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Numerical analysis of pile foundations in seasonally freezing soil ground

Abstract. The article presents the results of numerical analysis for pile foundation in seasonally freezing soil ground. This project uses the static tests of soil by piles at the construction site of Cargo off-loading facilities (Prorva, Atyrau region, Kazakhstan). The project area is located along the east coast of the Caspian Sea, both onshore and offshore, near the Prorva oilfield, Kazakhstan. At present, the North Caspian Sea has a limited water depth (max 8 m). According to the test results have been made design changes in the pile foundation. Static tests (SCLT) were carried out on the piles with 16m in length and precast concrete joint pile foundations with a total length of 22m to 27m. This research is important for an understanding of the interaction mechanism of precast composite joint piles with seasonally freezing soil ground of the Caspian Sea coastal area of the site.

Keywords: pile, numerical analysis, Load-Settlement, PIT.

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Introduction

Seasonal freezing of soils is a problem soil. In the production of winter conditions, engineers are faced with the problem of assessing frost-prone soils and making the right decisions to ensure the strength, reliability, durability, and stability of buildings. The frost hazard of soils in construction is understood as their ability to influence the stability of structures in the process of freezing-thawing when interacting with piles. According to the construction standards, the choice of the method of construction of the foundations should be determined based on engineering and geological studies. To make technological decisions, additional data are needed to characterize the cryogenic properties of soils in the process of freezing and thawing of soils.

Engineering and geological structure of site “Prorva”

Table 1 describes the engineering and geological conditions of the construction site. According to the physical and mechanical properties of the soil and the results of laboratory tests in the geological section, three engineering-geological elements (IGE) were identified. The standard values of the physical and mechanical properties of soils are given based on the results of testing samples of all wells.

The table 1 presents a geotechnical structure of the site.

Table1

Geological and lithological conditions of the construction site

EGE	Layer Description	C	φ, deg.	$\gamma_{natural}$ *), kN/m^3	Su, kPa	E*oed. ref*
EGE-2	Clay silt.	0.7	29,4	19.3	15	2.750
EGE-3	The sand is medium-dense, dense	2.7	31.5	19.0	-	30.000
EGE-7	The clay is light, dusty	20.8	24.7	19.1	80	2.000
EGE-8	The sandisdense	2.4	31.8	20.0	-	40.000
EGE-9	Clay	22.7	23.8	20.6	150	4.000
EGE-10	Clay	25	24.7	20.2	150	2.000

Pile Integrity Test (PIT) research

Mainly to ensure the safety of the head of a solid reinforced concrete composite pile, since most of the destruction is observed in its head part, even though 1.5 - 2.0 times higher than in the middle part. This phenomenon is explained by the fact that during immersion, the strength of the pile in the head part decreases due to the formation of microcracks, and then, as the number of impacts increases, the destruction of the head part of the pile occurs, while the strength of the pile trunk remains unchanged [1-5].

The quality of the pile is often determined by a low-stress continuity test, which is performed immediately after driving. The tests allow you to find out which piles should undergo additional inspection. The measurement is carried out by hitting the pile head with a hand hammer and evaluating the reaction of the head using an accelerometer [9]. For continuous control, non-destructive methods are used. To determine the actual pile lengths, locate defects (cracks, weak sections), and evaluate the mechanical characteristics of concrete piles, seismic-acoustic (sound) and ultrasonic control methods are used.

Working with seismoacoustic and ultrasonic devices is divided into two stages: testing piles on the construction site and interpreting the information obtained using special software.

To ensure the registration of the second wave in the piles, it is carried out with the help of special equipment, followed by leveling the surface of the head and mounting sensors (accelerometers) in accordance with Figures 1, 2.

The accuracy of determining the pile length depends on the accuracy of the stress wave velocity. When the pile length is known, the wave propagation velocity can be matched to the known length.

The solution to the issue of guaranteed safety of the reinforced concrete pile structure during its immersion in the ground is one of the main tasks of the developed problem.

The tests were carried out in seasonally freezing soils, the graphs show the integrity of the pile foundations in Figure 3.

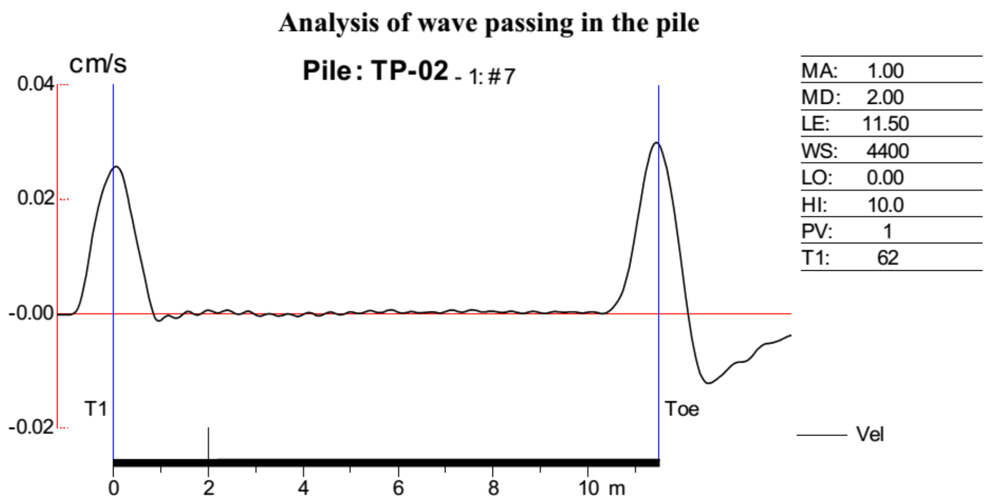


Figure1.Test results of piles TP-02by the method of PIT

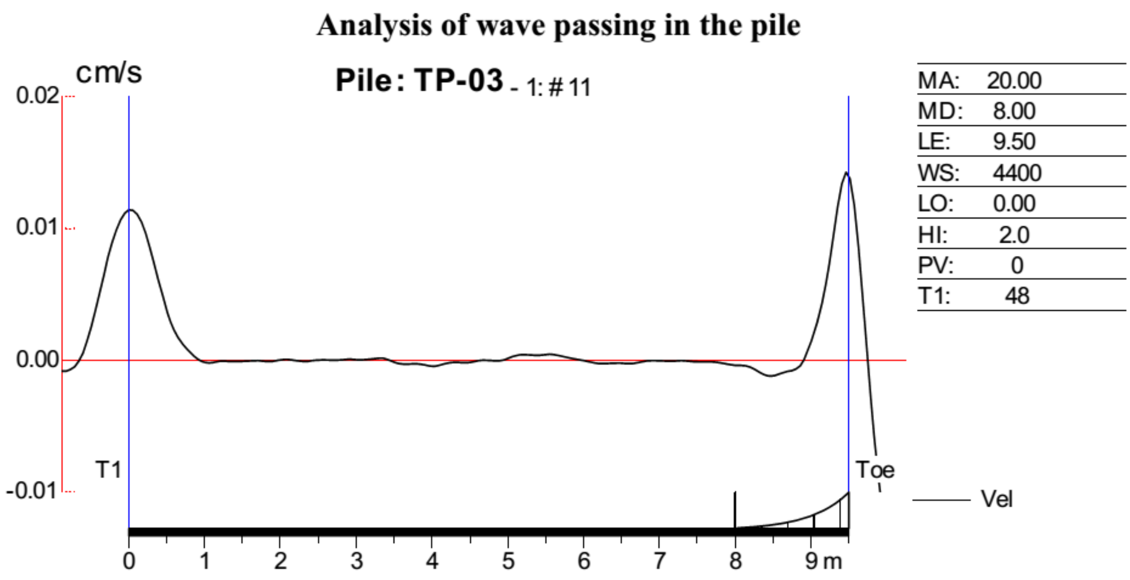


Figure 2. Test results of piles TP-03 by the method of PIT

The peculiarity of modern technology is the presence of docking units, which must retain their strength and shape after clogging each section. Thus, for the conditions of modern technology, it is necessary to introduce another condition, where the total number of blows of the pile-breaking equipment (or vibrations of the vibration loader) (N), capable of loading the pile at a given mark or before reaching its value of the effective load perceived by one pile, should be less than the impact resistance of the butt joint (Ncr), which is in the worst conditions (1) [1-4]:

$$N<N_{cr} \quad (1)$$

Fugure3. PIT pile testing

Numerical simulation by the finite element method in the Plaxis 2D

Currently, numerical calculation methods are used to quantify the VAT (stress-strain state) of inhomogeneous ground masses interacting with underground structures of buildings and structures, including FEM (finite element methods) [10]. The basis of these methods is the joint solution of a system of differential equations of equilibrium, continuity, and physical equations. The latter determine the dependence of the soil deformation on the stress state. Currently, there are different methods for describing physical equations, depending on the need to consider the linear, nonlinear, and rheological properties of soils.

The Plaxis 2D program has the advantages of relative simplicity and ease of use, as well as the availability of a soil model that is optimal for the task of this dissertation research [10].

The geometric dimensions of the composite pile model with a width of 0.4 m and various lengths from 22 to 27 meters were used in the calculation.

On the contact surface of the pile with the ground, interface elements were used to consider the displacement of the places of contact of the soil with the pile model.

The current version of PLAXIS 2D allows you to use only a linear color scale. In this regard, due to the large difference between the minimum and maximum shear deformations, it turned out that it was impossible to display them simultaneously in the same drawing.

Since the pile foundation is symmetrical to the vertical axis, only half of the area of the soil mass and the pile foundation were considered in the calculation scheme. The calculation scheme was automatically divided into triangular finite elements. The number of considered types of elements (layers) is 6 (the sequence of layers of the soil mass is shown in Figure 4).

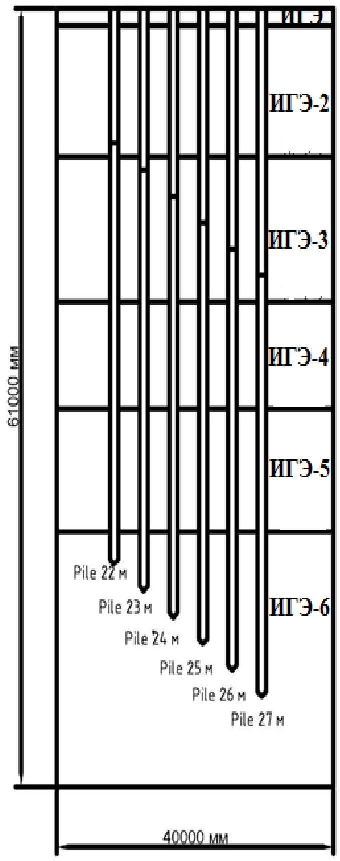


Figure 4. Diagram of the arrangement of the sequence of layers of the soil mass and the pile foundation

Piles of different lengths from 22 to 27 meters were tested using various simulations (Figure 4):

a) Pile 22m-the total length of the composite piles is 22 meters, the length of the first section is 16 meters, the length of the second section is 6 meters;

b) Pile 23m-the total length of the composite piles is 23 meters, the length of the first section is 16 meters, the length of the second section is 7 meters;

c) Pale 24m-the total length of the composite piles is 24 meters, the length of the first section is 16 meters, the length of the second section is 8 meters;

d) Pile 25 m-the total length of the composite piles is 25 meters, the length of the first section is 16 meters, the length of the second section is 9 meters;

e) Pile 26m-the total length of the composite piles is 26 meters, the length of the first section is 16 meters, the length of the second section is 10 meters;

e) Pile 27m-the total length of the composite piles is 27 meters, the length of the first section is 16 meters, the length of the second section is 11 meters.

Numerical simulation of testing of composite piles with a length of 22 to 27 meters

This section discusses the calculation of the pile foundation draft. The general methods of creating a geometric model, constructing a finite element grid, performing calculations using the finite element method, and evaluating the results obtained are considered in detail.

The load-bearing capacity of the piles was determined based on the results of numerical simulation of each pile operation in the PLAXIS 2D software package. The stress-strain state of the base was calculated using the Mora-Coulomb elastic-plastic model. The calculations were carried out in an axisymmetric setting.

Step-by-step pile loading was modeled by increasing the applied load on the pile, and the maximum vertical load was 3,278 kN. The main parameters tracked for the results are the amount of applied load and the pile draft. As a result of the calculation, the "load-draft" graphs were constructed.

Geometric models of numerical simulation of composite driving piles with a length of 22 meters to 27 meters (Pile 22 m-Pile27 m) are shown in Figure 5.

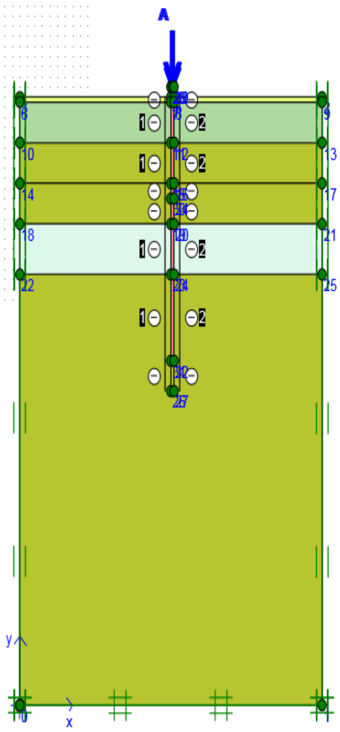
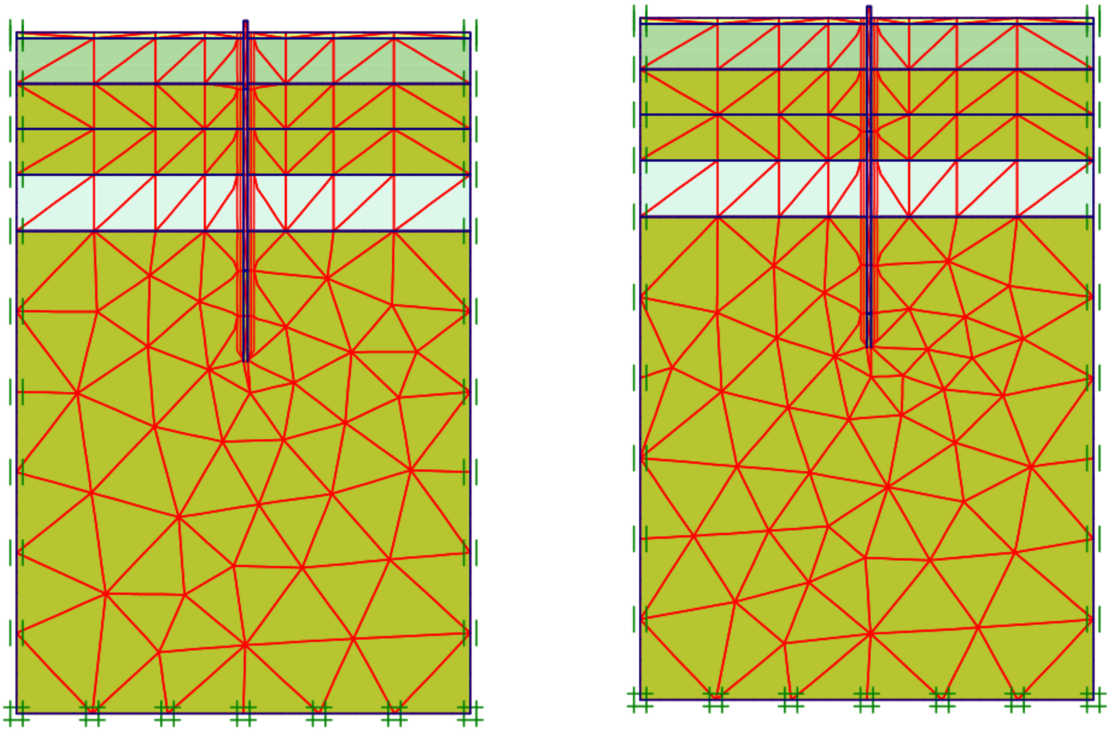


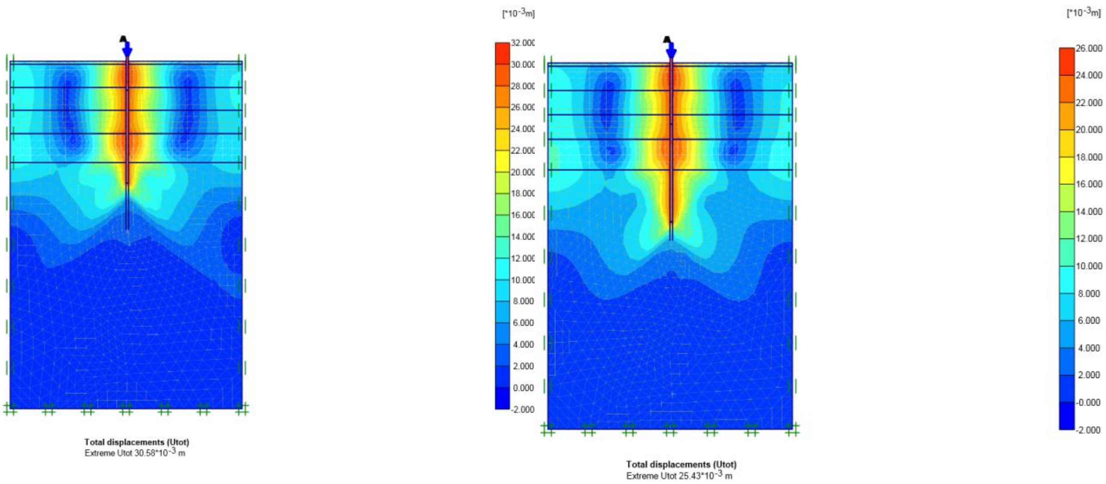
Figure 5. Geometric model of a composite pile with a length of 27 m

The finite element meshes generated automatically by the Plaxis 2D program for composite piles with a length of 22 meters to 27 meters (Pile 22 m - Pile27 m) are shown in Figure 6.



Fugure 6. Finite element grid (Pile 22, 27m)

Isolines of total ground movements under vertically static loads for composite piles with a length of 22 meters to 27 meters (Pile 22 m – Pile27 m) are shown in the figure 7.



Fugure 7. Full displacement (Pile 22, 27 m)

Vertical movement isolines for composite piles with a length of 22 meters to 27 meters (Pile 22 m – Pile27 m) are shown in the figure 8.

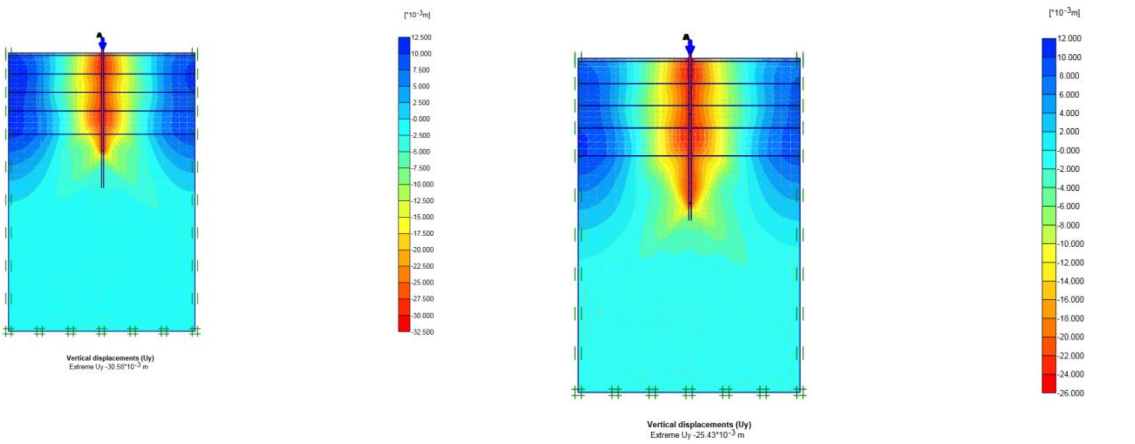


Figure 8. Vertical movement (Pile 22, 27m)

Isolines of horizontal ground movements under vertically static loads for composite piles with a length of 22 meters to 27 meters (Pile 22 m-Pile 27 m) are shown in the figure 9.

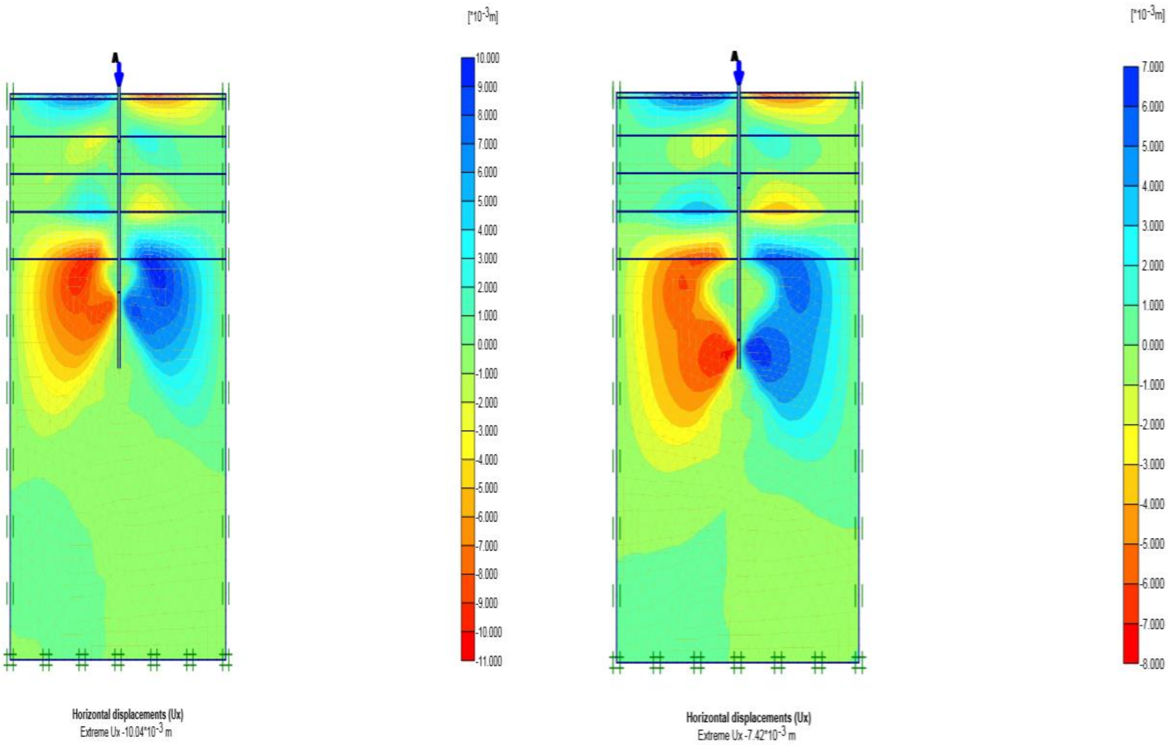


Figure 9. Horizontal movement (Pile 22, 27 m)

Comparison of numerical simulation results

Figure 10shows a comparison of the test results the "Load-Settlement" curve obtained by the SLT method, the length of the composite piles is from 22 meters to 27 meters [1, 4-9].

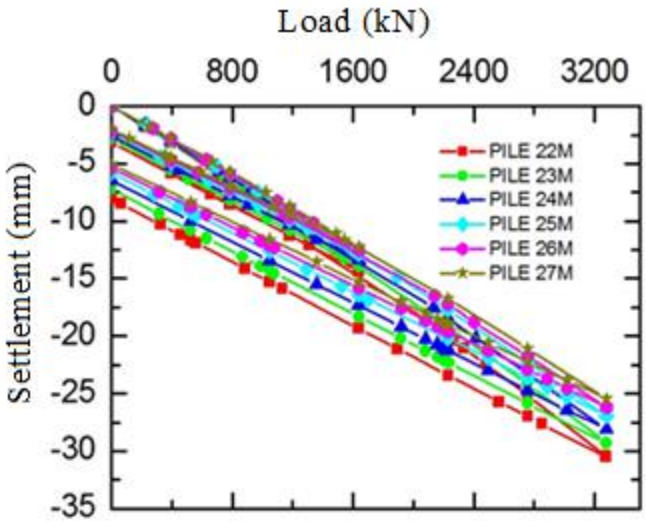


Figure 10.Load-Settlement graph based on Plaxis 2D results

The superposition of the curves showed that the convergence of the graphs is observed only at the initial stage of loading, then there is a change in the trajectory of the curve depending on the length of the pile. For a pile with a length of 22 meters, the draft was 30.58 mm, and for a maximum length of a composite pile of 27 meters, the draft was 25.43 mm.

For the partial value of the maximum resistance of the pile to the indentation load Fu, it is necessary to take the load under the influence of which the tested pile will receive a draft equal to S and determined by the formula 2 [10]:

$$S = \zeta S_{u,mt} = 0{,}2 \cdot 8 = 16\text{мм} \quad (2)$$

$S_{u,mt}$ =8см-the limit value of the average foundation draft of the projected building, set according to the instructions of the SNiP 5.01-01-2002 [6-8];

where: ζ is the transition coefficient from the limit value of the average foundation sediment of a building or structure Su, mtk to the pile sediment obtained during static tests with conditional sediment stabilization, according to the requirements of the SNIP 5.01-101-2003 the value of the coefficient should be taken as ζ=0.2.

The results on the maximum resistance of the piles to the indentation load under the influence, in which the tested pile received 16 mm of precipitation from the dependence of the length of the pile, can be seen in Table 2.

Table 2

Determination of the load-bearing capacity of piles at a fixed settlement

№	Pile number	The load-bearing capacity of the pile at a fixed draft of 16 mm
1.	№ pile 22m	1727 kN
2.	№ pile 23m	1815 kN
3.	№ pile 24m	1883 kN
4.	№ pile 25m	1975 kN
5.	№ pile 26m	2139 kN
6.	№ pile 27m	2229 kN

Conclusion

The estimated load-bearing capacity of the driving pile with a cross-section of 40x40 cm and a length of 25 m was 2400 kN, which confirms the sufficient load-bearing capacity of the foundation soils for piles of this depth of immersion.

The section has developed geometric models of composite driving piles with a length of 22 meters to 27 meters (Pile 22 m – Pile27) musing numerical simulation in the Plaxis 2D environment. The calculation of the stress-strain state of the base is based on the elastic-plastic Mohr-Coulomb model in an axisymmetric formulation. The piles were gradually loaded by increasing the applied load on the pile, resulting in a maximum vertical load of 3,278 kN.

Vertical displacements for composite piles with a length of 22 meters to 27 meters (Pile 22 m – Pile27 m) after the calculation stage in the Plaxis 2D environment ranged from 25 mm to 30 mm, this is consistent with the results of field tests.

The load-bearing capacity of the piles was compared at a fixed draft of 16 mm and the change in load-bearing capacity per one linear meter of the depth of immersion of the pile was calculated.

The method of testing composite piles by the SCLT method is performed in accordance with the ASTM standard. According to the results of field tests of composite piles by the SCLT method, the load-bearing capacity of the piles was 2067 kN, 2042 kN and 2333 kN, respectively, for pile lengths from 23 m to 26.75 m, and these values do not exceed the values of the maximum load-bearing capacity according to the Davisson limit method.

On the basis of conducting a series of field tests of composite piles in the conditions of complex multi-layered soils of Western Kazakhstan, it is recommended to use non-destructive methods for controlling the continuity of composite piles. The low-stress continuity test (PIT method) identifies pile defects that may reduce load-bearing capacity.

Geometric models of composite driving piles with a length from 22 meters to 27 meters (Pile 22 m – Pile 27 m) were developed using numerical modeling in the Plaxis 2D environment and the stress-strain state of the base was calculated using the elastic-plastic Mohr-Coulomb model in an axisymmetric formulation. As a result, vertical displacements were determined for composite piles with a length of 22 meters to 27 meters (Pile 22 m-Pile27 m) from 25 mm to 30 mm, which is confirmed by the results of field tests, and the load-bearing capacity of piles with a fixed settlement of 16 mm was compared.

Based on the results of numerical simulation of construction sites Prorvain seasonally freezing soil ground bearing capacity of pile foundations have a slight deviation of the pile settlement.

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Топырақтың маусымдық қатуы кезіндегі қадалық іргетастарды сандық талдау

Аңдатпа.Мақаладатопырақтыңмаусымдыққатужағдайындағықадалыіргетастыңнәтижелерікелтірілген. Бұлжобадақайтатиеуқұрылыстарының (Прорва, Атырауоблысы, Қазақстан) құрылысалаңындақадалармentопырақтыңстатикалықсынауларыпайдаланылады. Жоба ауданы Каспий теңізінің солтүстік-шығыс жағалауының бойында, Прорва, Қазақстан мұнай кен орнына жақын жерде орналасқан. Қазіргі уақытта Солтүстік Каспийдің тереңдігі шектеулі (максимум 8 м). Сынақ нәтижелері бойынша қадалық іргетасқа конструктивті өзгерістер енгізілді. Статикалық сынақтар жалпы ұзындығы 27 метрге дейін 16 метрлік қадалар мен құрастырмалы темірбетон байланыстырғыш қадаларда жүргізілді. Бұл зерттеулер құрама қадалардың Каспий теңізі учаскесінің жағалау аймағының проблемалы топырағымен өзара әрекеттесу механизмін түсіну үшін маңызды.

Түйін сөздер:қадалар, сандық сынақтар, жүктеме-отыру, PIT.

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Численный анализ свайных фундаментов в условиях сезонного промерзания грунта

Аннотация. В статье представлены результаты работы свайного фундамента в условиях сезонного промерзания грунта. В данном проекте используются статические испытания грунта сваями на строительной площадке перегрузочных сооружений (Прорва, Атырауская область, Казахстан). Район проекта расположен вдоль восточного побережья Северо-Восточного Каспийского моря, как на суше, так и на шельфе, недалеко от нефтяного месторождения Прорва (Казахстан). В настоящее время Северный Каспий имеет ограниченную глубину (максимум 8 м). По результатам испытаний были внесены конструктивные изменения в свайный фундамент. Статические испытания проводились на 16-метровых сваях и сборных железобетонных соединительных сваях общей длиной до 27 м. Эти исследования важны для понимания механизма взаимодействия сборных составных свай с проблемным грунтом прибрежной зоны участка Каспийского моря.

Ключевые слова: свая, численный анализ, нагрузка-осадка, PIT.

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