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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ВЗАЄМОДІЇ ПАЛЬ-ОБОЛОНОК З ВІДКРИТИМ НИЖНІМ КІНЦЕМ І ГРУНТОМ ОСНОВИ

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Анотація. *Результати експериментальних досліджень які наведені в статті передбачали вивчення взаємодії палі-оболонки з відкритим нижнім кінцем і ґрунтової основи при зануренні осьовим вертикальним навантаженням і висмикування з ґрунту, встановлення впливу різних форм нижнього кінця палі на напружено-деформований стан ґрунтової основи. Були отримані залежності опору ґрунту зануренню і висмикуванню палі-оболонки від величини осьового навантаження, визначення закономірностей розподілу бокового тиску ґрунту по зовнішній і внутрішній поверхнях палі-оболонки і опору ґрунту по її підошві, а так само встановлення висоти підйому ґрунту в порожнині оболонки при зануренні..*

Проведені попередні методологічні випробування запропонованої моделі палі-оболонки показали її високу точність, багатофункціональність і продуктивність. Запропонована модель палі-оболонки дозволяє досліджувати взаємодію ґрунту на зовнішню поверхню палі-оболонки, опір ґрунту з оболонкою. Результати випробувань на такій моделі дозволяють більш повно оцінити спільну роботу палі-оболонки і ґрунту, що контактує з нею, і ефективно використовувати сучасні методи розрахунку споруд.

У статті описано розроблені моделі для врахування не тільки структури, характеристики геоматеріала, а також його розташування в середині палі-оболонки. При цьому в моделі враховуються не тільки параметри ґрунту засипки, а також характеристики геоматеріала.

Ключові слова: *паля-оболонка, геоматеріал, ґрунтова основа, тензорезистори.*

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EXPERIMENTAL STUDIES OF THE INTERACTION OF SHELL PILES WITH THE OPEN BOTTOM END AND THE GROUND BASE

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Abstract. *The results of the experimental research presented in the article involve studying the interaction of the shell piles with an open bottom end and the ground base during immersion by an axial vertical load and pulling out of the soil, establishing the effect of various forms of the bottom end of the pile on the stress-deformed state of the ground base.*

The dependences of the soil resistance to immersion and pullout of the shell pile on the value of its axial load, the determination of the patterns of distribution of the lateral soil pressure on the outer and inner surfaces of the shell pile and the resistance of the soil on its sole, as well as the determination of the height of the soil rise in the shell cavity during immersion were obtained.

Preliminary methodological tests of the proposed shell pile model showed its high accuracy, multifunctionality and efficiency. The proposed shell pile model allows us to study the soil's interaction on the shell pile's outer surface and the soil's resistance to the shell. The results of tests on such a model make it possible to fully evaluate the interaction of the shell pile contact surface and use modern methods of calculating structures effectively.

The article describes the developed models to consider not only the structure and characteristics of the geomaterial but also its location inside the pile shell. At the same time, the model considers not only the parameters of the backfill soil but also the characteristics of the geomaterial.

Keywords: *shell pile, geomaterial, ground base, tensor resistors.*

Statement of the problem. Currently, a significant part of port structures is in a limited operational state, and some structures have completely exhausted their operational resource and reached their limit states. Therefore, the issue of continuing the operation of such structures and their modernization in accordance with modern technical and economic requirements is acute. One of the best solutions is the construction of new structures, but this requires large financial expenditures, which are impossible to implement due to the particularities of the real economic situation. Therefore, new technologies for the repair and reconstruction of port structures are currently coming to the forefront. Special attention is paid to technologies that allow the reconstruction of structures without taking them out of service or partially taking them out of service.

The first thing that a reconstruction project should begin with is the collection and analysis of the most objective information about the object: conditions of its operation, influencing factors, current operational and technical conditions, etc. Analysis of the causes that cause various destructive processes, clear recommendations for preventing the impact of such causes, and specific recommendations for the design organization for new technologies and materials applicable in the reconstruction.

Among the most important components of a complex solution to the efficiency problem of port structures is the availability and practical use of control methods in operating conditions at the modern scientific and technical level. The effectiveness of modern construction is determined by the degree of reliability and durability of the structure during its operation. In hydraulic construction, the most important and determining factor in ensuring reliability and durability during operation is its foundation. Most often, artificial foundations are used by application pile foundations suitable for weak soils that lack bearing capacity.

Many designs of shell foundations have been developed for various soil conditions [1]. However, the immersion process of shell piles has not been studied well enough from the point of view of interaction with the soil. The physical conditions of the immersion process are insufficiently studied. At the same time, the use of shell piles is widespread in the practice of hydraulic construction due to the simplicity of the design, progressive production methods, and high construction culture.

Analysis of research and publications. Experiments on dynamic soil resistance when driving piles were conducted by B.V. Bakholdin [2], L.Ya. Ginzburg [3] and others, most researchers of dynamic soil resistance determine it using the viscosity coefficient. In the work of L.R. Stavnitzer [4], the existence of a critical speed of the soil deformation was established, when it is exceeded, the reaction value practically does not depend on the speed of its deformation. B.V. Bakholdin [2], L.Ya. Ginzburg [3] showed that the valuef the critical speed in relation to the piles depends on the static resistance of the soil.

Models of the «pile-soil» system have been studied by a number of scientists for cases of sinusoidal loading. A comparison of the results of theoretical calculations of pile vibration immersion with experimental data showed significant discrepancies. The analysis of some researchers showed showed that for a satisfactory convergence of the results, it is necessary to take into account the influence of soil inertia. The issue of the influence of soil inertia during pile driving has not been investigated to date.

Current regulatory documents recommend calculations of structures interacting with the soil in the elastic stage of their work or by certain states [5; 6].

This approach does not allow tracking the stress-deformation state of the «structure–soil» system, starting from the moment of its loading and loss of bearing capacity because the elastic calculation does not take into account the plastic deformations of the material, and the calculation by the limit states allows determining only the destructive load.

The use of design models of hydraulic structures developed in the middle of the last century does not reflect their specific work during construction and operation. They do not take into account the joint interaction of the structure, soil, and marine environment, as a single system operating under conditions of complex load.

These calculation methods do not allow the realization of two groups of limit states on bearing capacity and deformations laid down in normative documents from common positions considering elastic and plastic properties of materials of structure and the ground base.

Many authors who use various soil models in their studies (linearly deformable medium, deformation theory of plasticity, etc.) first consider only the stress-strain state of the interacting soil under various loads and movements, and then, using the data obtained, calculate the structure design. These approaches do not allow determining the stress-strain state of the structure and the soil in contact in their actual joint work. It should be noted that the modeling of the immersion of shell foundations into the ground and the study of the process of their immersion into the ground were carried out by Khmara L.A., Panteleenko V.I. [7-9].

The purpose of the study is to increase the reliability of the stability of pile-based structures in various operating conditions by introducing the proposed models.

Many years of research experience show that structures in the process of construction and operation are under the influence of various factors: construction technology, operating load mode, local damage, rheological phenomena in the material of the structure and the soil base, environmental and time effects, which affect on the value of bearing capacity of the structure.

The rational operation of the structure requires the assignment of useful loads in accordance with the value of the bearing capacity of the structure, which may change during the entire period of its operation.

Next, within the framework of this article, we will consider experimental studies involve studying the interaction of the shell piles with an open bottom end and the ground base during immersion by an axial vertical load and pulling out of the soil, establishing the effect of various forms of the bottom end of the pile on the stress-deformed state of the ground base.

The results of the research. The results of these works are as follows: obtaining dependences of the ground resistance to immersion and pullout of the shell pile on the value of its axial load, the determination of the patterns of distribution of the lateral soil pressure on the outer and inner surfaces of the shell pile and the resistance of the soil on its sole, as well as the determination of the height of the soil rise in the shell cavity during immersion.

Due to the lack of normative documents on calculating tubular piles with an open bottom end, the only possibility to establish the bearing capacity is the static tests in field conditions, which require expensive technological machinery and equipment and a long timeline to conduct them. The main requirements for performing static and dynamic tests are outlined in DSTU B V.2.1-1-95 [6] and DSTU-N B V.2.1-28:2013 [10].

Considering the requirements of these documents, there may be a specific pile resistance, according to which a static assessment of its bearing capacity on the soil is carried out. Given the relevance of the task, a tested installation will be used to study the interaction of the shell pile with the soil.

The basis of the installation is the creation of a device for studying the interaction of the shell piles with the soil, which provides the possibility of dividing the soil resistance forces acting on the pile when it is immersed or pulled out of the soil by axial loads, into components on the inner and outer side surfaces and on the ring end the bottom of the pile, as well as establishing the depth distribution of normal pressure and frictional forces on the outer side surface of the shell pile.

Experimental installation, measuring equipment and testing methods.

The experimental installation (Fig. 1) includes:

1 - soil tray;

2 - a model of a shell pile of a unique design;

3 - a model of a tubular pile for studying the kinematics of a sandy foundation;

4 - a device for creating an axial load when immersing the model in the ground and pulling it out;

5 - measuring and recording equipment;

6 - method of conducting tests.

The soil tray has dimensions: height – 115 cm, width – 75 cm, length – 80 cm. The side walls of the tray are made of sheets of polished glass 15 mm thick, resting on its metal frame.

The back wall is collapsible and consists of separate boards with a thickness of 40 mm, which are installed at the ends in the provided guides. This design allows you to quickly empty the tray of sand and determine the angle of the natural slope, known as the angle of internal friction for dry sand.

The tray's front wall is made in the form of a rigid metal plate fixed from above on two sides by hinged supports. Along the axis of the plate, at a distance of 12 cm from the bottom of the tray, a third movable hinged support is installed, rigidly fixed with the other end to the tray's frame.

In addition, the plate performs the role of a rigid supporting wall to obtain the soil pressure on the wall. Behind its axis, pressure sensors are mounted in the provided slots with a step of 15 cm in height.

The design of the sensors was developed at the Department of Sea, river ports, waterways, and their technical operation of Odessa National Maritime University.

To study the kinematics of the movement of sand particles during immersion or extraction from the soil of the model, a grid with 5x5 cm cells is painted with thin lines on the side wall of the tray.

Fig. 1 and 2 show the general view and scheme of the experimental installation, respectively.

Fig. 1. General view of the experimental installation for testing shell pile and hard stamp

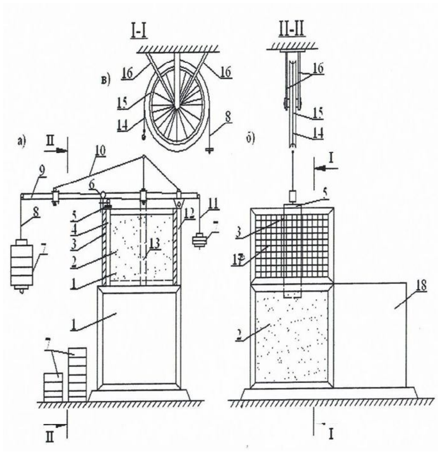

Fig. 2. Scheme of the experimental installation:
a – view along I-I, b – view along II-II,c – pulling out device.
Conventional designations: 1 – the upper and lower part of the tray;
2 – sand; 3 – glass side walls; 4 – half-shell model; 5 – loading semi-stamp;
6 – movement indicator; 7 – weights; 8 – cargo suspension; 9 – loading lever;
10 – stretch marks; 11 – suspension on the console; 12 – hinged lever support;
13 – a spot for pushing in piles; 14 – cargo cable;15 – wheel;
17 – grid on the tray glass; 18 – tray for sand supply

One of the main elements of the installation is a shell pile model of a unique design (Fig. 2), which includes a body (1) consisting of a set of cylindrical links 15 cm high with ducts on the ends measuring 4x4, connected from the inside by flat brackets with one elongated and the other round holes at the ends (2). Brackets are fixed with the help of bolts (3), with one end hinged fixed to the upper cylindrical link and the other – to the lower one with the possibility of longitudinal shift. Tensor resistors are pasted on the outer surface of each bracket to measure the tensile forces characterising the soil friction forces on the outer side surface of each link. In each cylindrical link of the shell pile, in the middle of the height, a nest is provided to install soil pressure sensors on the side surface of the shell. A hollow cylindrical core (4) is coaxially placed inside the shell body 1, on the outer surface of which tensor resistors (5) are glued for measuring soil pressure on the inner surface of the cylindrical core. From the bottom of the pile-shell model, removable tips of the ring section (6) and soil protection casing in the shape of a glass (7) are provided, rigidly connected with bolts to the shell stamp and freely move vertically along the pile body. A loading hard disk (9) is provided on the top of the model, connected to the body with bolts (11) and the core connected with a bolt (10).

The concentricity of the body (1) and core (4) is ensured by the grooves on the stamp (6) and loading disk (9), the diameters of which are equal to the internal diameters of the body and the core.

The experimental model of the shell pile has various replaceable constructive forms of the tips of the tip, which allows for studying their interaction with the soil base. The primary structural forms of the removable tips of the tip of the shell pile model are shown in Fig. 3 and Fig. 4.

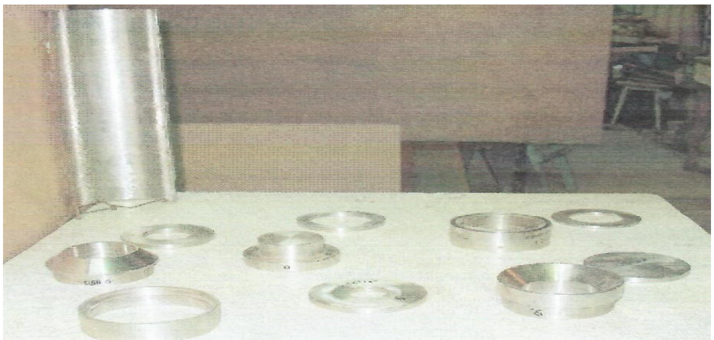

Fig. 3. Constructive forms of removable flanges of the tip of the shell pile model (photo)

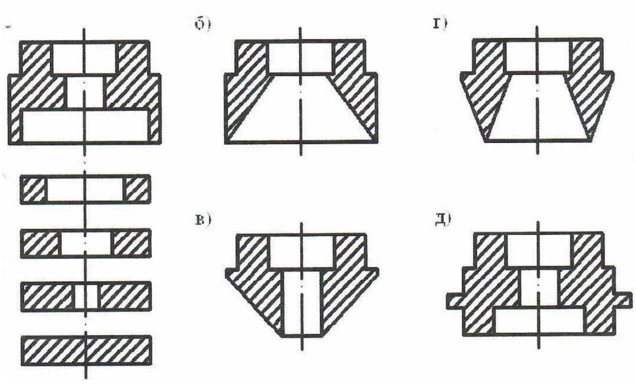

Fig. 4. Constructive forms of removable flanges of the tip of the shell pile model (cross sections)

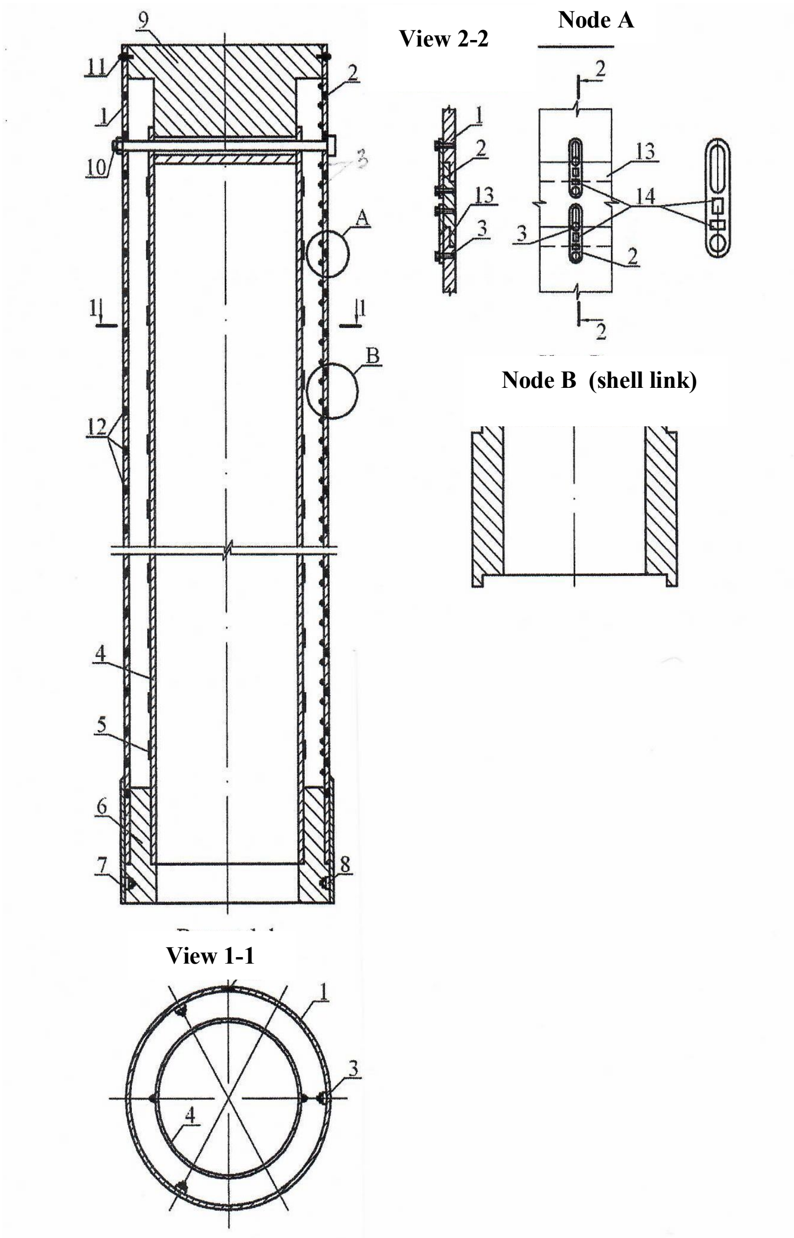

Fig. 5. Longitudinal section and plan of the shell pile model.
Designations: 1 – body; 2 – flat staples; 3 – fastening bolts; 4 – cylindrical core; 5 – tensor resistors; 6 – stamp; 7 – soil protection casing; 8 – fastening bolts; 9 – loading disk; 10 – connecting bolt; 11 – bolts attaching the body to the loading disk; 12 – soil pressure sensor; 13 – grooves-slots; 14 – working and compensation resistors

The main parameters of the shell pile model:

1. The model is made of stainless pipe;

2. Body, with length L = 105 cm, outer diameter D_H = 108 mm, wall thickness δ_w = 5 mm, consists of 7 links 15 cm high with grooves on the ends to ensure alignment and longitudinal movement by 4 mm, weight of each link 1, 9 kg. The total weight of the body is 13,7 kg;

3. Stainless steel tube core L = 102 cm, outer diameter D_H = 75 mm, wall thickness δ_w = 5 mm, weight – 6,9 kg;

4. Removable flanges made of stainless steel 70 mm high with grooves on top 5 mm high for the coaxial connection of the body and the core (Fig. 5);

5. Load capacity of a stainless-steel plate with an outer diameter of D_H = 98 mm, a height of H = 40 mm, with grooves of a height of 25 mm to ensure the alignment of the body and the core and the possibility of longitudinal movement. Plate load weight – 1,8 kg.

The experimental studies used fine-grained quartz sand with an angle of internal friction $\varphi = 33^o$, specific mass $\gamma = 26{,}5$ kN / m^3, and bulk mass $\gamma_{shell} = 15{,}5$ kN / m^3 as a soil base.

P.I. Yakovlev, M.M. Vargin, A.I. Pasichnyk and others conducted methodical experiments on friction's effect on the tray's side walls. They showed that the inhibitory effect of the walls is felt only in their immediate vicinity. This gives grounds for asserting that the side walls' influence on the model will not be affected in the middle part of the tray.

Tests of the shell pile model were carried out in the following sequence.

The tray was filled with sand up to the level of the sole of the model. The assembled shell pile model is installed vertically on a sand cushion under the loading device (Fig. 6). Its position is temporarily fixed. Sand is poured into the tray to a level 5 cm below the upper end of the model, and the cavity of the model's core is filled with sand to this level. The temporary fastening is removed, and the loading device, measuring and recording equipment are installed. Sensors are connected to the recording equipment, they are checked and balanced.

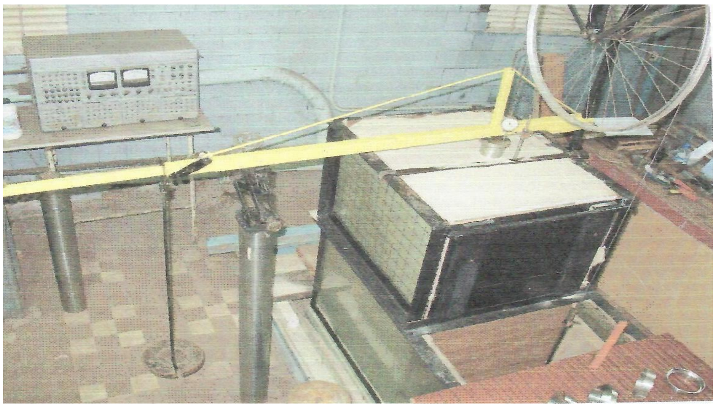

Fig. 6. Model of the shell pile under the loading device

Before starting the experiments, the connecting bolt (10) is removed, the core is separated from the body, and the loading disc is connected by bolts (11) to the body. It can move together with it vertically under the action of an axial load. After checking the functionality of the devices and equipment, they start testing the model.

Axial load tests of the model were carried out in four stages.

The first stage: The loading of the disk (9) is carried out by pressing and increasing degrees of force with the help of the lever of the device. At the same time, only the body is immersed in the soil, the bottom end of which freely enters the middle of the casing (7), and the core and stamp remain stationary. After each stage of loading the loading disk and stabilising the movements of the body, the average pressure on the side surface of the shell is recorded using sensors (12) and the total friction force on the outer surface of the body (1). This process is carried out until the ring protrusion of the loading disk (9) touches the upper end of the cylindrical core (4), the moment touching is fixed by turning on the indicator light.

Thus, in the first stage, the soil interacts only with the outer surface of the casing of the shell pile model.

Then the bolts (11) are removed, and the body is disconnected from the loading disk (9); the loading disk (9), the cylindrical core (4) and the stamp (6) start interacting, while the model body remains motionless. The second stage of model testing is underway.

The second stage shows the interaction of the soil with the inner surface of the cylindrical core (4) and the sole of the stamp (6), which is studied when the disc (9) is successively loaded. The load is brought to the calculated ultimate bearing capacity of the base. During this testing stage, the friction forces on the inner surface of the cylindrical core (4) and the soil pressure on the sole of the ring-type stamp (6) are determined.

The third stage of model testing is carried out to separate the soil resistance acting on the cylindrical core's inner surface and the stamp's sole into components.

The third stage witnesses the removal of the loading disc. In the holes provided in the upper part of the cylindrical core for the connecting bolt (10), a lifting bracket made of a wire with a diameter of 4 mm is fixed and connected to the cable of the pulling mechanism. In these tests, the body of the model and the die remain stationary.

The stepwise axial pull-out load is applied after preparing and equipping the model. During the tests, the total force of friction on the inner surface of the cylindrical core and its vertical movements are measured after each degree of loading. The vertical movements of the core were up to 5 cm.

In the fourth stage, the values and distribution of the normal pressure of the soil and the forces of its friction along the height of the outer surface of the model body when it is removed from the soil by an axial step load are determined.

The preparation of the model for the test of this stage consists of disconnecting the body from the core. During the experiment, only the body interacts with the sand in contact.

The core and stamp are stationary. Initially, only the first link of the body (1) interacts with the sand, which moves up under the action of the growing pulling force. At the moment of reaching the maximum resistance of the sand on the side surface of the link, it is shifted by the size of the elongated hole in the flat clamps of the first link (about 4 mm).

The average pressure of the soil is recorded using sensor (5), and the friction force on the outer surface of the first link is recorded with sensors (12) and (14). The second link comes into operation when the pulling load is further increased. It moves together with the first until the onset of the sand's limit resistance on the second link's surface and the displacement by the number of elongated holes in the flat brackets of the second link. Normal soil pressure and friction forces on the outer surfaces of the first and second links are measured. Then, when the pull-out load increases, the third link enters into interaction with the sand and moves up together with the first and second links until the limit resistance of the sand on the side surface and the displacement by the size of the elongated holes in the flat brackets of the third link, etc. until the model body is completely removed from the ground.

The following equipment was used in the experimental studies:

- clock-type indicators with a division number of 0.01 mm for measuring the movement of model nodes;
- contact sensors of soil pressure on the side surface of the casing of the shell pile model;
- strain gauges for measuring the deflection of the wall of the core of the model when determining the normal pressure of the soil and tensile forces in the flat ears to assess the friction of the soil against the side surface of the links of the model body.

The electric tensor resistor circuit was included in the half-bridge with automatic compensation of temperature deformations.

The readings of soil pressure sensors and tensile forces in the flat ears and structural wall devices were recorded using the SIIT-3 measuring system.

In the experiments, a lever device was used to create a compressive axial load on the pile model, specially made of profiled steel with a square section of 40x40 mm, a wall thickness of 3 mm and a total length of 1625 mm. To create the necessary rigidity, a truss made of bar steel is welded to the lever. Suspensions for load weights were hinged at the ends of the lever. The suspension on the console served to balance the lever. At a distance of 325 mm from the cantilever end to the lever, a hinge is welded to which a support welded to the body of the tray was attached. The lever arms of the device were as follows: the distance from the hinge to the centre of the pile was 355 mm, and from the hinge to the load suspension – was 1410 mm. Thus, the attitude of the arms was – 4.

The pull-out mechanism was a fixed wheel, hinged to the laboratory's ceiling in a particular place with the help of brackets. For this, a bicycle wheel with a diameter of 60 cm without a tyre was used. A cargo steel cable with a diameter of 3 mm was wound through the wheel along the groove of the rim; one end was attached to the head of the model to pull out the piles and the other to the cargo suspension. Thus, the load applied to the suspension corresponded to the tensile load. This made it easier to control the pulling force.

Preliminary methodological tests of the proposed shell pile model showed its high accuracy, multifunctionality and productivity. The proposed model of the pile-shell allows us to study the interaction of the soil on the outer surface of the pile-shell, the resistance of the soil with the shell separately to determine the normal pressure of the soil on the outer surface of the pile-shell, the resistance of the soil on the outer and inner side surfaces of the shell and its lower end, as well as to establish distribution along the height of the shell and its lower end, as well as establishing the distribution along the height of the shell of normal soil pressure and its resistance on the outer surface of the pile-sheath. The results of tests on such a model make it possible to more fully evaluate the joint work of the pile shell and the soil in contact with it and to effectively use modern methods of calculating structures.

Thus, the created experimental installation, a particular model of the tubular pile, the measuring equipment used, and the developed test method allow for the necessary information about the load-bearing capacity of the shell pile with an open lower end. This is the difference between the developed experimental model of the pile shell and the existing ones, which allows measuring the total resistance of the soil foundation.

Conclusions. The method of step-by-step creation of a spatial model «shell piles – soil base» is proposed. An analysis of the stress-strain state of this system with the help of an experimental model is presented. The solutions of the stress-strain state of the «shell piles – soil base» system are obtained. The results of these solutions show the possibility of modeling the operation of piles on pulling out of the loads.

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