the dynamic parameters, such as the number of blows and height of the hammer per penetration depth. DLT was performed using 16 piles after their rest according to [10]. During testing, the falling height of the hammer’s impact part was recorded at 10 cm intervals over the last meter of penetration, along with the number of hammer strikes required for each meter of pile penetration. Since the number of piles tested in a similar soil condition was more than 6, statistical processing of DLT results was performed according to [11]. When determining the bearing capacity of piles, a safety factor of 1.4 was applied according to [10].

SLT was conducted according to [10] using 4 piles at the site’s weakest soils, incorporating a testing setup (Figure 1) consisting of primary and secondary beams, a hydraulic jack, a manometer, settlement gauges, and reinforced concrete blocks. The compressive load was subjected vertically with steps of 140 kN up to 1400 kN (design load accounting for the safety factor [12]). The bearing capacity estimates here incorporated a safety factor of 1.2 in line with [10].

Figure 1 – Testing setup for SLT

Additional analysis of the pile-base state and deformations was made by numerical simulation of SLT using Plaxis 2D as in [13]. A Mohr-Coulomb elastoplastic model was used to simulate the stress-strain state of the soil base. A linear elastic model was applied to simulate the pile. The calculations were performed in an axisymmetric setup. The loading procedure was similar to the field SLT.

3. Results and Discussion

Figure 2 demonstrates the change in dynamic parameters measured during the driving.

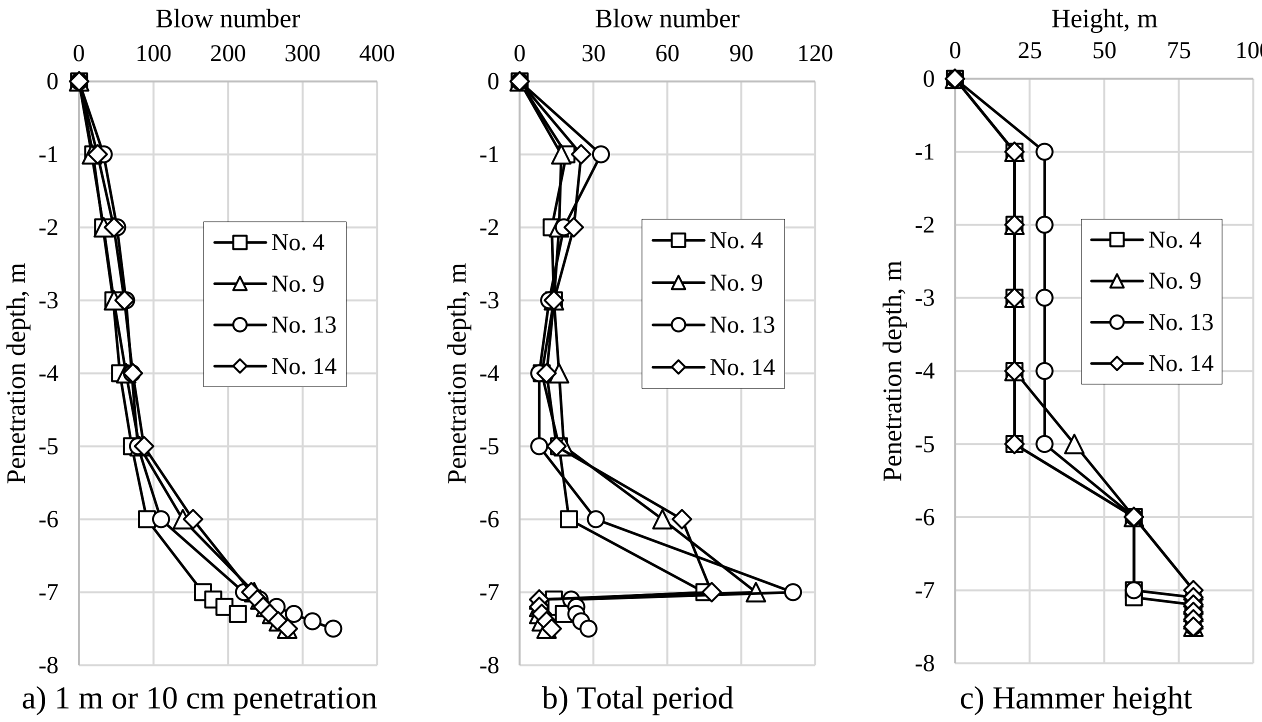


Figure 2 – DLT results

While the dynamic parameters were measured for all 16 piles, Figure 2 above shows their values for the most important ones, installed in the weak soils of the construction site, including the piles numbered 4, 9, 13, and 14. Thus, it took around 280 blows to penetrate the piles to a depth of 7.5 m (Figure 2a). It can be observed from Figure 2b that the hammer-blowing intensity at 1 m depth was 1.5 times higher than at the depths of 2-5 m. This can be explained by the fact that in February when the piles were installed, the freezing depth of local soils may still reach 1-2 m. Besides the upper layers of the soil-base of the site are comprised mostly of loams, which are rather saturated and prone to icing that may create additional friction on the lateral surface of piles. Additionally, the hammer height stood steady in the depths of 1-5 m (Figure 2c), suggesting the existence of creep behavior of the soils at these depths. These results complement the thoughts about the omissions [8].

Table 2 below shows the results of DLT.

Table 2 – DLT results

Pile No.	Driving depth, m	Hammer height, m	Refusal of driving, cm	Re-driving height, m	Refusals of re-driving, cm	Individual value of ultimate pile resistance, kN	Bearing capacity of piles, kN
1	7.3	60	0.36	0.40	0.34	903	960
2	7.5	60	0.53	0.50	0.36	986	
3	7.1	60	0.40	0.40	0.27	1021	
4	6.5	60	0.40	0.50	0.38	958	
5	6.8	60	0.40	0.40	0.30	965	
6	6.2	60	0.37	0.40	0.28	1001	
7	6.7	60	0.38	0.40	0.22	1138	
8	7.1	60	0.38	0.40	0.23	1111	
9	7.5	60	0.50	0.40	0.23	1111	
10	5.9	60	0.36	0.40	0.28	1001	
11	5.9	60	0.36	0.50	0.40	932	
12	6.2	60	0.42	0.40	0.27	1021	
13	6.2	60	0.43	0.40	0.30	965	
14	6.5	60	0.36	0.40	0.34	903	
15	5.8	60	0.37	0.40	0.30	965	
16	6.4	70	0.36	0.50	0.43	897	

* Installed in weak soils of the site

DLT results presented in Table 2 above show that the piles were driven to depths ranging from 5.8 to 7.5 m with a constant driving height of 60 m (70 m in one case) and they showed low refusal rates (0.36 to 0.53 cm), while the re-driving heights were also stable at 0.40-0.50 m and refusals of 0.22-0.43 cm. Individual ultimate resistance ranged from 897 kN to 1138 kN, while the estimated by [10] bearing capacity of the piles was 960 kN. These trends reflect the heterogeneous soil profile at the site, where upper alluvial deposits consisting of loams and medium-grained sands with moderate density and lower strength are combined with underlying layers of gravelly sands and gravel soils that provide higher friction angles and stiffness. Consequently, the behavior of the composite soil is consistent with the results of the DLT.

Figure 3 below shows the SLT results.

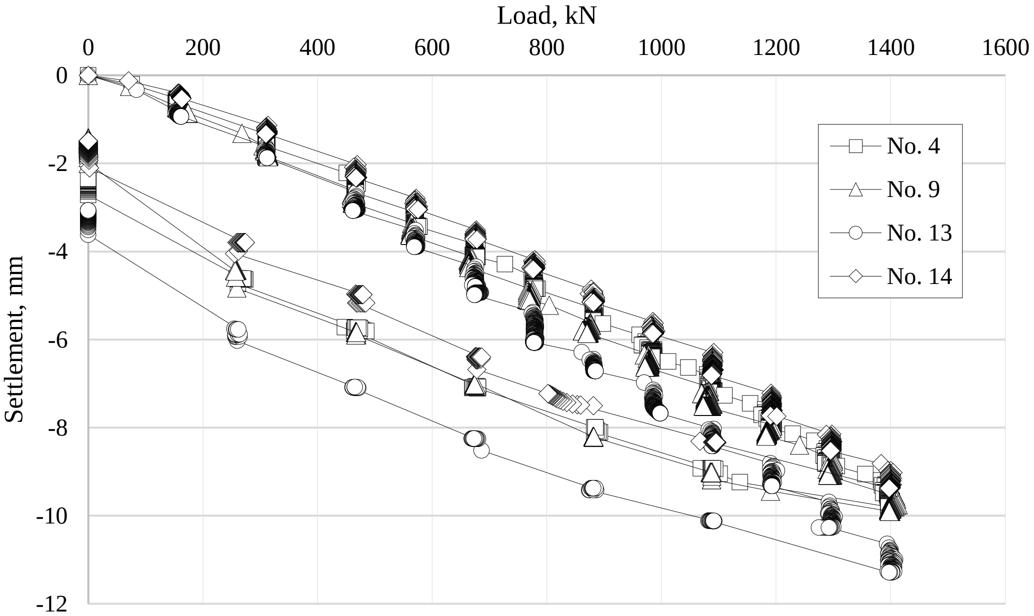
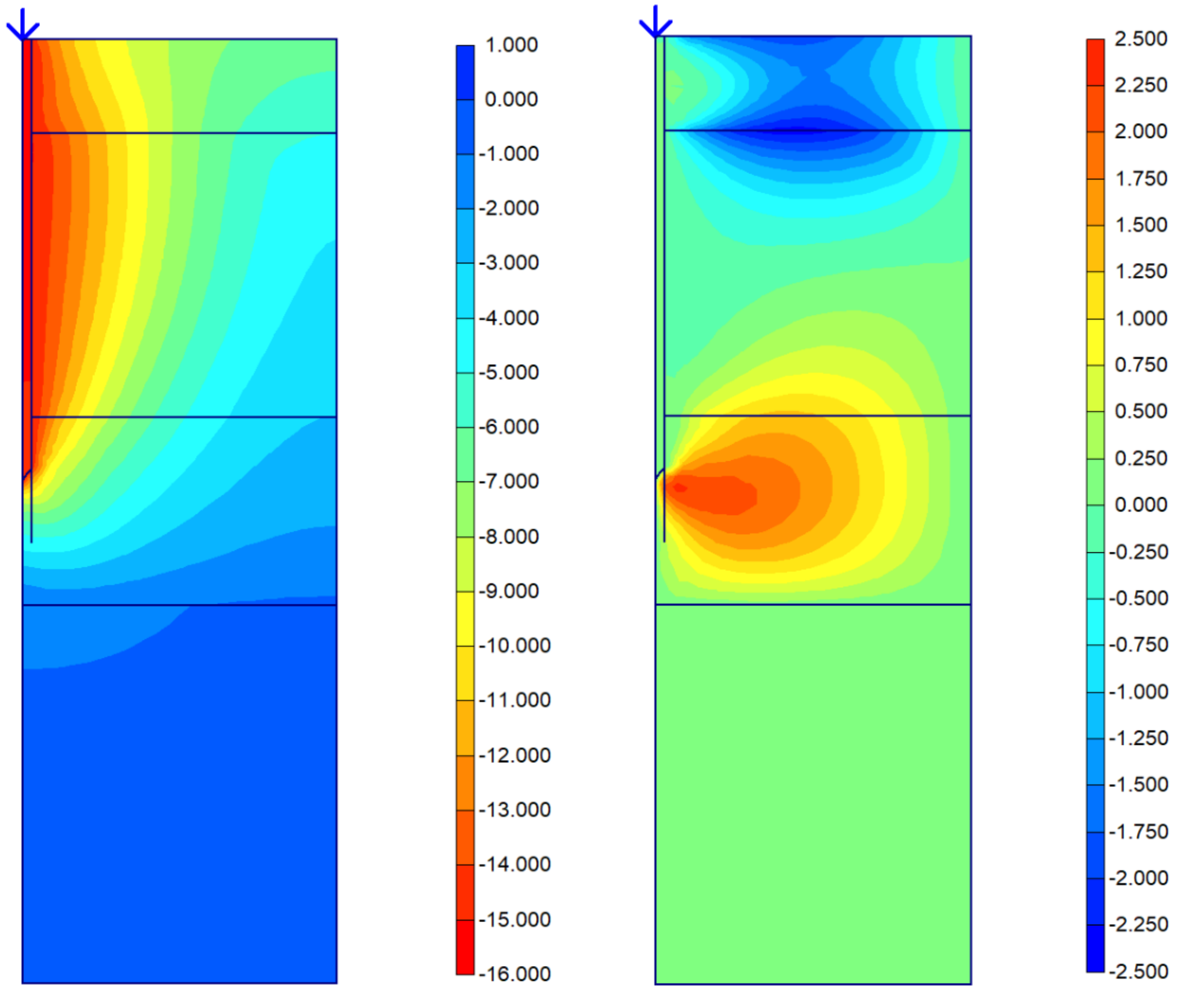


Figure 3 – SLT results

All four tested piles No. 4, 9, 13, and 14 showed similar trends in their SLTs, with settlement remaining minimal (often below 2 mm) at lower loads, then gradually increasing but still staying under 10–11 mm at the maximum applied load of around 1400 kN, which is way below the 20 mm threshold mandated by [12]. This indicates that, although the shallow soil may include permafrost to a depth of about 2.5 m, the deeper alluvial layers (loams, sands, and gravelly soils) effectively limit overall deformation. Consequently, none of the piles exhibited signs of bearing failure or excessive settlement, and each can safely be assigned a bearing capacity of 1167 kN, derived by applying a 1.2 safety factor to the maximum test load of 1400 kN.

Figure 4 below shows the results of numerical simulations of SLT in Plaxis 2D.



a) Vertical displacements b) Horizontal displacements

Figure 4 – Results of numerical simulations

The heatmaps from Figure 4 demonstrate that the simulation of SLT using a pile subjected to the load of 1400 kN with steps of 140 kN resulted in both vertical and lateral displacements of the soils to some extent. The values of displacements are reflected by the legend with gradient colors from blue to red for the vertical (Figure 4a), and vice-versa for the horizontal displacements (Figure 4b), corresponding to the positivity and negativity of the values, respectively. As is seen from a failure pattern in Figure 4a, the loading process initiated the pulling of the part of the soil base so that the closer it was to the pile the more its vertical displacement, suggesting the logical behavior of such a process. Unlike the vertical one, the lateral displacement created two dissimilar failure patterns. The pattern appeared close to the pile tip represented by a lateral movement, likely due to the resting of the pile on hard soils. Another pattern, somewhere in the depths of 1-2 m took a concave shape. This most likely is evidence of the creep behavior of soils due to permafrost at those depths, which coincides with [8], suggesting the necessity for future work in this direction.

Nevertheless, the highest values of vertical and horizontal displacements amounted to 15.17 mm and 2.38 mm, respectively, which are lower than the threshold of 20 mm [12]. This advocates that the bearing capacity of piles may be derived similarly to the field SLT using a safety factor of 1.2 and the highest load of 1400 kN, which results in 1167 kN as above.

4. Conclusions

The field tests demonstrate that the driven piles exhibit positive performance in frozen soils at the construction site of Central Mosque in Astana, Kazakhstan, with settlements remaining significantly below the 20 mm limit under a maximum load of 1400 kN. After applying a 1.2 safety factor, a bearing capacity of 1167 kN is achieved.

Due to the inherent variability and unique characteristics of permafrost soils from site to site, the findings of this study are pivotal in expanding our knowledge of frozen soil properties and behavior.

Observations of creep behavior in the upper, partially frozen soils and emerging patterns of lateral displacements underscore the complexity of soil-pile interactions in such environments. Further investigations into soil creep and lateral displacement behavior are essential to optimize foundation design and ensure long-term performance under variable temperature regimes.

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