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Article

# Bearing Capacity of Precast Concrete Joint Micropile Foundations in Embedded Layers: Predictions from Dynamic and Static Load Tests according to ASTM Standards

**Abdulla Omarov [1], Assel Sarsembayeva [1,2,*], Askar Zhussupbekov [1], Malika Nurgozhina [1,*], Gulshat Tleulenova [1], Akmaral Yeleussinova [1] and Baizak Isakulov [3]**

[1] Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Astana 010008, Kazakhstan; omarov_01@bk.ru (A.O.); astana-geostroi@mail.ru (A.Z.); gulshattleulenova23@mail.ru (G.T.); yeleussinova70@mail.ru (A.Y.)
[2] Department of Civil Engineering and Geodesy, Shakarim University, Semey 071412, Kazakhstan
[3] Department of Civil Engineering and Design, Baishev University, Aktobe 030000, Kazakhstan; mr.baizak@mail.ru
* Correspondence: assel_enu@mail.ru (A.S.); malika_nur@list.ru (M.N.); Tel.: +7-7078503035 (A.S.)

**Abstract:** In this paper, joint precast piles with a cross-section of 400 × 400 mm and a pin-joined connection were considered, and their interaction with the soil of Western Kazakhstan has been analyzed. The following methods were used: assessment of the bearing capacity using the static compression load test (SCLT by ASTM) method, interpretation of the field test data, and the dynamic loading test (DLT) method for driving precast concrete joint piles, including Pile Driving Analyzer (PDA by ASTM) and Control and Provisioning of Wireless Access Points (CAPWAP) methods. According to the results, the composite piles tested by the PDA (by ASTM) method differ by 15 percent compared to the static load method, while the difference between the dynamic DLT (by ASTM) method and the static load (by ASTM) method was only 7 percent. So, according to the results, the alternative dynamic method DLT (by ASTM) is very effective and more accurate compared to other existing methods.

**Keywords:** joint piles; dynamic load test; Pile Driving Analyzer; static compression load test

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## 1. Introduction

Precast concrete piles are commonly used on foundations. Problems often arise during the installation of long precast concrete piles. These problems include the cracking of long piles during handling, the extreme weight of piles, and the cost involved in handling long piles. To alleviate these problems, shorter pile lengths are spliced together versus driving a single pile. Splicing is an attractive solution because shorter pile lengths weigh less and are easier to handle and transport. Splicing also alleviates the need to calculate exact pile lengths prior to installation, which will reduce the waste of piles that are too long. A splice develops adequate strength in compression, tension, and bending moments during installation and in service. Splices are effective without significantly extending the duration of construction, are as durable as the pile, and are inexpensive. There have also been evaluations of the performance of various types of splices used around the world: mechanical ABB splice (Sweden), sleeve Anderson splice (USA), welded Bolognesi–Moretto splice (Argentina), bolted Japanese splice (Japan), dowel splice (USA), post-tensioned Macalloy splice (UK), connector ring Pile Coupler splice (USA), and wedge Wennstrom splice (Sweden). Precast reinforced concrete piles are multi-section reinforced concrete structures consisting of several connecting elements. These piles make it possible to create supports of maximum length (up to 36 m), which cannot be done with solid piles due to the limited capacity of pile-driving machines. A standard square precast concrete joint pile is composed of two components with a maximum total length of 24–30 m [1]. The first component has a pointed end on the lower side and a joint-fixing device on the upper side. The second section is equipped with an anchor part for connection to the first section. Significant contributions to precast pile foundation engineering were made by Gaido A.N., Stepanova M.A. et al., Mayyer V. et al., Shulman S.A. et al., and many others [2–5]. Precast piles, manufactured in accordance with current GOST standards, consist of two connecting parts: upper and lower. Such piles can have the following sections:

- 30 × 30 cm; the length of the pile in this section varies from 14 to 24 m [1];
- 35 × 35 cm, 40 × 40 cm—the length varies from 16 to 40 m [6].

Due to the widespread use of pile foundations in soft soil conditions, as well as an increase in the number of floors in construction, there is a need to install precast concrete joint piles more than 12 m long. There are many ways to connect piles, and it is difficult to determine which method is the most effective. The length of the upper and lower parts of precast concrete joint piles may vary. In 30 × 30 cm cross-section products, the length of the bottom part starts at 7 m and increases in 1 m increments up to 12 m. Depending on the geological complexity and load from buildings and structures, the length of precast concrete joint pile foundations changes. The lower piles remain unchanged since the precast concrete joint piles are driven into a pile-driving machine, which is limited in height, and the upper precast concrete joint piles can change depending on the required length according to the project. In piles with cross sections of 35 × 35 and 40 × 40 cm, the minimum length of the lower section is 8 m, and the maximum length is 16 m. The size of the upper sections in 30 × 30 cm piles varies from 5 to 16 m; in 35 × 35 and 40 × 40 piles, it varies from 6 to 16 m (Figure 1).

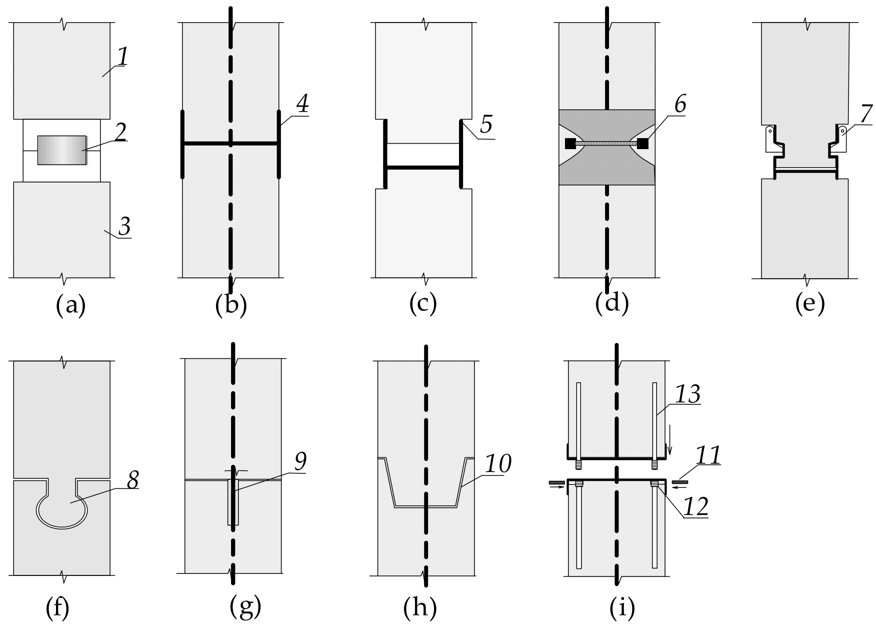



**Figure 1.** Structural and technological solutions of pile joints [2]: (**a**–**c**)—welded connection with a metal sheet protruding on the surface and without a protrusion; (**d**)—bolted connection; (**e**)—locking connection with special hinged locks; (**f**–**h**)—groove connection with and without adhesive; (**i**)—connection with fixing pin; 1—top pile section; 2—steel plate welded around the perimeter; 3—bottom pile section; 4—jig; 5—corrugated reinforced concrete projection; 6—bolted connection; 7—flap lock; 8—keyway; 9—reinforcing bars of the upper section on adhesive material; 10—sealing tape; 11—pins; 12—groove; 13—fixing pin.

In a paper by Gaido A.N. [2], various joints between sections are considered, and as a result of the experiment, the technological feasibility of using pin connections for pile sections is established. The application of the new joint reduces the time spent driving one pile by 25 min and increases the productivity of a shift during indentation by 30%. The pin connection provides stability and wear resistance to pile sections during pile driving. In a paper by the authors V. Mayer et al. [4], the optimal joints of precast reinforced concrete piles were determined using four types of joints. L.I. Kachanovskaya and S.P. Kasatkina considered the feasibility of composite reinforced concrete piles developed on the basis of the typical use of such piles in the construction of linear structures [6]. According to A.V. Buchkink et al., wide application of the LEIMET ABB+ joint is currently limited by the insufficient study of its parameters and, in particular, strength characteristics [7,8]. When testing for compression, transverse shear, and bending, it was established that the destruction of the prototypes occurred along the concrete body of the pile without signs of destruction of the metal pin connection or the formation of concrete spalls in the area of the Leimet ABB+ 350 pin connection on four locks. This indicates that the connection has equal strength to the body of the fragment sections of the reinforced concrete composite pile under the specified impacts [8]. At the same time, with a tensile load of 475.8–503.3 kN, no signs of damage to the pin connection were revealed (the tests were stopped before the samples failed). In the studies reviewed, it can be said that precast concrete joint piles were tested for joints between piles, as well as material properties under bending, compression, and tension. However, it should be noted that pile foundations should be tested not only by material but also in conjunction with the surrounding ground conditions for static and dynamic loads on the pile. This research is very important for determining the bearing capacity of precast concrete joint piles in weak soil conditions.

To date, various technologies for joints in precast reinforced concrete pile sections have been used in the construction industry, which include the following [1–3]: welded joint, cup-type joint, bolted joint, locking joint, collet joint, glue joint, pin-type joint, etc. (Figure 1). This experience of using joint pile foundations shows the advantages of precast concrete piles, according to the works by Mayer et al., Shulman et al., and others [4–9].

Nowadays, the use of pin joint technology for sections of precast reinforced concrete piles is gaining popularity [3–9]. The main advantages of this joint are low labor intensity (relative to widely used welded joints) in connecting the pile elements with each other, high speed of installation, and the elimination of the need for welding, concreting, etc. [10,11]. The main advantages of this joint are the following: The Leimet ABB+ pin connection is a metal header with integrated anchor outlets and locking elements (fixing pins and sockets) for the insertion of wedging pins, which is carried out directly at the connection of two sections of precast concrete piles on the construction site. The basic design of the Leimet ABB + pin connection (conceptual design of the Leimet ABB + pile joint [8]: 1—metallic cap consisting of the end frame and the shell along its contour; 2—anchor bars; 3,4—locking elements: the locking dowel and locking block, respectively; 5—locking pin; 6—reinforced concrete pile sections) is shown in Figure 2.

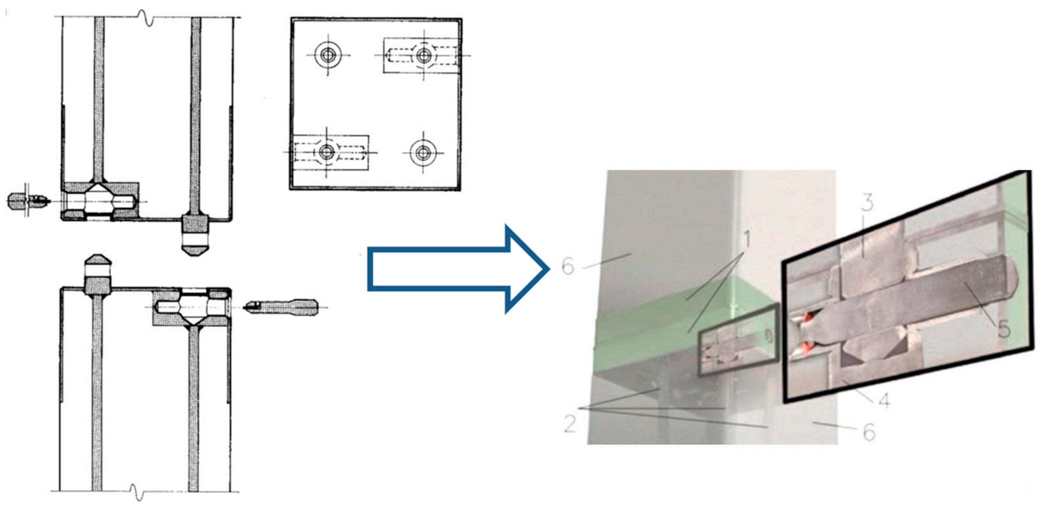



**Figure 2.** Principal design of pin connection in precast concrete joint reinforced concrete piles [8].

In Kazakhstan, this technology has found its application in construction projects at the seaport of Prorva on the Caspian Sea coast. The Project Cargo Offloading Facility is an essential strategic project for the expansion of oil fields. The Project Cargo Offloading Facility is located along the quay and represents a special reinforced concrete surface supporting the large cranes needed to unload cargo, handling bulky and general cargo. Sheet pile walls surround the Project Cargo Offloading Facility surface [12–14].

## 2. Analysis (State) of the Problems

Modern construction places appropriate requirements on engineers and designers, so new economically and environmentally efficient energy-saving technologies, including pile foundation technologies, have replaced established traditional solutions [15–17].

Today, in the period of large-scale construction in the Republic of Kazakhstan, especially where industrial construction is carried out, pile foundations play a primary function. The expediency of using pile foundations is explained by the need to provide a large bearing capacity for buildings and structures. In this article, the methods of field tests for soil piles are relevant, which allow obtaining data on the dependence of the stress–strain state and bearing capacity of the pile, which are especially important at the initial stage of construction and as a result of which control changes are made in the project. Static and dynamic tests, according to GOST 5686 [18], are considered the basic tests in the Republic of Kazakhstan; however, as practice shows, these methods have a number of disadvantages related to the labor intensity of such tests (static tests) and the quality of results (dynamic tests). Instead, we apply the PDA method used in Southeast Asia, Europe, and the USA to test precast concrete joint piles in soil.

According to the design drawings, the cargo offloading facility (Figure 3) construction site was planned to be installed with a precast concrete joint pile. This was my first experience installing such a type of pile in Kazakhstan. Applying precast concrete joint piles for the first time demanded a comprehensive approach [19–22].

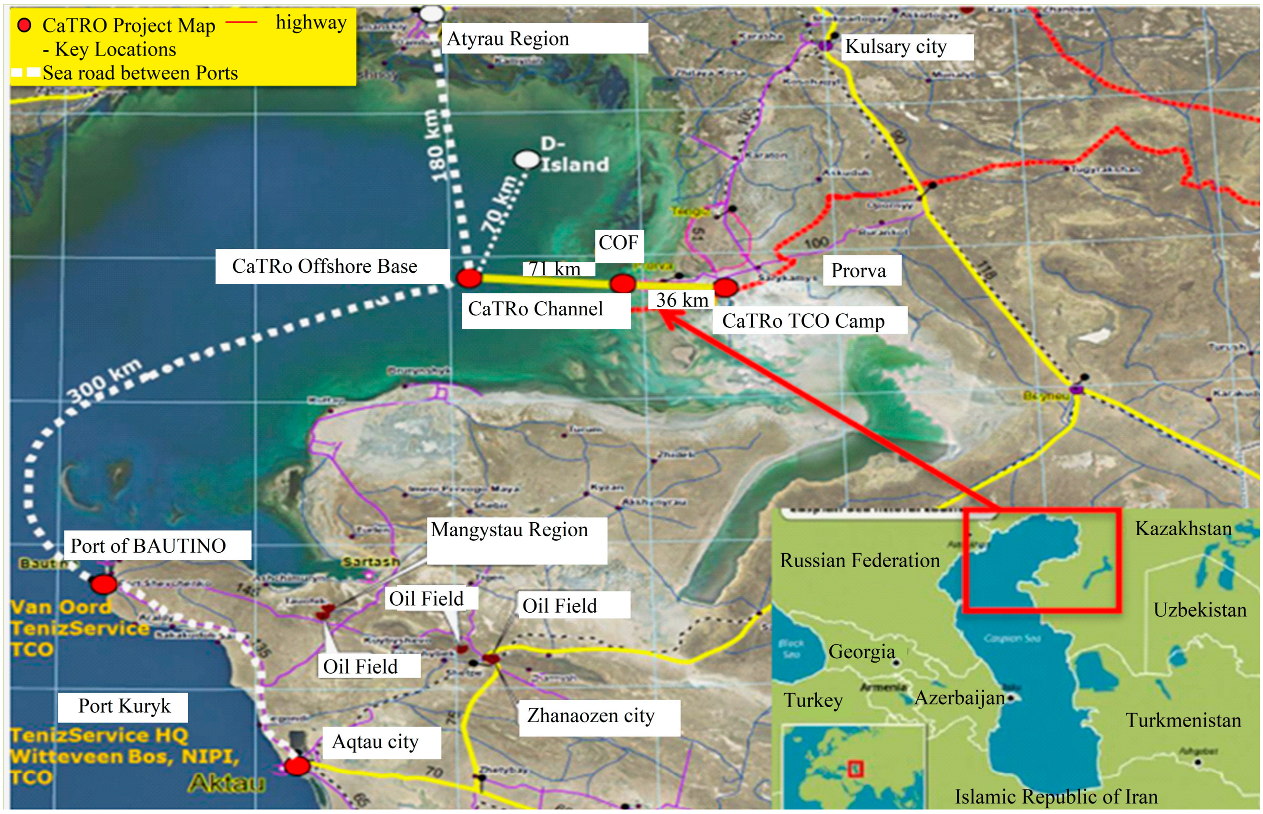



**Figure 3.** Location of Prorva seaport on the Caspian Sea coast (cargo offloading facility) [16].

The project area is situated on the Northern Caspian Shelf. At present, the North Caspian Sea has a limited water depth (a maximum of 5 to 8 m). The water level in the Caspian Sea depends on a balance between the inflow of river water and evaporation (Figure 4). This has resulted in large variations in sea level in the past. In the sedimentary succession within the planned construction site, with regard to lithology, depositional setting, structure, compositional petrology, state, and physical and mechanical properties of sediments, and with regard to the State Standard (GOST) 25100-2020 [23], the following geotechnical elements (GE) were specified: the physical and mechanical characteristics of soils at construction sites are shown in Table 1.

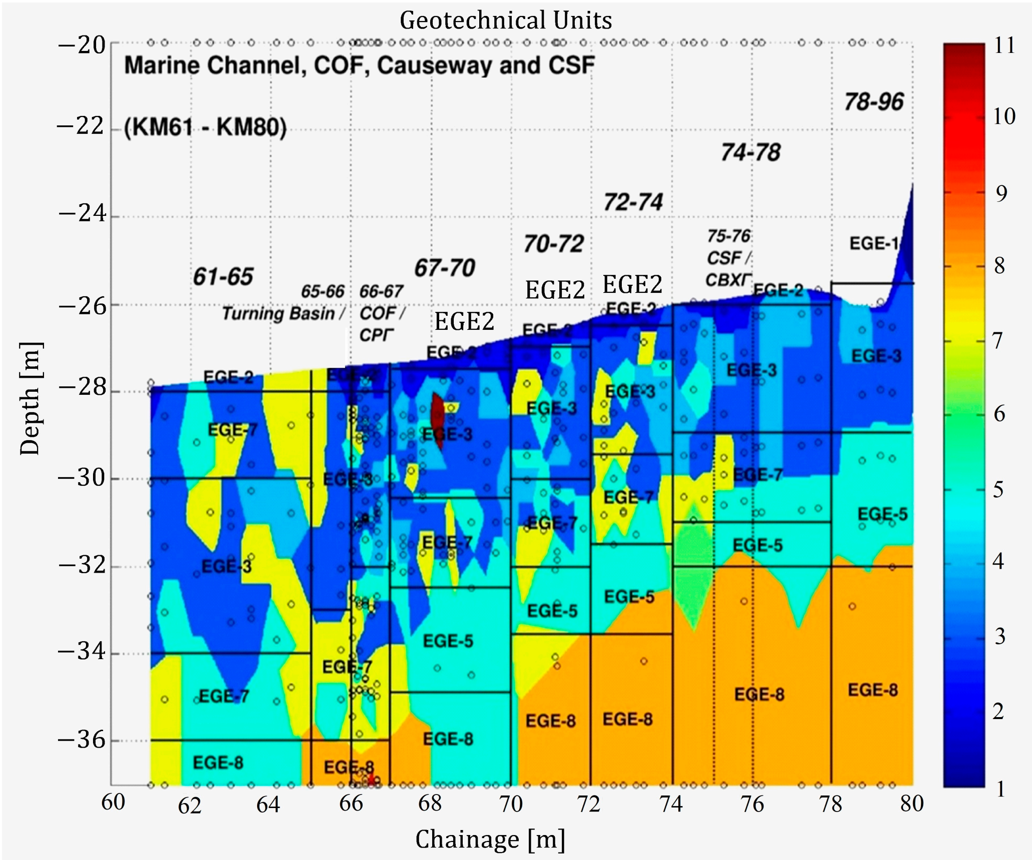


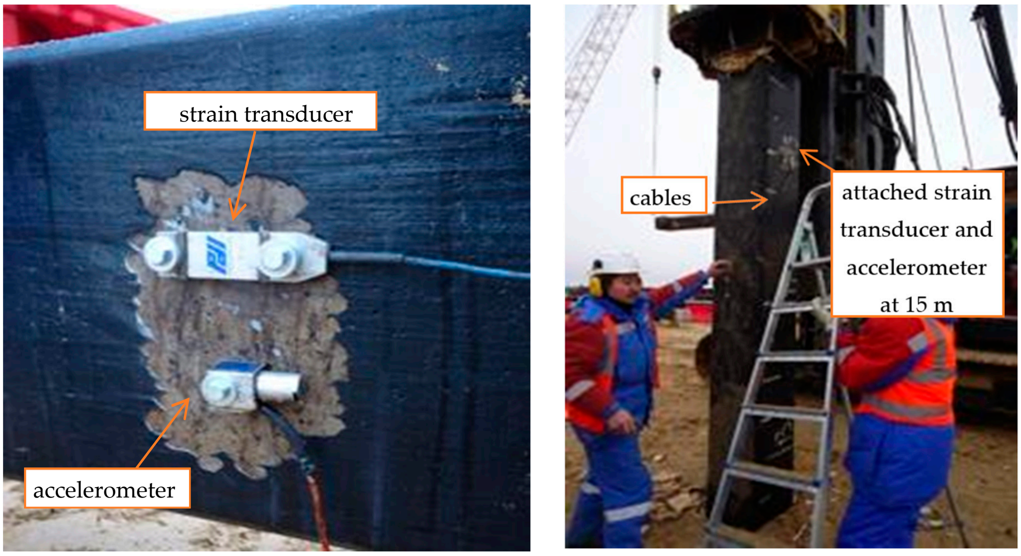

**Figure 4.** Longitudinal geotechnical profile of the construction site.

**Table 1.** Physical and mechanical characteristics of soils at construction sites.

| GE | Soil Type | $\gamma_{sat}$, kN/m$^3$ | Static Probing | | | | Strength Parameters in Effective Stress (Triaxial Test) | |
|---|---|---|---|---|---|---|---|---|
| | | | φ, deg | C, kPa | E, MPa | Su, kPa | φ′, deg | C′, kPa |
| GE2 | SILT, slightly organic, calcareous | 19.3 | 29.4 | 7.21 | 2.26 | 18 | - | - |
| GE3 | SAND, silty, calcareous | 20.2 | 31.5 | 4.86 | 6.62 | - | 39 | 9.5 |
| GE7 | CLAY, silty, calcareous | 19.1 | 24.7 | 19.57 | 2.16 | 17 | 21 | 55.6 |
| GE8 | SAND, silty, calcareous | 20.0 | 31.8 | 11.65 | 27.67 | - | 31 | 21.4 |
| GE9 | CLAY, silty, calcareous | 20.6 | 23.8 | 26.36 | 12.95 | 150 | 16 | 71.1 |
| GE10 | CLAY, silty, calcareous | 20.2 | 24.7 | 24.94 | 38.72 | 150 | 24 | 89.4 |

## 3. Materials and Methods

The Pile Driving Analyzer (PDA) system is the most widely employed system for dynamic load testing (DLT) and pile driving monitoring in the world. High-strain dynamic load tests, also called PDA tests, assess the capacity of several piles in a single day. Pile Driving Analyzer systems also evaluate shaft integrity, driving stresses, and hammer energy when monitoring installation. The dynamic tests of PCJPs were carried out by PDA Model PAX using the piling machine JUNTTAN PM25LC, which had a hydraulic hammer HHK-9A with a weight of 9 tons and a 990 kg head cap during driving piles. The tested PCJPs were attached to a pair of accelerometers and strain transducers at a distance of two widths below the pile head. The sensors were connected to the PDA via special cables. The PDA internally performs all the necessary signal conditioning and processing to obtain output results while driving. For each hammer blow, it immediately displays on the monitor screen the measured force at the pile head ($F_{measured(t)}$) and pile head movement velocity ($v_{measured(t)}$) as a function of time (Figure 5). Sensors should always be above the waterline or ground level. The method and procedure of measurement are standardized by the standard ASTM D4945 [24] and defined in accordance with EU 7. In this case, dynamic tests using the PDA were carried out on joint piles in a total of 62 pieces, but 7 piles were taken for the study, as they were later subjected to static tests of the soil with piles to determine the bearing capacity. Dynamic tests of piles were carried out while driving piles. Before the test, work was done to prepare the piles. A pair of accelerometers and strain transducers were attached to the pile at 15 m from two sides (Figure 5), which were connected to the PDA using cables. The piles were recorded by type, cross-section, diameter, and length of the leader well.




(**a**) (**b**)

**Figure 5.** Installation of accelerometers and transducers: (**a**)—attached accelerometer and transducer on pile; (**b**)—PDA during the installation of pile.

Dynamic tests were carried out on two parts of precast concrete joint reinforced concrete piles separately, and the results of the bearing capacity were determined automatically by the program as an average value (Figure 6). After driving the first part of the joint pile, a pair of accelerometers and strain transducers were attached to the second part of the pile at 8 m. The data from the piles were entered into the program, and the PDA dynamic tests were continued. After the execution of the field part of the dynamic test, selected blow data (often one of the last blows) were analyzed in the computer program Case Method and iCAP® in the software PDIPLOT2, Ver. 2016.1.56.3. CAPWAP (Case Pile Wave Analysis Program), which is based on wave equations. The pile model and soil model are initiated with a measured value of pile velocity ($V_{measured(t)}$). The result of CAPWAP analysis is the calculated response ($F_{calculated(t)}$), which, in the case of perfectly accurate pile and soil model data, should be completely identical to the measured force curve. Static loading tests of PCJPs were carried out according to the requirements of ASTM D1143 [25], Standard Test Methods for Deep Foundations Under Static Axial Compressive Load. The testing platform (Figure 7) presented itself as a system made of steel, which consists of a metallic beam and two load platforms (total weight of concrete blocks 450 tons) located at equidistant distances from the center main beams. Static load stages are presented in Table 2.


**Figure 6.** Installation of precast concrete pile: (**a**)—metal grooves for connection between precast reinforced concrete piles, (**b**)—alignment process when connecting precast reinforced concrete piles, (**c**)—installation of a pin at the junction of precast reinforced concrete piles, (**d**)—completed connection between precast concrete piles.

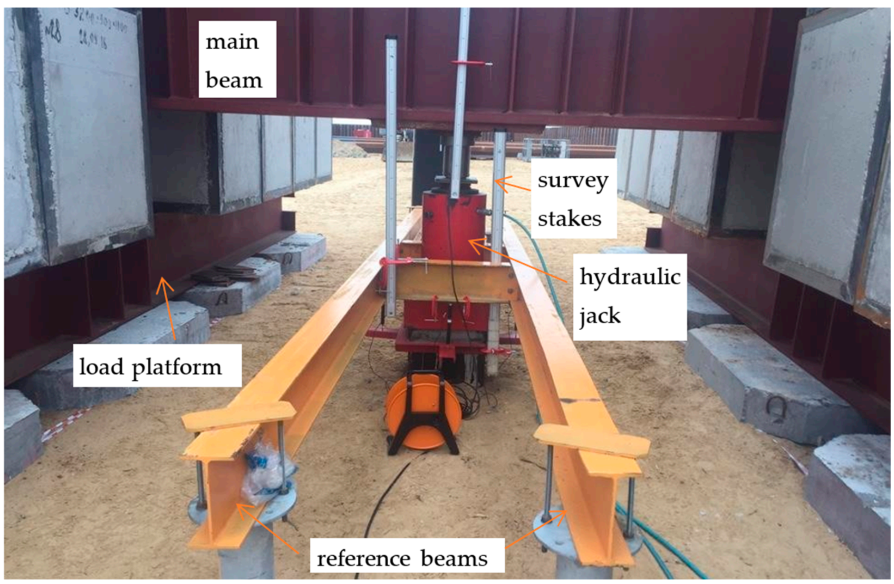



**Figure 7.** Testing platform for static compression load test.

**Table 2.** Static load stages of the preliminary pile, Prorva construction site.

| Loading (Maximum Compression Test Load Equals 2.5 × Working Load) | | | | | |
|---|---|---|---|---|---|
| **Step No.** | **Percentage** | **Pressure, Bar** | **Increment Load, kN** | **Full Load, kN** | **Min. Time of Hold. Load** |
| 1 | 30 | 55 | 393 | 393 | 1 h |
| 2 | 60 | 110 | 393 | 786 | 1 h |
| 3 | 90 | 165 | 393 | 1179 | 1 h |
| 4 | 125 | 228 | 460 | 1639 | 1 h |
| 5 | 90 | 165 | 460 | 1179 | 10 min |
| 6 | 60 | 110 | 393 | 786 | 10 min |
| 7 | 30 | 55 | 393 | 393 | 10 min |
| 8 | 0 | 0 | 393 | 0 | 1 h |
| 9 | 170 | 310 | 2229 | 2229 | 6 h |
| 10 | 210 | 383 | 527 | 2756 | 1 h |
| 11 | 250 | 456 | 522 | 3278 | 6 h |
| 12 | 210 | 383 | 522 | 2756 | 10 min |
| 13 | 170 | 310 | 527 | 2229 | 10 min |
| 14 | 125 | 228 | 590 | 1639 | 10 min |
| 15 | 80 | 146 | 590 | 1049 | 10 min |
| 16 | 40 | 73 | 524 | 525 | 10 min |
| 17 | 0 | 0 | 525 | 0 | 1 h |

Figure 6a,b show a block diagram of the work performed using the technology of constructing precast concrete joint pile foundations. It is obvious that the processes of engineering-geological research at a construction site and the design of pile foundations practically do not depend on the manufacture of precast concrete joint piles and their delivery to construction sites. This indicates that a flexible technological process has been obtained, where stages of work that are independent of each other are carried out, aimed at obtaining a single final product. Manufacturing plants, regardless of the design solutions for pile foundations in a particular facility and taking into account the production plan for reinforced concrete products, can produce precast concrete joint piles and have a certain stock of products. Contracting organizations can obtain the required volume of precast concrete joint piles, indicating their specific dimensions and holding the product until it reaches the strength specified in the project. With the new technology for constructing pile foundations, in addition to the advantages described above, their design is greatly simplified. Factory production technology for precast concrete joint piles can be carried out using automated production lines, and special vehicles equipped with equipment for loading and unloading operations can be used to deliver them to construction sites. The use of precast concrete joint piles for the construction of a pile foundation will improve labor safety and ensure compliance with technical requirements for delivery, storage, and work.

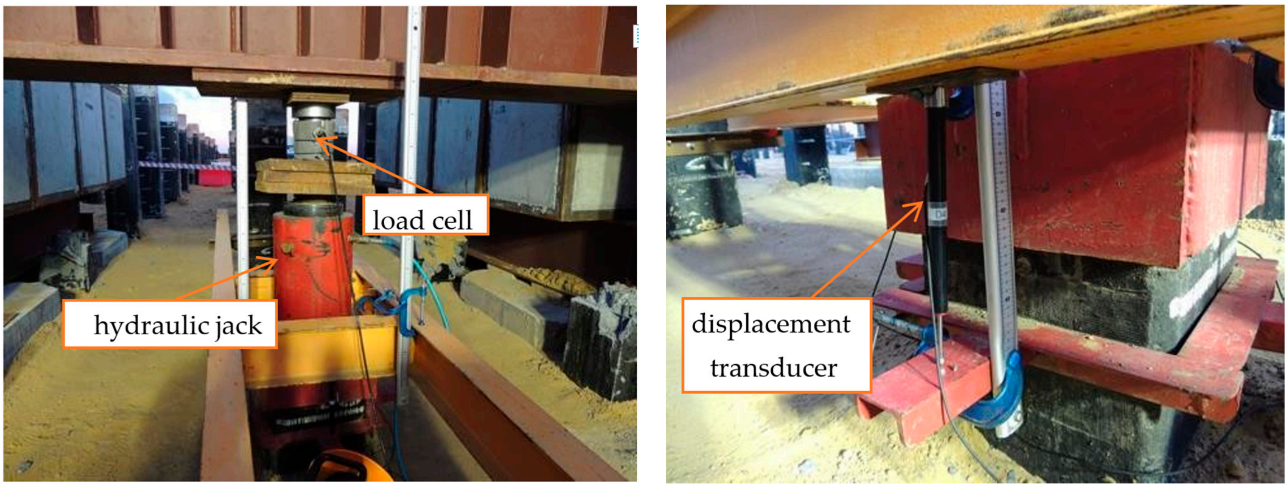
Static and dynamic tests were carried out on precast concrete joint piles with a total length of 27.5 m. They consist of two sections with a cross-section of 40 cm × 40 cm: a lower section with a length of 16.0 m and an upper section with a length of 9.5 to 11.5 m (Figure 6).

When constructing a pile foundation, each loaded pile can be subjected to control, which provides very valuable information that we believe needs to be used from calculation and design to the production of pile work. In addition, to obtain an effective type of pile foundation, as has been noted repeatedly, it is necessary to strive to maximize the use of the load-bearing capacity of piles on the ground, bringing it closer to the load-bearing capacity of piles on the material.

Static compression tests were performed on prefabricated reinforced concrete precast concrete joint piles No. TP-03, No. TP-02, No. TP-01.5, and No. K-3, which are moved under the control of a cargo unloading facility (COF) zone at depths of 23 and 26.75 m, and pre-drilled with an auger with a diameter of 330 mm to a depth of 11.40 m.

The platform is made of steel and consists of a metal beam and two platforms located at equidistant distances from the center of the main beams (Figure 7).

For the loading, a 250-ton (Type DG500G250) ENERPAC hydraulic jack was mobilized. The pressure in the jack was created by using the electro-hydraulic pump NER-1,6A40T1 with a manual distributor. The pressure, controlled with the pressure gauge MA100BU100, has a scale division value from 0 to 1000 bar. The jack was placed on a specially fabricated steel pile head cover measuring 25 mm. The space between the pile head and the main beam was bridged with a hydraulic jack, steel plates, and a load cell (Figure 8a). To measure the pile movement, the clamp was bolted to the test pile. And the space between the clamp surface and reference frame was bridged by four electronic displacement transducers (sensors). The sensors had a stroke of 100 mm and an accuracy of 0.01 mm. The equipment consisted of a data acquisition unit, a 25 m cable reel, four electronic displacement transducers (025D1, 025D2, 025D3, and 025D4), and one load cell. The system is supplied with software for the acquisition, display, and printing of results (Figure 8b).




(**a**) (**b**)

**Figure 8.** Measurement equipment for static compression load test: (**a**)—hydraulic jack, load cell; (**b**)—displacement sensors.

## 4. Results and Discussion

When constructing a pile foundation, each immersed pile can be subject to control, which provides very valuable information that, in our opinion, needs to be used, starting with calculation and design and ending with the production of pile work. In addition, to obtain an effective type of pile foundation, as has been noted repeatedly, it is necessary to strive to maximize the use of the load-bearing capacity of piles on the ground, bringing it closer to the load-bearing capacity of piles on the material.

Figures 9–16 show the results obtained by the PDA method when driving precast concrete joint piles.

According to the DLT method, a pile is driven into the ground until it reaches the value of the compliance parameter of the pile in the ground from one blow of the pile-driving equipment, corresponding to the value of the effective load perceived by the pile. In cases where it is inappropriate to assume the load-bearing capacity of a pile on the ground is equal to the load-bearing capacity of the material (from the design features of the pile foundation), the effective load carried by one pile is established by technical and economic calculations. It should not exceed the value of the calculated resistance of the pile material to axial compression [26–28].

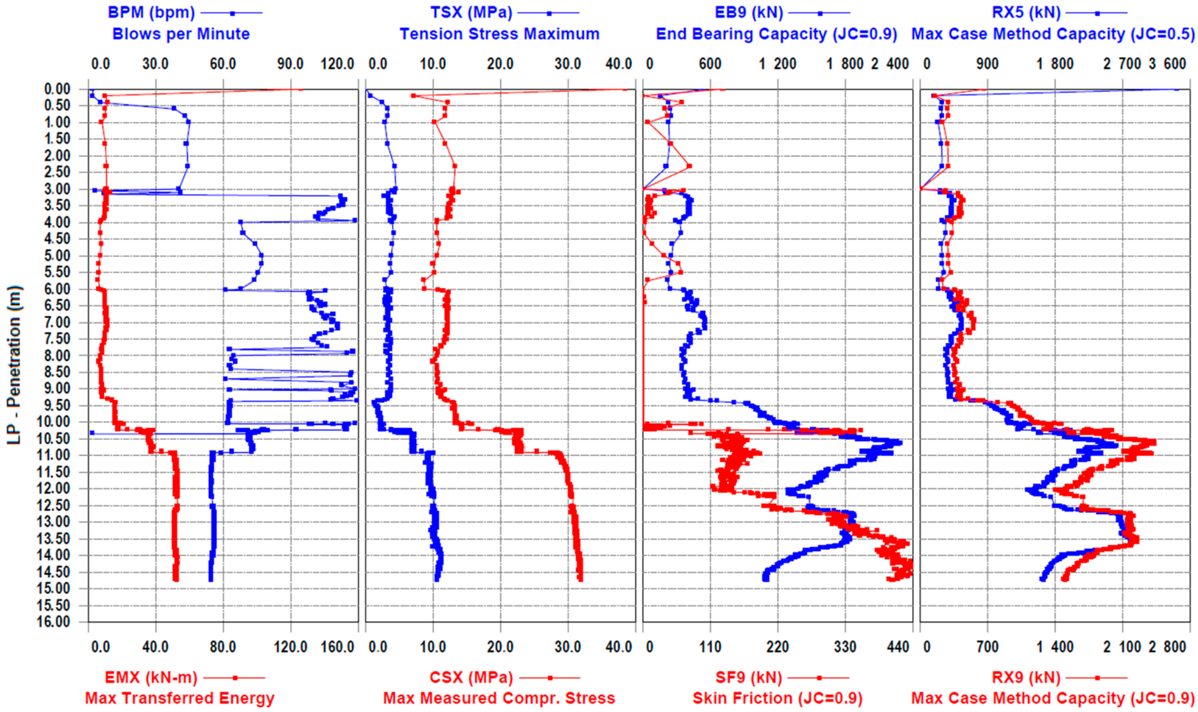



**Figure 9.** Graphic results of driving precast concrete joint piles using the PDA method, TP-01.2, from the beginning of driving to a depth of 14.8 m.

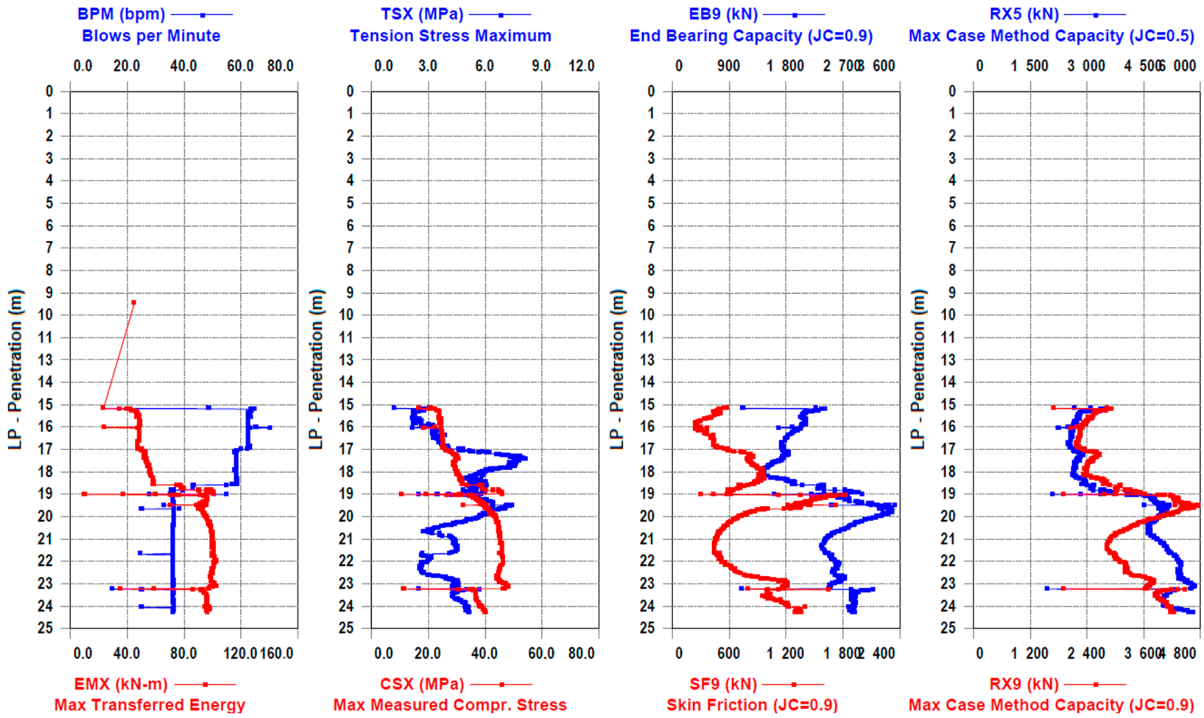



**Figure 10.** Graphic results of driving precast concrete joint piles using the PDA method, TR-01.2; depth from 14.8 to 24.3 m.

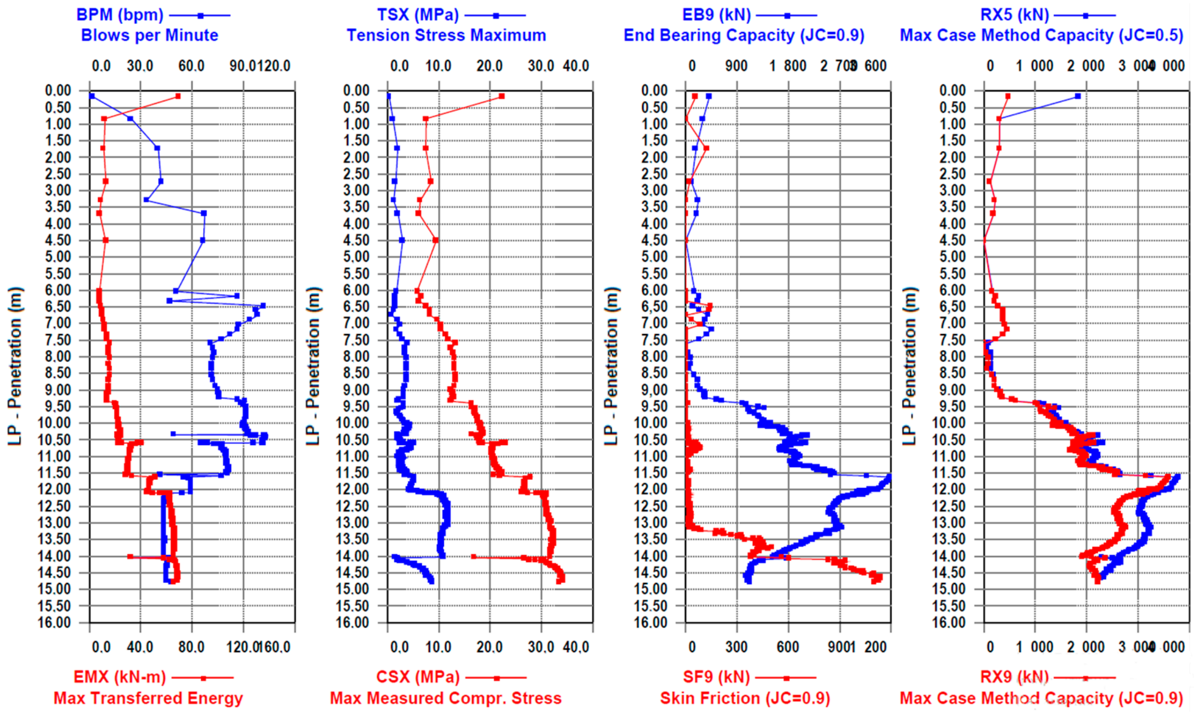



**Figure 11.** Graphic results of driving precast concrete joint piles using the PDA method, TP-01.3, from the beginning of driving to a depth of 14.8.

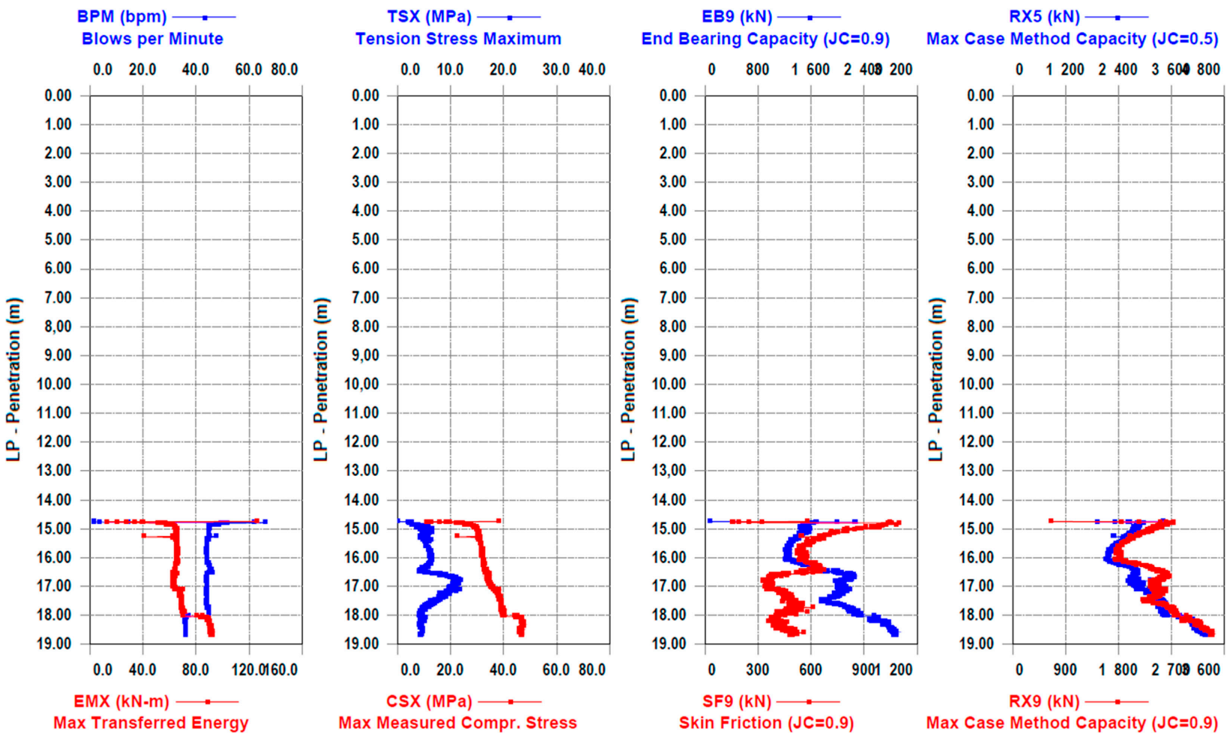



**Figure 12.** Graphic results of driving precast concrete joint piles using the PDA method, TR-01.3; depth from 14.8 m to 19.2 m.

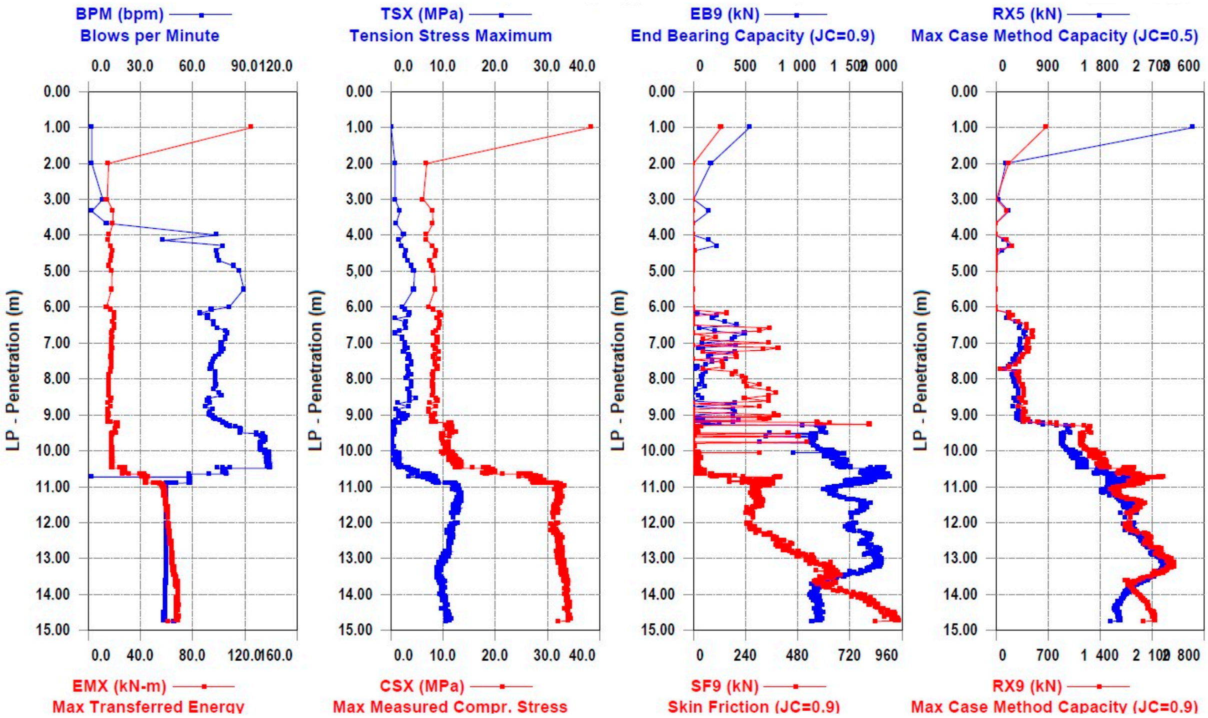



**Figure 13.** Graphic results of driving precast concrete joint piles using the PDA method, TR-01.5, from the beginning of driving to a depth of 14.75 m.

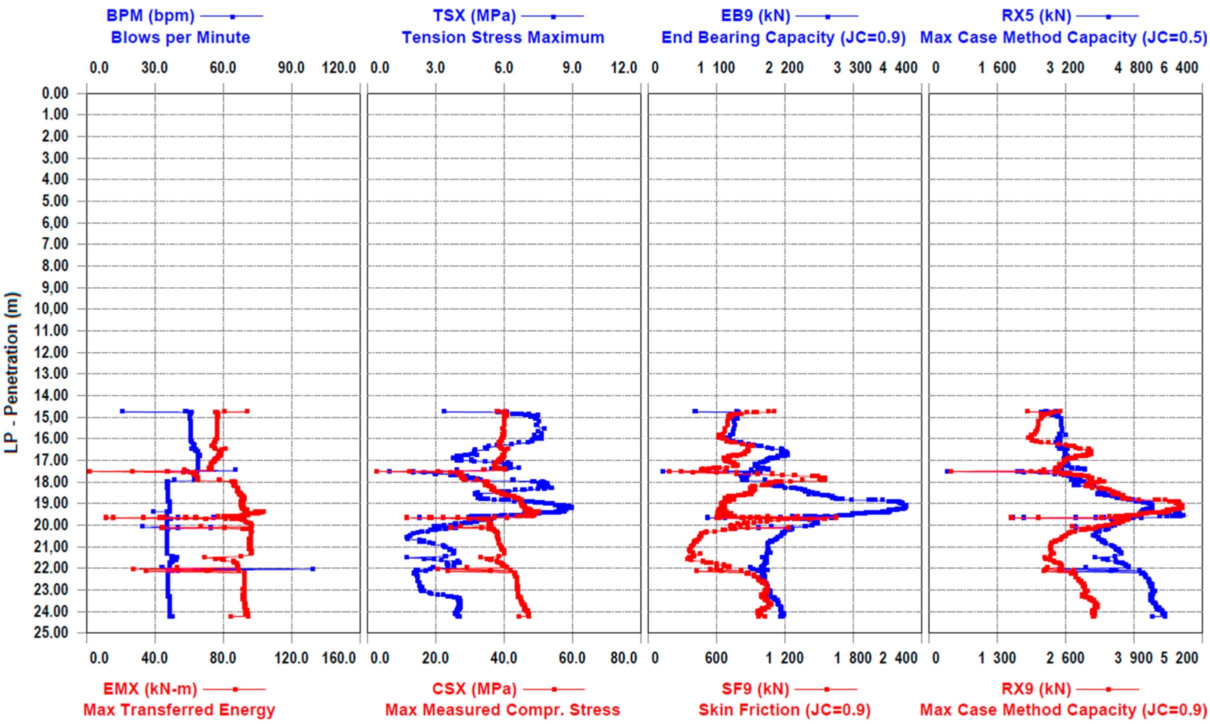



**Figure 14.** Graphic results of driving precast concrete joint piles using the PDA method, TR-01.5; depth from 14.75 m to 24.25 m.

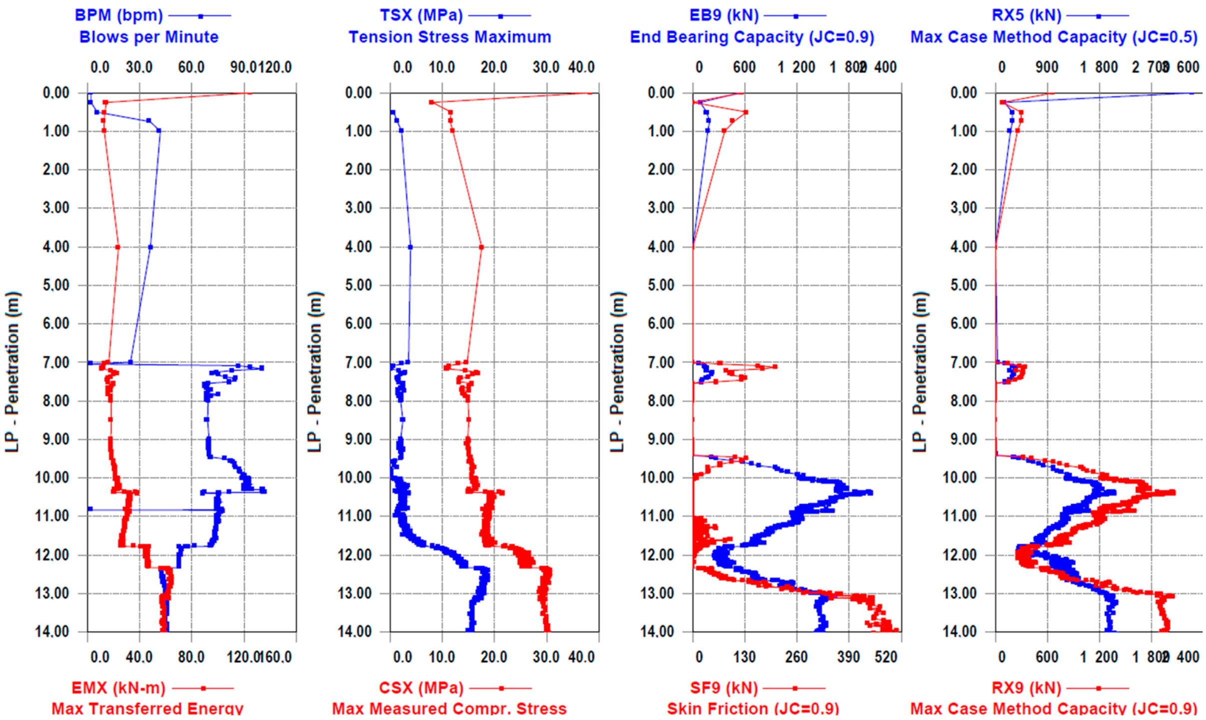



**Figure 15.** Graphic results of driving precast concrete joint piles using the PDA method, TP-02, from the beginning of driving to a depth of 14.75 m.

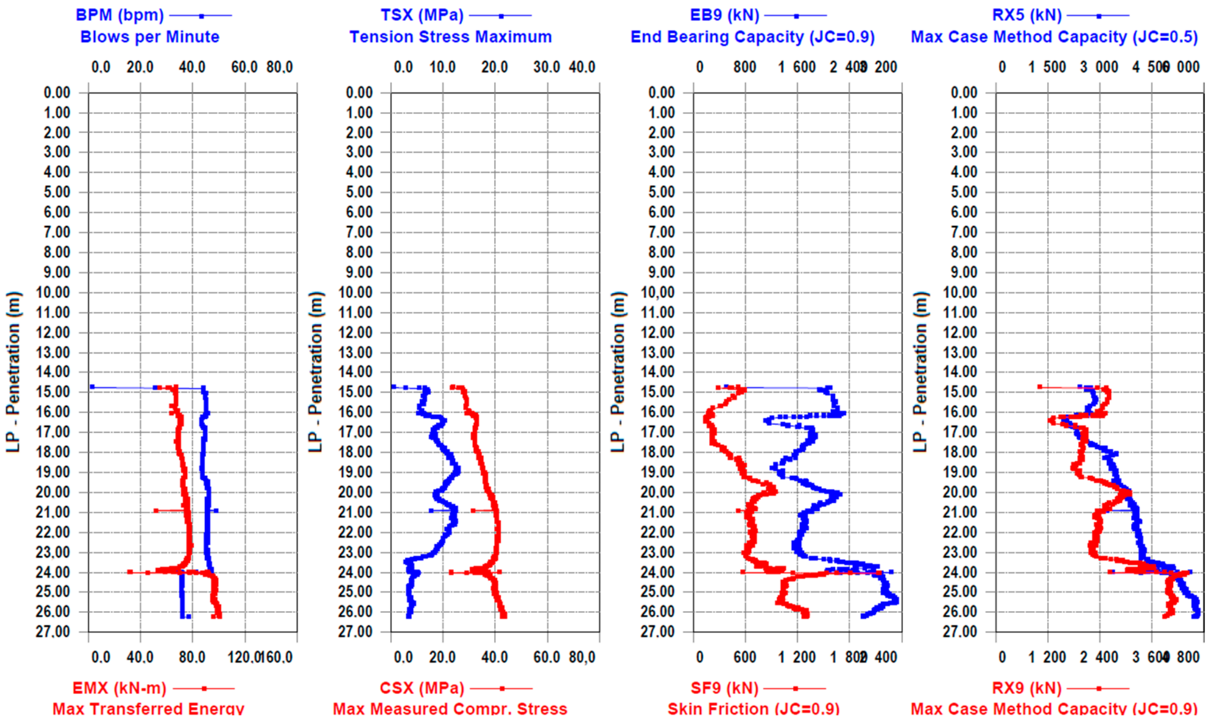



**Figure 16.** Graphic results of driving precast concrete joint piles using the PDA method, TR-02; depth from 14.75 m to 26.25 m.

Figures 17–21 show the results obtained by the DLT method after resting when finishing precast concrete joint reinforced concrete piles.

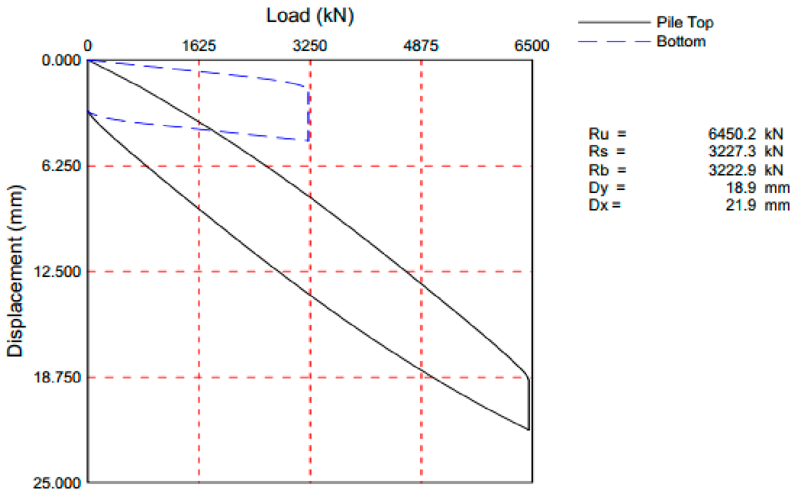



**Figure 17.** Test results of precast concrete joint piles using the DLT method, TR-01.2; depth 24.70 m.

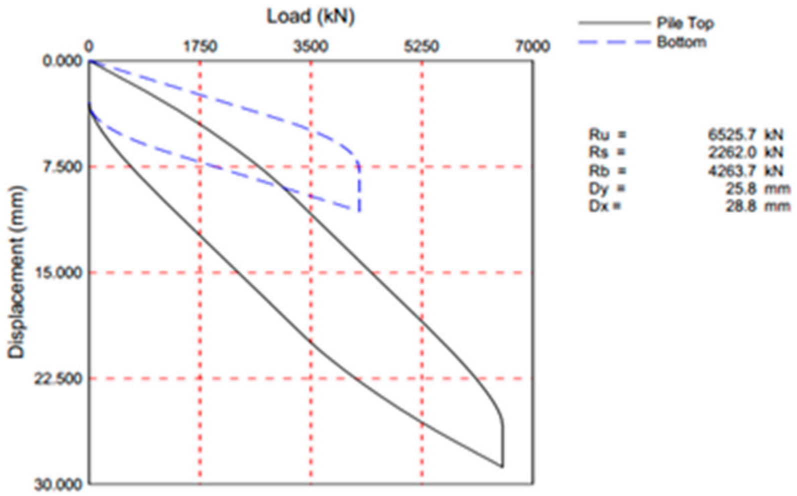



**Figure 18.** Test results of precast concrete joint piles using the DLT method, TR-01.3; depth 24.70 m.

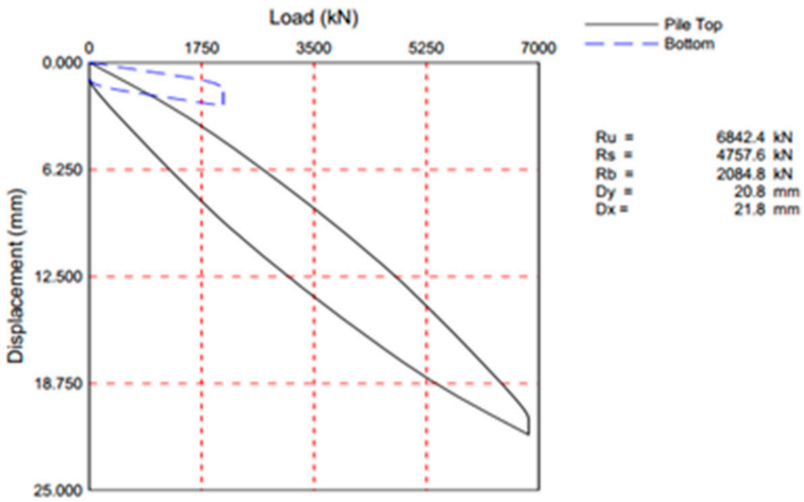



**Figure 19.** Test results of precast concrete joint piles using the DLT method, TR-01.5; depth 24.70 m.

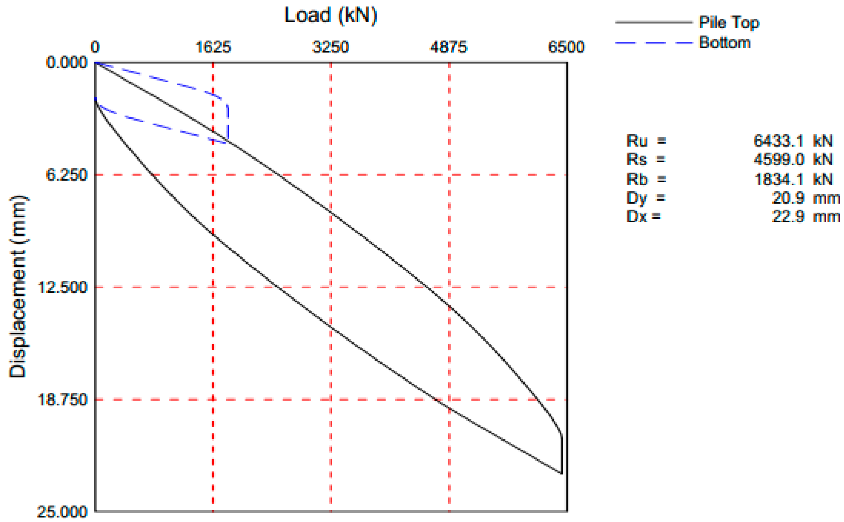



**Figure 20.** Test results of precast concrete joint piles using the DLT method, TR-02; depth 26.70 m.

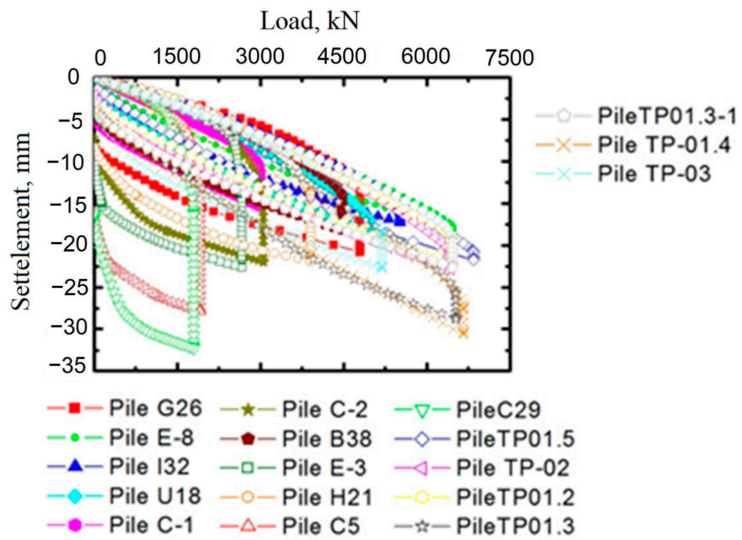



**Figure 21.** Results of tests of precast concrete joint piles using the DLT method.

Numerous theoretical and experimental studies indicate a large discrepancy between the results obtained by calculations performed using current building codes and regulations and the physical data established in production conditions. One of the reasons for this phenomenon is the fact that the existing calculation and design methodologies have practically no close connection with the production test data of each foundation structure being built. Even if there are data on full-scale tests of individual foundation structures, they are used for a generalized assessment of the entire technical solution as a whole only at the stage of calculation and design.

Mainly to ensure the safety of the head of a solid reinforced concrete precast concrete joint pile, it is important to note that destruction is mainly observed in its head part, despite the fact that its strength is 1.5–2.0 times higher than in the middle part. This phenomenon is explained by the fact that during the driving process, 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 head part of the pile is completely destroyed, while the strength of the pile shaft remains unchanged.

Figure 22 shows the results of static (SCLT method) and dynamic (DLT method) tests.

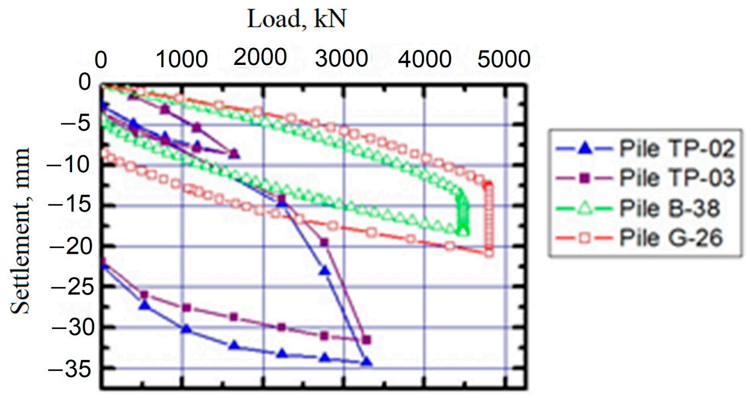



**Figure 22.** Test results of precast concrete joint piles using the DLT method and the SCLT method.

*Calculation of the Bearing Capacity of a Precast Concrete Joint Pile with a Section of 40 × 40 cm and a Length of 25 m*

Current regulatory documents for the design of pile foundations recommend that the total resistance of piles along the foundation soil be determined as the sum of their resistances along the tip and along the side surface. The load-bearing capacity of the pile Fd is determined by Formula 1.1 in the Standard MSP 5.01-101-2003 "Design and installation of pile foundations" [22]:

$$F_d = \gamma_c \left( \gamma_{cR} RA + u \sum \gamma_{cf} f_i h_i \right) \quad (1)$$

where $\gamma_c$ = 1.0—coefficient of working conditions of the pile in the ground;

R = 9000 kPa—design resistance of the soil under the bottom of the pile;

A = 0.4 × 0.4 = 0.16 $m^2$—the area of the pile resting on the ground;

u = 0.4 × 4 = 1.6 m—the outer perimeter of the cross-section of the pile shaft;

$f_i$—design resistance of the *i*-th pile soil on the side surface of the pile, kPa, taken from Table 7.2 [22];

$h_i$—thickness of the *i*-th pile of soil in contact with the lateral surface of the pile, m;

$\gamma_{cR}$ = 1.0—coefficient of soil working conditions under the bottom of the pile, according to Table 7.3;

$\gamma_{cf}$ = 1.0—coefficient of soil working conditions on the lateral surface of the pile.

According to Table 7.2 [22] we take the following:

$f_1$ = 23 kPa; $f_2$ = 35 kPa; $f_3$ = 40 kPa; $f_4$ = 43 kPa; $f_5$ = 45 kPa; $f_6$ = 47 kPa; $f_7$ = 50 kPa; $f_8$ = 52 kPa; $f_9$ = 56 kPa; $f_{10}$ = 61 kPa.

$F_d$ = 1[1 × 9000 × 0.16 + 1.6(23 × 2 + 35 × 2 + 40 × 2 + 43 × 2 + 45 × 2 + 47 × 2 + 50 × 2 + 52 × 2 + 56 × 2 + 61 × 2)] = 3360 kN.

The bearing capacity of piles with a 40 × 40 cm cross-section and a 25 m length in ground conditions of construction (cargo transportation route for the objects of the north-eastern part of the Caspian Sea and the north Caspian Sea channel with berthing facilities) is calculated as follows:

$$F_d = 3360 \text{ kN},$$

With allowable pile load:

$$N = F_d/\gamma_k \quad (2)$$

In Kazakhstan, the safety factor (by dynamic method) is equal to 1.2 (FS (safety factor)). Therefore, the design value of the allowable pile capacity *N* was estimated as N = 3360/1.4 = 2400 kN.

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

Table 3 summarizes the analysis of the comprehensive tests and calculations.

**Table 3.** Analysis of complex tests and calculations.

| Testing Method | FS | Settlement, mm | Depth of Immersion of Precast Piles, mm | Bearing Capacity Up to FS | Bearing Capacity of the Pile after FS | % |
|---|---|---|---|---|---|---|
| SCLT (pile No. TP-01.2) ASTM | 1.2 | 22.91 | 26.25 | 2480 | 2067 | 100 |
| SCLT (pile No. TP-01.3) | 1.2 | 22 | 22.50 | 2450 | 2042 | 99 |
| SCLT (pile No. TP-01.5) | 1.2 | 21.47 | 24.25 | 2800 | 2333 | 113 |
| PDA (pile No. TP-01.2) by ASTM | - | - | 26.25 | - | 2859 | 138 |
| PDA (pile No. TP-01.3) | - | - | 22.50 | - | 2235 | 108 |
| PDA (pile No. TP-01.5) | - | - | 24.25 | - | 2245 | 109 |
| DLT (pile No. G-26) by ASTM | 2 | 20.8 | - | 4799 | 2400 | 117 |
| DLT (pile No. U-18) by ASTM | 2 | 18.61 | - | 4969 | 2485 | 121 |
| DLT (pile No. B-38) by ASTM | 2 | 18.18 | - | 4471 | 2236 | 109 |
| DLT (pile No. H-21) by ASTM | 2 | 21.30 | - | 3904 | 1952 | 95 |
| DLT (in accordance with RK regulations) | 1.4 | - | 25 | 3360 | 2400 | 117 |

$SCLT_{Medium(ASTM)}$ = (2067 + 2042 + 2333)/3 = 2148 кН = 104%; $PDA_{Medium(ASTM)}$ = (2859 + 2235 + 2245)/3 = 2447 кН = 119%; $DLT_{Medium(ASTM)}$ = (2400 + 2485 + 2236 + 1952)/4 = 2366 кН = 111%; $DLT_{Medium(ASTM)} - SCLT_{Medium(ASTM)}$ =2366кН − 2148кН = 218кН = 7%; $PDA_{Medium(ASTM)} - SCLT_{Medium(ASTM)}$ = 2447 кН − 2148 кН = 299 кН = 15%.

## 5. Conclusions

Field methods of testing soils with piles made it possible to obtain data on the relationship between the stress–strain state and the bearing capacity of the pile, which is especially important in the initial stages of construction. Based on the results obtained, the main changes to the project are carried out. Static and dynamic tests are considered the basic tests; however, according to the experimental results, these methods have a number of disadvantages, which relate both to the labor intensity of such tests (static tests) and to the quality of the results obtained (dynamic tests).

Based on the research, it became clear that when driving piles, the soil became overcompacted, and it was necessary to carry out leader drilling up to 12 m. The calculated bearing capacity of precast concrete joint driven piles with a 40 × 40 cm cross-section and a 25 m length was 2400 kN, which confirms the sufficient bearing capacity of the foundation soils for piles of this depth.

The SCLT method of testing precast concrete joint driven piles was performed in accordance with the ASTM standard. According to the results of field tests of precast driven piles by the SCLT method, the bearing capacity of piles was 2067 kN, 2042 kN, and 2333 kN for pile lengths from 23 m to 26.75 m, respectively, and these values do not exceed the values of maximum bearing capacity by Davisson's ultimate limit method.

For the test precast concrete joint piles, the design allowable load on the precast concrete joint driven pile, taking into account the safety factor according to GOST (for static loading on the pile), is 2067 kN, 2042 kN, and 2333 kN.

According to the obtained results, the similarity of the data was observed by SCLT and DLT methods (after CAPWAP interpretation). An insignificant deviation of DLT from SCLT equal to 7 percent was observed, which does not deteriorate the quality indicators. However, the PDA method differs from the static method by 15 percent.

Based on the above, we can conclude that DLT (by ASTM) results showed higher comparability with static tests by ASTM. The dynamic test method for pile foundations shows quicker results than the static test method; a short-term impact force is applied to the pile foundation. Dynamic DLT (by ASTM) pile testing is considerably more mobile than static pile testing. It is possible to test six piles per day and obtain preliminary results directly at the construction site. The main advantage of this DLT (by ASTM) method is that it is applicable to all pile designs. The piles are not damaged during testing and can be used in the foundation of the structure. DLT (by ASTM) tests have shown that this methodology is an alternative to standard static load testing of pile soils and is undoubtedly relevant for modern pile foundation construction in Kazakhstan.

It should be noted that modern geotechnics in Kazakhstan is also undergoing changes associated with the development of modern high-tech and energy-saving geotechnologies by leading foreign manufacturers, which include modern piling technologies and equipment, equipment for engineering and geological surveys, and field and laboratory testing of soils. Modern geotechnologies are economically and environmentally efficient and allow for a significant increase in productivity and quality of construction.

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