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Determination of generalized vibration table forces

Korotych Yuriy[1]*

[1] Poltava National Technical Yuri Kondratyuk University https://orcid.org/0000-0002-1961-5318
*Corresponding author E-mail: korotitch.iury@ukr.net

The article determines the generalized forces of the technological set of equipment for concrete products production (vibrating table), in which the vibration exciter is fixed on the lever vertically in the center under the vibrating plate. This equipment is used for the manufacture of small-sized concrete products. Methods of mathematical physics and physical and mathematical modeling by methods of applied mechanics were used in the research. To determine the position and describe the free motions of the material bodies that make up the mechanical system under consideration, an orthogonal vibrational reference system of three coordinate systems was used. As a result, seven generalized forces acting on this mechanical system were determined. The obtained dependencies for the generalized forces will be used to compose a mathematical model of the above-mentioned equipment using the Lagrange equations of the second kind

Key words: vibrating table, lever, vibrator, unbalance, generalized force, mechanical system

Визначення узагальнених сил вібраційного столу

Коротич Ю. Ю.[1]*.

[1] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: korotitch.iury@ukr.net

В статті проводиться визначення узагальнених сил технологічного комплекту обладнання для виробництва бетонних виробів (вібростолу), у якого віброзбуджувач закріплюється на важелі вертикально по центру під віброплитою. Дане обладнання використовується для виготовлення малогабаритних бетонних виробів. При виконанні досліджень були використанні методи математичної фізики та фізико-математичне моделювання методами прикладної механіки. Для визначення положення і опису вільних рухів матеріальних тіл, з яких складається розглядувана механічна система, була застосована ортогональна вібраційна система відліку з трьох систем координат. Аналізуючи кінематичну схему вібраційного столу, визначено, що положення в просторі усіх матеріальних тіл механічної системи, яка моделює зазначений вібростіл, можна однозначно задати такими незалежними параметрами: декартовими координатами, вібраційними кутами та кутом повороту дебалансу. Таким чином, розглядувана механічна система має сім ступенів вільності з сімома узагальненими координатами. Оскільки кожній узагальненій координаті відповідає узагальнена сила, то їх число дорівнює числу узагальнених координат системи, через що розглядувана механічна система має сім узагальнених сил. Беручи до уваги, що на дану механічну систему діють зовнішні сили у вигляді сили тяжіння, сили пружності чотирьох віброопор та механічного крутного моменту приводного двигуна, були визначені сім узагальнених сил,діючих на дану механічну систему. Отримані залежності для узагальнених сил будуть використані для складання в подальшому математичної моделі вищезгаданого обладнання за допомогою рівнянь Лагранжа другого роду

Ключові слова: вібростіл, важіль, вібратор, дебаланс, узагальнена сила, механічна система

Introduction.

Vibration is the most common method of compaction of concrete composites [1,2]. More than 90% of all concrete and reinforced concrete building products are made using this method of concrete mix compaction [3]. This is due to the fact that in the process of vibration action on concrete mixtures, favorable conditions are created for thixotropic dilution and the most compact placement of aggregate particles [4,5].

Modern development of construction requires the introduction of the latest technologies and the installation of engineering equipment for various purposes according to the criteria of minimizing energy and high efficiency of the technological process. There is a huge variety of vibration machines used in construction, which differ in design and purpose. And, first of all, great attention should be paid to the development and implementation of energy-saving technologies and equipment.

A review of various designs of vibration equipment shows that in the production of a wide range of concrete products, equipment with the necessary operating parameters is used, with the help of which high-quality vibration compaction of the concrete mixture is achieved. In order to find out the individual parameters influence of the technological set of equipment for concrete products production developed by us [6] on the movement of its working body and energy consumption, it is necessary to make a mathematical model of this mechanical system.

Review of the research sources and publications.

In modern production, vibration machines with harmonic (circular oscillations in the vertical plane, vertically and horizontally directional oscillations, spatial oscillations) and with shock-vibration (on elastic pads, dual-mass with horizontal or vertical directional oscillations) movements of the working body are used to form concrete products. Such technologies for forming concrete products as vibration compression, vibration vacuum and pulse compaction method are increasingly being developed and implemented [7].

The widespread use of vibration technology, numerous theoretical and experimental studies of the dynamics of vibration machines have made it possible to identify the features of their operation, to explain and apply in practice the peculiar effects that occur during the action of vibration on mechanical systems [8,9,10]. Therefore, a lot of research and development is devoted to this issue [11,12], which reveals such advantages of vibration equipment as high compaction efficiency, simplicity of design, high reliability and relatively low metal and energy consumption.

One of the priority areas for the development of construction vibration equipment is to reduce energy costs in production. Energy-saving technologies, along with increasing productivity and improving product quality, are at the forefront of modern construction. The direction of energy saving is developing due to the optimization of technological parameters of equipment and the use of modern technologies.

Definition of unsolved aspects of the problem.

In our case, it is necessary to create a vibrating table, which, by placing a vibrating exciter on a vertical lever under the vibrating plate, would save energy costs in the manufacture of concrete products by reducing the power of the vibrator while maintaining the required vibration compaction parameters.

Problem statement.

The purpose of this work is to determine the generalized forces of a mechanical system that simulates a vibrating table with a vibrating exciter placed on a vertical lever under a vibrating plate. The data of the dependence of generalized forces are necessary for the analysis of technological factors, in particular the length of the lever, which have an impact on the energy intensity of this mechanical system, as well as for the subsequent compilation of a mathematical model of the technological set of equipment for the production of concrete products (vibrating table) using the Lagrange equations of the second kind.

This work is an integral part and continuation of the results obtained in the work [13].

Basic material and results.

The general view of the technological set of equipment for the production of concrete products (vibrating table) is shown in Fig. 1.

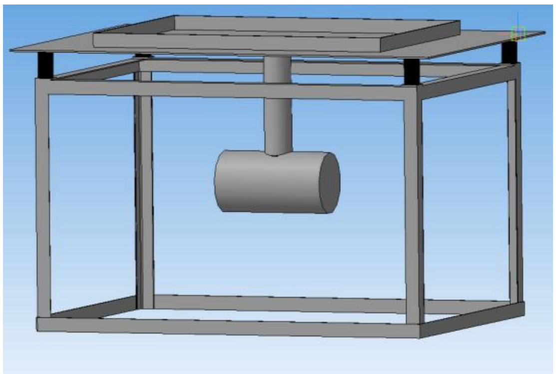

Fig. 1. General view of the technological set of equipment for the manufacture of concrete products

Mathematical model of a vibrating table for the manufacture of small-sized concrete products in the form of Lagrange equations of the second kind [14]

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} = Q_i \quad (i = 1, 2, \ldots, i, \ldots, s) \quad (1)$$

contains generalized forces $Q_1, Q_2, \ldots, Q_i, \ldots, Q_s$, where Q_i – the generalized force corresponding to the generalized coordinate q_i. In the system (1) of differential equations, the coordinates are generalized $q_1 = q_1(t)$, $q_2 = q_2(t)$, …, $q_i = q_i(t)$, …, $q_s = q_s(t)$ – these are independent parameters that uniquely define the position of a mechanical system in space, the number of which determines the number of s degrees of this system freedom, a$\dot{q}_1 = \frac{dq_1}{dt} = \dot{q}_1(t)$, $\dot{q}_2 = \frac{dq_2}{dt} =$

$\dot{q}_2(t)$, …, $\dot{q}_i = \frac{dq_i}{dt} = \dot{q}_i(t)$, …, $\dot{q}_s = \frac{dq_s}{dt} = \dot{q}_s(t)$ – corresponding generalized velocities.

From the analysis of the kinematic scheme of the vibrating table [13], it is obvious that the position in space of all material bodies of the mechanical system that simulates the specified vibrating table can be uniquely given by the following independent parameters:

- Cartesian coordinates $x_C = x_C(t)$, $y_C = y_C(t)$ i $z_C = z_C(t)$, which determine the position of the center C inertia of plate 1 in a fixed coordinate system $Oxyz$;
- vibrating angles $\alpha = \alpha(t)$, $\beta = \beta(t)$ i $\psi = \psi(t)$, which define the position of plate 1 with respect to the moving coordinate system $Cx'y'z'$;
- angle $\phi = \phi(t)$ unbalance rotation 5 around the axis ϕ rotation of an unbalanced shaft 4 that passes through a point C_3 and coincides (coincides) with the central longitudinal axis of the housing 3 of the vibration exciter.

Thus, the mechanical system in question has $s = 7$ degrees of freedom, the generalized coordinates are $q_1 = x_C$, $q_2 = y_C$, $q_3 = z_C$, $q_4 = \alpha$, $q_5 = \beta$, $q_6 = \psi$ i $q_7 = \phi$, and generalized speeds – $\dot{q}_1 = \frac{dx_C}{dt} = \dot{x}_C$, $\dot{q}_2 = \frac{dy_C}{dt} = \dot{y}_C$, $\dot{q}_3 = \frac{dz_C}{dt} = \dot{z}_C$, $\dot{q}_4 = \frac{d\alpha}{dt} = \dot{\alpha}$, $\dot{q}_5 = \frac{d\beta}{dt} = \dot{\beta}$, $\dot{q}_6 = \frac{d\psi}{dt} = \dot{\psi}$ i $\dot{q}_7 = \frac{d\phi}{dt} = \dot{\phi}$.

For the sake of clarity and for further considerations, let us imagine and depict in Figures 2 ÷ 4 a mechanical system in its three projections at an arbitrary moment in time t so that all the generalized coordinates are positive, and assuming that at that moment each generalized coordinate is increasing (of course, in this case, all time derivatives of the generalized coordinates will also be only positive).

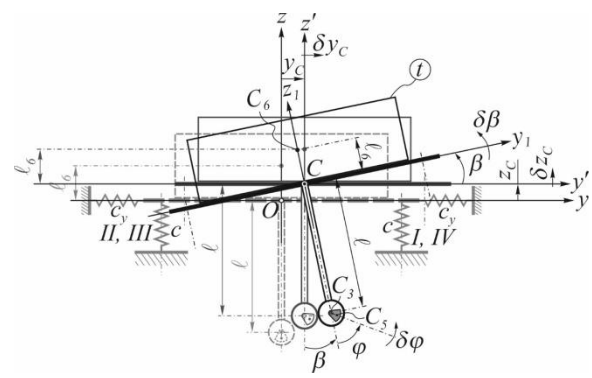

Fig. 2. Mechanical system in projection on the frontal plane

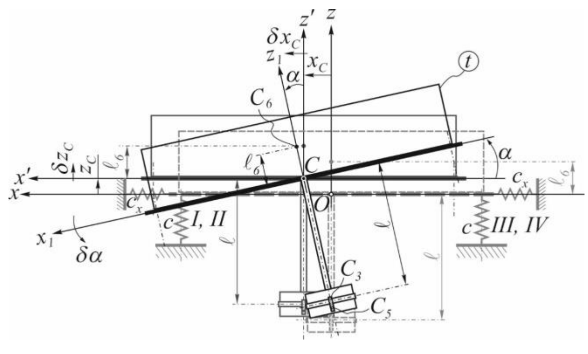

Fig. 3. Mechanical system in projection on the profile plane

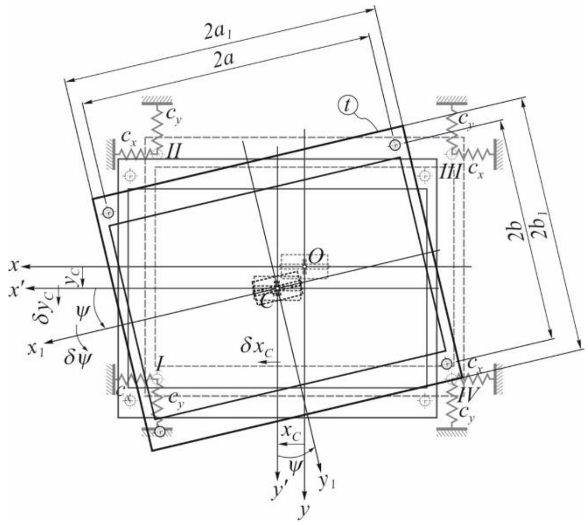

Fig. 4. Mechanical system in projection on the horizontal plane

Since each generalized coordinate corresponds to a generalized force, their number is equal to the number of generalized coordinates of the system, which is why the mechanical system in question has seven generalized forces. The significance of these forces directly depends on external forces $\vec{P}_1, \vec{P}_2, \ldots, \vec{P}_j, \ldots, \vec{P}_n$, acting on certain points of the system.

To determine the generalized force, for example, Q_i corresponding generalized coordinate q_i give an infinitesimal increment δq_i, leaving the other generalized coordinates unchanged. As a result, the infinitesimal increases δq_i all points of the mechanical system will receive infinitesimal displacements $\delta s_1, \delta s_2, \ldots, \delta s_j, \ldots, \delta s_n$, which are possible point movements. Next, the sum of the elementary work of all external forces on these possible displacements is calculated, which is equal to

$$\sum_{j=1}^{n} \left[P_j \cdot \delta s_j \cdot \cos\left(\vec{P}_j;\ \delta\vec{s}_j\right)\right] = \delta A_i,$$

and believe that

$$\delta A_i = Q_i \cdot \delta q_i.$$

Value Q_i, what is determined from this equation,

$$Q_i = \frac{\delta A_i}{\delta q_i} \tag{2}$$

and is a generalized force that corresponds to a generalized coordinate q_i, defined through possible work δA_i.

As is known [15], the elementary work of an arbitrary force $\vec{P}_j$ on a certain possible displacement in the coordinate form of the notation, determines the dependence

$$\delta A(\vec{P}_j) = P_{jx} \cdot \delta x + P_{jy} \cdot \delta y + P_{jz} \cdot \delta z, \quad (3)$$

where P_{jx}, P_{jy} і P_{jz} – projections of this arbitrary force $\vec{P}_j$ on the appropriate axes; δx, δy і δz – projections of possible displacement of the point of force application $\vec{P}_j$ on the same axes.

Any resistance to the movements of the material bodies of the mechanical system in question shall be neglected. In this case, it is affected by the following external forces:

a) gravity

$$\vec{G}_1 = m_1 \cdot \vec{g}, \;\; \vec{G}_3 = m_3 \cdot \vec{g}, \;\; \vec{G}_6 = m_6 \cdot \vec{g} \;\; \text{і} \;\; \vec{G}_5 = m \cdot \vec{g}$$

corresponding material bodies, which are attached in points C, C_3, C_6 і C_5 (see Fig. 5);

б) elastic forces of the four elastic elements on which the plate rests 1 (see Fig. 7);

в) mechanical torque (or rotational) $M_{дв.}$ Of an engine (see Fig. 8, a).

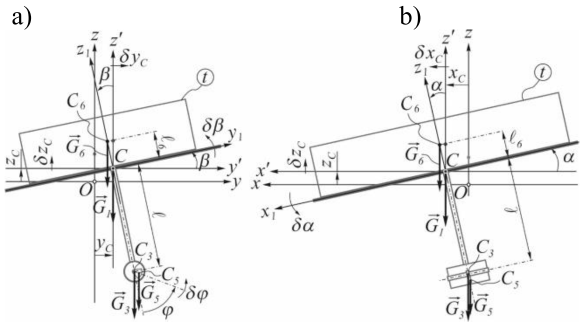

Fig. 5. On the of gravitational forces elementary works definition

As is known [16], according to Hooke's law, the linear elastic force $F_{пр.}$, that occurs in linear deformation $\Delta \ell$, proportional to said deformation

$$F_{пр.} = \mathrm{c} \cdot \Delta \ell,$$

where c – proportionality coefficient, for an elastic element – stiffness coefficient.

Due to the fact that during the direct formation of concrete products, slab 1 is in free motion, the vertical elastic elements on which it rests undergo not only linear deformations along the vertical axis Oz. To take into account the stiffness of each elastic element in the direction of the horizontal axes Ox and Oy let's introduce virtual elastic elements with stiffnesses c_x and c_Y respectively (see Fig. 4). In this case, three orthogonal elastic forces will act on plate 1 from each elastic element

$$F_{пр.x} = \mathrm{c}_x \cdot \Delta \ell_x, \;\; F_{пр.y} = \mathrm{c}_y \cdot \Delta \ell_y \;\; \text{і} \;\; F_{пр.z} = \mathrm{c} \cdot \Delta \ell, \quad (4)$$

where $\Delta \ell_x$, $\Delta \ell_y$ and $\Delta \ell$ – deformations of the corresponding elastic elements.

Since for the working body of the vibrating table, its angular displacements determine the vibration angles α, β and ψ, which acquire only small values, then we neglect the torsional rigidity of each elastic element.

Consider in Figure 6 a mechanical system in its position of static equilibrium (PSE), where $\ell_{нед.}$ – length of each elastic element in the undeformed state.

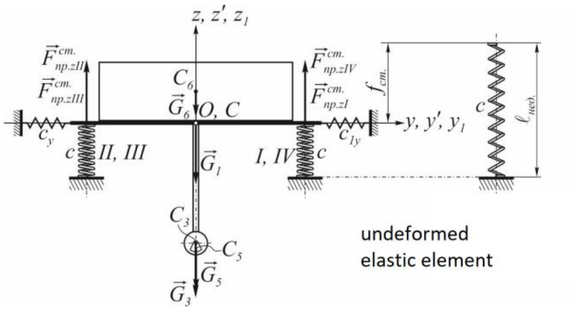

Fig. 6. Mechanical system in static equilibrium position

From the equilibrium condition $\sum Z = 0$ getting the corresponding equilibrium equation

$$-m_1 \cdot g - m_3 \cdot g - m \cdot g - m_6 \cdot g + c \cdot f_{ст.} + c \cdot f_{ст.} + c \cdot f_{ст.} + c \cdot f_{ст.} = 0,$$

from where

$$-M \cdot g + c_е \cdot f_{ст.} = 0, \quad (5)$$

where $M = m_1 + m_3 + m_6 + m$, $c_е = c + c + c + c = 4 \cdot c$– equivalent stiffness of elastic elements or stiffness of equivalent elastic support [13], $f_{ст.}$– static vertical deformation of equivalent elastic support (of course, in the static equilibrium position of a mechanical system, each of the elastic elements on which plate 1 rests has the same vertical static deformation, and all the introduced virtual elastic elements are undeformed).

To find the generalized force $Q_3 = Q_{z_C}$:

1) will give to a generalized coordinate $q_3 = z_C$ infinitesimal linear increment $\delta q_3 = \delta z_C$ (see Fig. 1 and 2), and leaving other generalized coordinates unchanged;

2) will establish what possible displacements were made by the points of application of all external forces acting on the mechanical system, as a result of the increase provided $\delta q_3 = \delta z_C$;

3) will calculate the possible work δA_3 of all external forces at the indicated possible displacements of points.

Will look for a possible work δA_3 according to the formula

$$\delta A_3 = \delta A_3(\vec{G}) + \delta A_3(\vec{F}_{пр.}), \quad (6)$$

where $\delta A_3(\vec{G})$ i $\delta A_3(\vec{F}_{\text{пр.}})$ – Accordingly, the possible work of gravity forces and elastic forces of elastic elements.

As the increasing $\delta q_3 = \delta z_C$ directed vertically, then the possible works of the elastic forces of horizontally arranged virtual elastic elements at such a possible displacement are equal to zero and therefore

$$\delta A_3(\vec{F}_{\text{пр.}}) = \delta A_3(\vec{F}_{\text{пр.}\,z}),$$

where $\delta A_3(\vec{F}_{\text{пр.}\,z})$ – possible works of elastic forces of real elastic elements.

For sure,

$$\delta A_3(\vec{G}) = \delta A_3(\vec{G}_1) + \delta A_3(\vec{G}_3) + \delta A_3(\vec{G}_6) + \delta A_3(\vec{G}_5),$$

where $\delta A_3(\vec{G}_1)$, $\delta A_3(\vec{G}_3)$, $\delta A_3(\vec{G}_6)$ i $\delta A_3(\vec{G}_5)$ – elementary works of the corresponding gravitational forces, which are determined by the formula (3).

Directly from Figure 4 we can see that the corresponding projections of forces

$$G_{1x} = 0,\ \ G_{1y} = 0,\ \ G_{1z} = -G_1 = -m_1 \cdot g,\ \ G_{3x} = 0,\ \ G_{3y} = 0,$$
$$G_{3z} = -G_3 = -m_3 \cdot g,\ \ G_{6x} = 0,\ \ G_{6y} = 0,\ \ G_{6z} = -G_6 = -m_6 \cdot g,$$
$$G_{5x} = 0,\ \ G_{5y} = 0,\ \ G_{5z} = -G_5 = -m \cdot g$$

and projections of possible point displacements C, C_3, C_6 and C_5 on the same axes

$$\delta x_C = \delta x_{C_3} = \delta x_{C_6} = \delta x_{C_5} = \delta y_C = \delta y_{C_3} = \delta y_{C_6} = \delta y_{C_5} = 0,$$
$$\delta z_{C_3} = \delta z_{C_6} = \delta z_{C_5} = \delta z_C.$$

Then

$$\delta A_3(\vec{G}) = -m_1 \cdot g \cdot \delta z_C - m_3 \cdot g \cdot \delta z_C - m_6 \cdot g \cdot \delta z_C - m \cdot g \cdot \delta z_C =$$
$$= -(m_1 + m_3 + m_6 + m) \cdot g \cdot \delta z_C =$$
$$= -M \cdot g \cdot \delta z_C. \qquad (7)$$

Now let's find in formula (6) the component $\delta A_3(\vec{F}_{\text{пр.}}) = \delta A_3(\vec{F}_{\text{пр.}\,z})$ as the sum of the elementary works of the real elastic elements elastic forces I, II, III i IV:

$$\delta A_3(\vec{F}_{\text{пр.}}) = \delta A_3(\vec{F}_{\text{пр.}zI}) + \delta A_3(\vec{F}_{\text{пр.}zII}) + \delta A_3(\vec{F}_{\text{пр.}zIII}) + \delta A_3(\vec{F}_{\text{пр.}zIV}),$$

where $\delta A_3(\vec{F}_{\text{пр.}zI})$, $\delta A_3(\vec{F}_{\text{пр.}zII})$, $\delta A_3(\vec{F}_{\text{пр.}zIII})$ and $\delta A_3(\vec{F}_{\text{пр.}zIV})$ determined by the formula (3), and the elastic forces themselves by the formula (4).

Calculating for each of the elastic elements the elementary work of its elastic force at a specific displacement of the point of its application, we will take into account the fact that the specified work is positive when the elastic force contributes to the reduction of the deformation of the elastic support, and negative if the elastic force increases the deformation of the elastic support.

When finding deformations of elastic elements at the considered moment of time t Let us take into account the fact that the movement of their anchoring points to plate 1 from its rotations to vibration angles α, β and ψ in reality, they are carried out along the arcs of the corresponding circles, but because of the smallness of these displacements, we neglect their curvature, assuming that the points move in straight lines along the corresponding coordinate axes at a distance equal to the lengths of the indicated arcs. Then, from the cumulative analysis of Figures 6 and 7, we establish that

$$\Delta\,\ell_I = f_{\text{ст.}} - z_C + a \cdot \alpha - b \cdot \beta,\ \ \ \Delta\,\ell_{II} = f_{\text{ст.}} - z_C + a \cdot \alpha + b \cdot \beta,$$
$$\Delta\,\ell_{III} = f_{\text{ст.}} - z_C - a \cdot \alpha + b \cdot \beta,\ \ \ \Delta\,\ell_{IV} = f_{\text{ст.}} - z_C - a \cdot \alpha - b \cdot \beta,$$

Because of what

$$\left.\begin{aligned} F_{\text{пр.}z\,I} &= \mathrm{c} \cdot \Delta\,\ell_I = c \cdot (f_{\text{ст.}} - z_C + a \cdot \alpha - b \cdot \beta)\,, \\ F_{\text{пр.}z\,II} &= \mathrm{c} \cdot \Delta\,\ell_{II} = c \cdot (f_{\text{ст.}} - z_C + a \cdot \alpha + b \cdot \beta)\,, \\ F_{\text{пр.}z\,III} &= \mathrm{c} \cdot \Delta\,\ell_{III} = c \cdot (f_{\text{ст.}} - z_C - a \cdot \alpha + b \cdot \beta)\,, \\ F_{\text{пр.}z\,IV} &= \mathrm{c} \cdot \Delta\,\ell_{IV} = c \cdot (f_{\text{ст.}} - z_C - a \cdot \alpha - b \cdot \beta)\,. \end{aligned}\right\} \qquad (8)$$

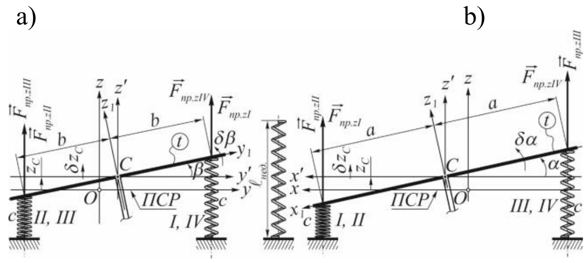

Fig. 7. On the Elastic Forces Elementary Works Determination

Since in Figure 7 all the elastic forces $\vec{F}_{\text{пр.}z\,I}$, $\vec{F}_{\text{пр.}z\,II}$, $\vec{F}_{\text{пр.}z\,III}$ i $\vec{F}_{\text{пр.}z\,IV}$ vertically upwards, then, of course, they are all projected on the axis Oz life-size with a positive sign, and are not projected on other axes. It is also evident that projections on the axis Oz possible displacements of the points of attachment of elastic elements to plate 1 are positive and are equal to the given infinitesimal increment δz_C, and the projections on the other axes are zero.

Then, according to the formula (3)

$$\delta A_3(\vec{F}_{\text{пр.}\,zI}) = F_{\text{пр.}z\,I} \cdot \delta z_C = c \cdot (f_{\text{ст.}} - z_C + a \cdot \alpha - b \cdot \beta) \cdot \delta z_C,$$
$$\delta A_3(\vec{F}_{\text{пр.}\,zII}) = F_{\text{пр.}z\,II} \cdot \delta z_C = c \cdot (f_{\text{ст.}} - z_C + a \cdot \alpha + b \cdot \beta) \cdot \delta z_C,$$
$$\delta A_3(\vec{F}_{\text{пр.}\,zIII}) = F_{\text{пр.}z\,III} \cdot \delta z_C = c \cdot (f_{\text{ст.}} - z_C - a \cdot \alpha + b \cdot \beta) \cdot \delta z_C,$$
$$\delta A_3(\vec{F}_{\text{пр.}\,zIV}) = F_{\text{пр.}z\,IV} \cdot \delta z_C = c \cdot (f_{\text{ст.}} - z_C - a \cdot \alpha - b \cdot \beta) \cdot \delta z_C$$

and

$$\delta A_3(\vec{F}_{\text{пр.}}) = c(f_{\text{ст.}} - z_C + a \cdot \alpha - b \cdot \beta) \cdot \delta z_C + c(f_{\text{ст.}} - z_C + a \cdot \alpha + b \cdot \beta) \cdot \delta z_C +$$
$$+ c \cdot (f_{\text{ст.}} - z_C - a \cdot \alpha + b \cdot \beta) \cdot \delta z_C + c \cdot (f_{\text{ст.}} - z_C - a \cdot \alpha - b \cdot \beta) \cdot \delta z_C$$

or (after conversions)

$$\delta A_3(\vec{F}_{\text{пр.}}) = c \cdot (f_{\text{ст.}} - z_C + a \cdot \alpha - b \cdot \beta + f_{\text{ст.}} - z_C + a \cdot \alpha + b \cdot \beta +$$

$$+f_{\text{ст.}} - z_C - a \cdot \alpha + b \cdot \beta + f_{\text{ст.}} - z_C - a \cdot \alpha - b \cdot \beta) \cdot \delta z_C =$$

$$= \mathrm{c} \cdot (4 \cdot f_{\text{ст.}} - 4 \cdot z_C) \cdot \delta z_C = 4 \cdot \mathrm{c} \cdot (f_{\text{ст.}} - z_C) \cdot \delta z_C.$$

Since the same $4 \cdot c = c_{\mathrm{e}}$, then

$$\delta A_3(\vec{F}_{\text{пр.}}) = \mathrm{c_e} \cdot f_{\text{ст.}} \cdot \delta z_C - \mathrm{c_e} \cdot z_C \cdot \delta z_C. \qquad (9)$$

By substituting the values (7) and (9) into formula (6), we have

$$\delta A_3 = -M \cdot g \cdot \delta z_C - m_5 \cdot g \cdot \delta z_C + \mathrm{c_e} \cdot f_{\text{ст.}} \cdot \delta z_C - \mathrm{c_e} \cdot z_C \cdot \delta z_C =$$

$$= (-M \cdot g - m_5 \cdot g + \mathrm{c_e} \cdot f_{\text{ст.}} - \mathrm{c_e} \cdot z_C) \cdot \delta z_C,$$

whence we get the equality (5)

$$\delta A_3 = -\mathrm{c_e} \cdot z_C \cdot \delta z_C;$$

then, according to formula (2), the generalized force corresponding to the generalized coordinate $q_3 = z_C$,

$$Q_3 = \frac{\delta A_3}{\delta q_3} = \frac{\delta A_3}{\delta z_C} = \frac{-\mathrm{c_e} \cdot z_C \cdot \delta z_C}{\delta z_C}$$

and, after the reduction of δz_C, finally

$$Q_3 = -\mathrm{c_e} \cdot z_C.$$

Computing the other generalized forces of our mechanical system in the same way, we get

$$Q_1 = -c_{ex} \cdot x_C + c_{ex} \cdot \delta \cdot \alpha.$$

$$Q_2 = -c_{ey} \cdot y_C - c_{ey} \cdot \delta \cdot \beta.$$

$$Q_4 = -(m_3 + m) \cdot g\ell \cdot \sin\alpha + m_6 \cdot g\ell_6 \cdot \sin\alpha - - m \cdot ge \cdot \sin\alpha \cdot \cos\phi - c_e \cdot a^2 \cdot \alpha$$

$$Q_5 = -(m_3 + m) \cdot g \cdot \ell \cdot \sin\beta + + m_6 \cdot g \cdot \ell_6 \cdot \sin\beta - c_e \cdot b^2 \cdot \beta.$$

$$Q_6 = -c_{ex} \cdot b^2 \cdot \psi - c_{ey} \cdot a^2 \cdot \psi.$$

$$Q_7 = M_{\text{дв.}} - m \cdot g \cdot e \cdot \sin\phi.$$

Conclusions

To obtain a mathematical model of the developed vibrating table design, we propose to use the Lagrange equation of the second kind. This method is the most common method used in solving problems concerning the motion of mechanical systems.

The vibrating table in question was modeled by a mechanical system consisting of several material bodies - a plate, a vibration exciter body, an imbalance and a container with a concrete mixture. To determine the position and describe the free motions of the above-mentioned material bodies of the mechanical system under consideration, an orthogonal vibrational reference system of three coordinate systems was used.

Having depicted and considered the mechanical system of the developed design of the vibrating table, seven generalized forces acting on it were determined.

The defined generalized forces of this mechanical system will be further used to compile a mathematical model of the vibration table in the Lagrange equations of the second kind, with the help of which it will be possible to analyze the influence of its constituent parameters - geometric and kinematic - on the process of compaction of the concrete mixture to reduce energy consumption during vibration compaction of products.

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Mobile complex of equipment for 3D printing

Nesterenko Mykola[1], Orysenko Olexandr[2], Zhyla Ihor[3], Sidan Denis[4]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-4073-1233
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-8961-2147
[3] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-8750-7650
[4] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0009-0006-7945-5615
*Corresponding author E-mail: nesterenkonikola@gmail.com

The research explores the possibility of using mobile 3D printing technologies in construction and manufacturing. It is noted that many equipment manufacturers are already utilizing 3D printing for constructing various objects, but one of the limitations has been the lack of mobility. However, new concepts and prototypes of mobile 3D printers are emerging, which allow for construction and manufacturing in different locations without the need for additional transportation equipment. The proposed design of a mobile 3D construction printer-complex, housed on a cargo semi-trailer, is suggested as a mobile and autonomous system for construction purposes

Keywords: additive manufacturing, 3D printing, robotic printers, concrete printing, concrete mixture, vibrator

Мобільний комплекс обладнання для 3D-друку

Нестеренко М.М.[1]*, Орисенко О.В.[2], Жила І.В.[3], Сідан Д.О.[4]

[1] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[2] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[3] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[4] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: nesterenkonikola@gmail.com

В роботі досліджується можливість використання мобільних технологій 3D-друку в будівництві і виробництві. Зазначається, що багато виробників обладнання вже використовують 3D-друк для будівництва різних об'єктів, але одним з обмежень була відсутність мобільності. Проте, з'являються нові концепції та прототипи мобільних 3D-принтерів, які дозволяють виконувати будівництво та виробництво в різних місцях без необхідності використання додаткового обладнання для переміщення. Зосереджено увагу на двох основних напрямках розвитку. Перший - рухомі робочі комплекси з вбудованим 3D-принтером, що можуть переміщатися по будівельному майданчику та автоматично налаштовувати своє положення для друку. Другий - портативні 3D-принтери, які можна легко переносити та використовувати в різних місцях. Зазначається, що ці технології розширюють можливості будівельної індустрії, знижують залежність від фіксованих станцій та дозволяють виконувати роботи на віддалених або важкодоступних місцях. Запропонована конструкція 3D будівельного принтера-комплексу, розміщеного на базі вантажного напівпричепу, пропонується як рухома та автономна система для будівництва. У цій конструкції використовується здвоєний екструдер з можливістю відключення одного сопла подачі, що дозволяє ефективно управляти процесом роздрукування. За рахунок того, що комплекс обладнаний механізмами, які забезпечують його автономну роботу та можливість пересування по дорогам різних категорій, його можна використовувати на місці будівництва, одразу після переміщення на будівельний майданчик

Ключові слова: адитивне виробництво; 3D друк; роботизовані принтери, друк бетонним розчином, бетонна суміш, віброзбуджувач

Introduction

Many equipment manufacturers for construction purposes have started utilizing 3D printing technologies. One of the drawbacks of most of these printer designs is the lack of mobility. The printer constructs the building or object within its working area, and subsequently, after completing the printing of the construction or product, lifting and transportation machinery is required to move the equipment to a new work location. However, modern research and development efforts are actively working on solving this problem. New concepts and prototypes of mobile 3D printers are emerging, which allow for construction and manufacturing in different locations without the need for additional transportation equipment.

One of the directions of development is the creation of mobile working complexes with an integrated 3D printer. These complexes can be equipped with wheeled or tracked chassis, allowing them to freely move around construction sites or other areas. Such equipment working complexes can autonomously find optimal routes for construction and automatically adjust their positions for printing objects [1].

Another solution is the development of portable 3D printers that can be easily carried and used in various locations. These printers can have compact dimensions and be collapsible, allowing them to be transported to hard-to-reach places or over long distances. Such printers should be equipped with an automated navigation system that assists the user in spatial orientation and adjusting printing parameters.

In addition, attention is being given to the development of construction robots that can build and dismantle structures. These robots have the ability to perform complex construction tasks, including 3D printing, and provide maximum mobility as they can be transported and configured in different sections of a construction site. These construction robots are capable of autonomous movement across the terrain using mechanisms such as wheels or tracks. They are equipped with powerful sensors that enable them to analyze the surrounding environment and perform precise movements without colliding with obstacles [2, 3].

Such mobile 3D printers and construction robots significantly expand the possibilities of using 3D printing technology in construction. They reduce dependence on fixed stations and enable work to be carried out in remote or hard-to-reach locations. Additionally, they contribute to the more efficient use of resources and reduce the time spent on equipment relocation.

The application of mobile 3D printing technologies in construction holds significant potential for the fast and efficient execution of various types of projects. They can be utilized for prototyping, small-scale construction, architectural elements, and other structures. These technologies enable quick responsiveness to changing requirements and client needs, while also reducing costs and improving the overall quality of construction.

Indeed, in the future, we can expect even greater innovations in the field of mobile 3D printing technologies, which will open up new possibilities for the construction industry and accelerate construction and manufacturing processes. The continuous advancements in this field are likely to lead to improved efficiency, expanded capabilities, and enhanced integration with other construction technologies. This can revolutionize the way buildings are designed, constructed, and customized, ultimately shaping the future of the industry.

Definition of unsolved aspects of the problem

Despite the progress in the development of mobile 3D printing technologies for construction, there are still several unresolved issues associated with this problem [4, 5].

The size and weight of the equipment are important considerations. Mobile 3D printers and construction robots require a compact and lightweight design to ensure mobility. However, this can limit their capabilities and power. Addressing this issue requires a balanced approach to the size and functionality of the equipment.

Power supply is another important aspect. Mobile devices require a stable and efficient source of energy. Ensuring a reliable power supply that allows for extended operation without the need for frequent recharging or battery replacement is essential.

Stability and precision are crucial factors when it comes to the movement of mobile equipment on uneven surfaces. Addressing this issue involves developing mechanisms to compensate for vibrations, implementing sensors for accurate positioning, and designing control algorithms to maintain printer stability during operation.

Problem statement

The objective of this work is to review the designs of volumetric construction 3D printers and analyze the technologies that are most suitable for their use in mobile conditions.

To achieve this objective, the following tasks need to be accomplished:

Conduct a review of the most common designs of construction 3D printers that provide mobility and the ability to operate on moving platforms.

Analyze the advantages and disadvantages of different construction 3D printer designs in the context of their mobile application.

Evaluate their maneuverability, stability, and printing accuracy, as well as their energy efficiency and reliability.

Assess the capabilities of different construction 3D printer designs for quick reconfiguration when changing the production program.

Investigate the technical solutions and functional capabilities that enable rapid parameter changes and transitioning from one project to another.

Propose a concept for combining a 3D printer with automotive chassis and suggest possible areas of application.

This research approach will help identify the most suitable designs of mobile construction 3D printers and recognize potential directions for further development of 3D printing technologies in the construction industry.

Basic material and results

A construction 3D printer consists of the same structural elements as its counterparts in other industries. It has important components such as a gantry, used for the printer's movement in both vertical and horizontal directions; an extruder, which deposits material layer by layer, and electric drives that control the platform's motion in the desired direction. The size of a construction 3D printer is typically determined by the dimensions of the object being built and can vary significantly [6]..

However, specialized construction 3D printers can be used in the construction industry, which may have additional components or modifications to ensure high precision, speed, and efficiency during construction projects. This indicates that construction 3D printers have a general structural concept but can be customized and modified to suit the needs of the construction industry and be placed on mobile platforms.

Researchers from the Massachusetts Institute of Technology (MIT) have developed a design for a 3D construction printer that combines the printer structure with a tracked crawler, making the machine more mobile and reducing the need for specialized equipment during construction (Figure 1) [5]..

A distinctive feature of this printer is that instead of traditional concrete walls, it proposes printing a foam insulation framework that will later be filled with a concrete mixture.

In the photo, you can see the already printed framework of the building structure (Figure 2). There is also a known printer design from Cazza Construction, the X1 3D Printing model (Figure 3). The mobile X1 3D Printing system is capable of independently moving to the construction site [7].

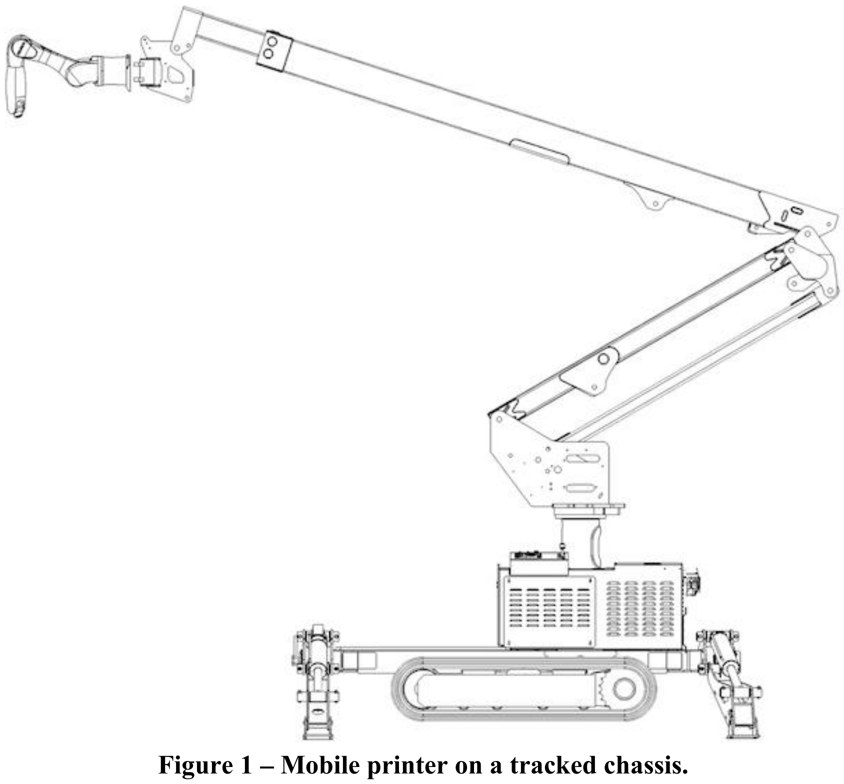

Figure 1 – Mobile printer on a tracked chassis.

Figure 2 - Polyurethane insulation frame of a building

Figure 3 - Mobile X1 3D Printing Complex

A drawback of printers on a tracked chassis is their limited mobility between construction sites and the need to involve specialized equipment for transportation (Figure 4) [7].

Mobile 3D printer designs mounted on a wheeled trailer base, incorporating a robotic arm for performing various operations, have started to emerge (Figure 5) [4].

Figure 4 – Transportation of the mobile 3D Printing system

Figure 5 – A trailer with a versatile robotic arm manipulator

The main component that ensures reliable operation of the printer is the extruder. Considering the possible options for using different extruder designs, namely, single (Figure 6) [8].and dual (Figure 7) [9].

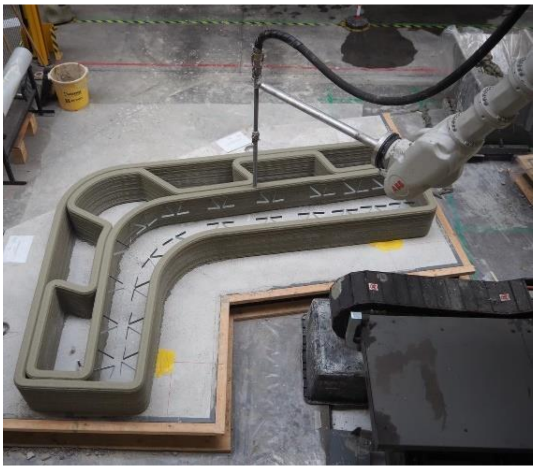

Figure 6 – Single extruder

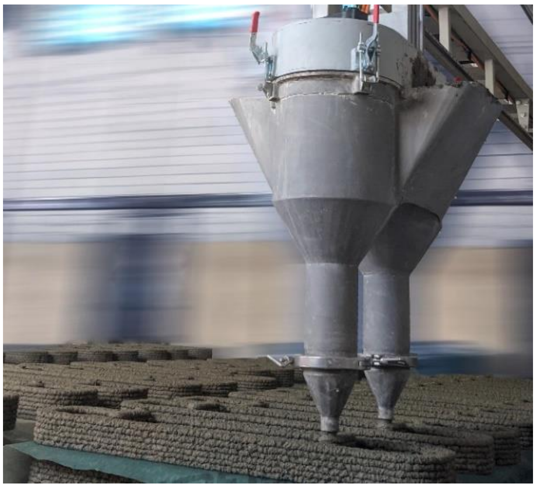

Figure 7 – Dual extruder

The use of a dual extruder nearly doubles the productivity of the machine, but it has a drawback - it complicates the work with different (curved) motion trajectories while simultaneously feeding the mixture.

We propose a design for a 3D construction printer complex, which is mounted on a cargo semi-trailer (Figure 8) equipped with a dual extruder that allows for disconnecting one feeding nozzle.

The mobile complex can be used as a self-contained unit equipped with a mixer (7) and a concrete pump (6) that supplies the ready mix to the extruder (5). The extruder is placed on the metal framework of the portal (4), which is supported by telescopic outriggers (3). The capacity of the semi-trailer allows for the placement of the mixture for preparing the solution and other components.

The operation of the complex begins with the deployment of the portal with the extruder upon arrival at the construction site, which is supported by telescopic outriggers. Then, the preparation of the working mixture takes place, where the components are mixed using the built-in mixer. The delivery of the prepared mixture occurs through pressure pipelines to the extruder with the assistance of a concrete pump.

The electrical part of the complex can be powered either by connecting to an external power supply or by utilizing the built-in diesel generator.

The schematic structure of the printer consists of two structural blocks (Figure 9). The first block comprises the preparation and pump-ing unit for the construction mixture (Figure 10), which is con-veyed through delivery hoses to the second block. To enhance the design of the first unit, a vibration exciter has been installed on the bunker (Figure 11).

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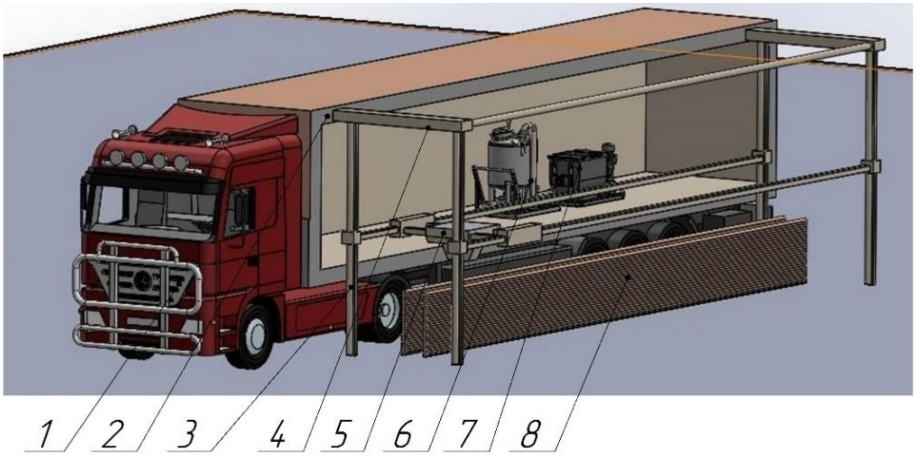

Figure 8 - 3D construction printer complex mounted on a cargo semi-trailer
1 – Truck tractor, 2 – Semi-trailer, 3 – Telescopic outriggers, 4 – Portal,
5 – Extruder, 6 – Concrete pump, 7 – Mixer 8 – Printed element

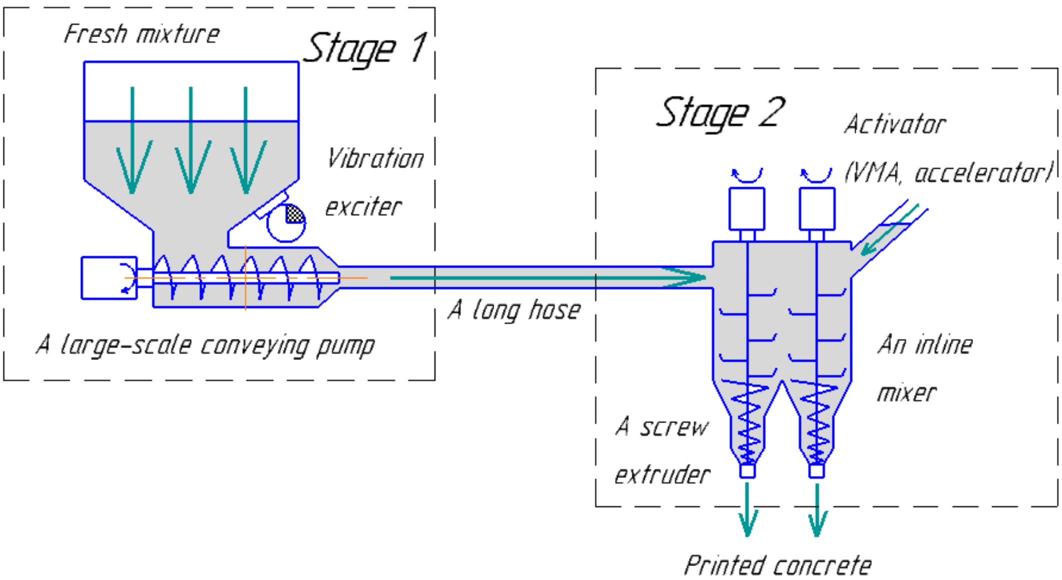

Figure 9 – The scheme of feeding the concrete mixture into the printing area

This will optimize the process of mixing and homogenizing the mixture, ensuring its uniformity and preventing the presence of hardened particles on the walls. The second block consists of a housing that houses two shafts with mixture-agitating blades and screws. Printing of building structures can occur simultane-ously using two streams or one stream by utilizing separate drive motors.

This structural proposal allows for nearly doubling the printing speed. To expedite the curing process of the mixture deposited into the second block, a curing accelerator is introduced.

The obtained structural elements can be further utilized, if needed, as permanent formwork and filled with insulation material or concrete mix.

Figure 10 – Mixer for preparing construction mix

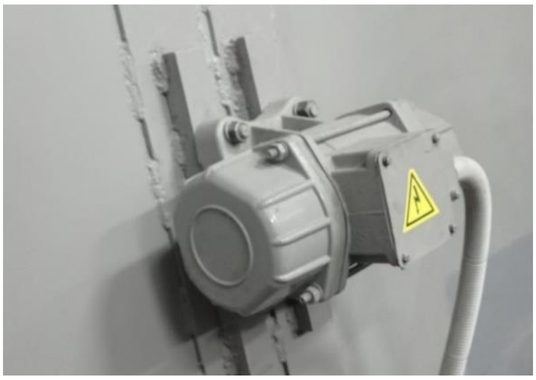

Figure 11 – Vibrator is installed on the hopper

Conclusions

The proposed concept of using a printer installed on a semi-trailer offers significant prospects in construction. It can be utilized for various purposes such as residential and industrial building construction, protective structures, retaining walls, and fences. The complex's autonomous operation and its ability to move on roads of different categories enable its immediate use at the construction site after transportation. Furthermore, the printing block's design can be enhanced by incorporating mechanisms for the placement of reinforcing elements.

Overall, mobile 3D printing technologies open up new possibilities for the construction industry, where speed, maneuverability, and quality are critical factors for success. Thanks to these innovations, we can expect faster, more efficient, and durable construction processes, promoting the development of modern construction practices and enhancing the quality of our lives.

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Analysis of vibration machine parameters affecting compaction quality

Vasiliev Oleksii[1]*, Yakovenko Andrii[2]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-9914-5482
[2] National University «Yuri Kondratyuk Poltava Polytechnic»; https://orcid.org/0000-0003-0818-6332
*Corresponding author E-mail: a.s.vasiliev.76@gmail.com

Compaction of products is an important stage of construction work and engineering projects. It has a significant impact on the stability and reliability of the construction. However, the compacting quality of the products depends on various parameters that are controlled and adjusted on vibration machine. Analysis of these parameters will allow us to determine the optimal values to achieve the maximum quality of compacting products using a vibration machine. The article studies the influence of different parameters of the vibration machine on the quality of the material compaction. The purpose of this article is to determine the choice of the optimal design of vibration machine, depending on the specific conditions of production and the size of reinforced concrete products. The authors emphasise on such key factors as vibration amplitude, frequency, workload and duration of exposure. Therefore, taking into account the fact that these parameters can help to understand better the vibration compaction process and develop optimal conditions for achieving high quality material compaction. This study presents the most rational design scheme of a small-sized vibration machine and its optimal dynamic parameters. The results of this study will be interesting for engineers, construction contractors and specialists who are engaged in the design or working on compaction of products

Keywords: vibration, vibration oscillation amplitude, vibration exciter, vibration machine, debalance, forced oscillations

Аналіз параметрів вібраційної установки, що впливають на якість ущільнення

Васильєв О.С.[1]*, Яковенко А.М.[2]

[1, 2] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: a.s.vasiliev.76@gmail.com

Ущільнення виробів є важливим етапом будівельних робіт та інженерних проектів і має значний вплив на стійкість і надійність конструкції. Однак, якість ущільнення виробів залежить від різних параметрів, які контролюються та налаштовуються на вібраційних установках. Аналіз цих параметрів дозволить визначити оптимальні значення для досягнення максимальної якості ущільнення виробів за допомогою вібраційної установки. Метою цієї статті є представлення результатів дослідження для визначення вибору оптимальної конструктивної схеми вібраційного обладнання в залежності від конкретних умов виробництва та розмірів залізобетонних виробів. Особливість вібраційного методу полягає в тому, що тільки за рахунок зниження інтенсивності коливань робочого органу вібраційної машини можна здійснювати принципово окремі технологічні процеси, причому ці технологічні процеси не виділяються чітко за режимами коливань, а поступово переходять у різні процеси. В статті досліджується вплив різних параметрів вібраційної установки на якість ущільнення матеріалу. Автори звертають увагу на такі ключові фактори, як амплітуда коливань, частота, навантаження і тривалість впливу. Тому врахування цих параметрів може допомогти краще зрозуміти процес вібраційного ущільнення і розробити оптимальні умови для досягнення високої якості ущільнення матеріалу. У дослідженні проведено аналіз основних матеріалів, що використовуються під час виготовлення вібраційної машини, та їхньої ефективної ролі в забезпеченні ефективного ущільнення. В роботі представлено найбільш раціональну конструктивну схему малогабаритної вібраційної установки та її оптимальні динамічні параметри. Автори наводять приклади позитивного впливу зміни цих параметрів на густину матеріалу, його стабільність та здатність опиратись руйнуванню. Результати цього дослідження будуть цікаві інженерам, будівельним підрядникам і фахівцям, які займаються проєктуванням і проведенням робіт з ущільнення виробів.

Ключові слова: вібрація, амплітуда віброколивань, віброзбуджувач, вібраційна машина, дебаланс, вібраційна установка, вимушені коливання

Introduction

Compaction of products is an important stage of construction work and engineering projects and has a significant impact on the stability and reliability of the structure. One of the most effective compaction methods is the use of vibration machines. Vibrating machine creates vibration waves to reduce porosity and increase material density [1].

However, the quality of product compaction depends on various parameters that are monitored and adjusted on the vibration machines. Engineers and specialists involved in this field feel the need to have a deep understanding of how these parameters affect the compaction process and the quality of the final result [2].

This article is devoted to the analysis of the parameters of the vibrating machine, which affect the quality of compaction of the products. Our goal is to look at various factors such as vibration amplitude, vibration frequency, workload and machine design and determine their correlation with compaction quality.

The analysis of these parameters will allow us to determine optimal values and recommendations for achieving maximum quality of material compaction using vibration machines. These results can be used by engineers, construction contractors and industry professionals to improve compaction processes and achieve optimal results in construction and engineering projects [3].

Review of Research Resources and Publications

A review and analysis of literary sources shows that at the national and international levels, two concepts of structural modeling of concrete mixtures have been developed: corpuscular, which represents concrete mixture as a three-component medium consisting of solid particles divided into liquid and vapor phases; the corpuscular and phenomenological phase describe the concrete mixture as a uniform material of constant density, changing its retention properties during compression. Both concepts with all their variations still cause a lot of discussion [4,5].

The peculiarity of the vibration method is that it is possible to carry out fundamentally separate technological processes only by reducing the vibration intensity of the platform of the vibration machine, and these technological processes are not clearly separated by vibration modes, but gradually transition from one into one another [6,7].

To achieve a certain technical result of vibration, the active inertia forces must act in a certain way in correlation to the friction forces, viscosity and viscous resistance forces, and if the inertia forces differ slightly from the optimal value, the same result can be achieved by changing the duration of the vibration process [8-10].

The vibration effect necessarily requires a very useful effect of vibrational activation of the mixed components, which is absent in non-vibration methods.

Definition of unsolved aspects of the problem

Strengthening products is an important process in construction and engineering projects, and vibration machines are one of the key tools to achieve an optimal level of compaction. However, the quality of the compaction can vary greatly depending on the different parameters of the vibration machine, such as vibration amplitude, vibration frequency, workload and machine design.

Analysis of these parameters will allow us to determine the optimal values for achieving the maximum quality of products compaction using vibration technology. The results of the study can be useful for engineers, construction contractors and specialists involved in the design or working on compacting the material [11, 12].

This article studies the issue of analyzing the parameters of the vibration machine, which affect the quality of the compaction. One of the key aspects that requires attention is the amplitude of the vibrations, since the magnitude of the vibrations can affect the depth of compaction of the material. Studying the optimum amplitude values can improve the performance of the vibration compaction and ensure uniform sealing over the entire surface.

Thus, taking into account these parameters will help to better understand the vibration compaction process and develop optimal conditions for achieving high quality material compaction.

Problem statement

The purpose of this article is to determine the choice of the best design scheme of the vibrating machine depending on the specific production conditions and dimensions of the molded reinforced concrete products.

Basic material and results

The study covers the analysis of the main materials used in the manufacture of the vibrating machine and their effective role in providing effective compaction [13].

The obtained dependencies determine the nature of the oscillating movements of the movable frame of the vibrating machine and, when the form is rigidly fixed, also attached to its pallet.

Non-rigid fastening of the form and its massive elastic sides make the graphics (Fig. 1), where $\bar{x}_0$ – offset from the center of gravity of the zero point in the first embodiment, $\bar{y}_0$ – offset from the center of gravity of the zero point according to the second option.

Consider the nature of the multicomponent oscillations of the system depending on the amount of displacement of the vibration exciter below the working surface of the movable frame. An absolutely solid body on elastic point supports of constant rigidity is taken as a dynamic model of a vibration installation with a shape rigidly fixed on it (Fig. 2), where $2b_1$ – height of mold rigidly fixed on movable frame of vibration machine, $2b_2$ – height of movable frame, p.1, p.2, p.3 – vibrational movements that are considered.

It is also accepted that the trigger force is the horizontal and angular speed of the shaft is constant. The flat problem is solved in the inertial coordinate system, the beginning of which correlates with the center of gravity of the vibration machine in the static equilibrium position, in accordance with the cross section of the vibration platform.

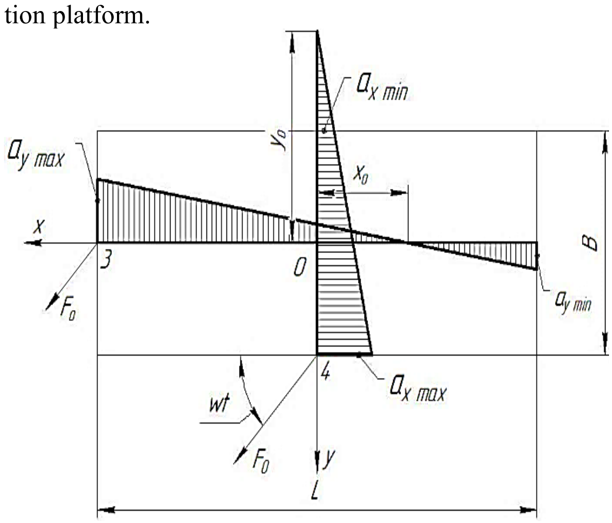

Figure 1 – Nature of vibration amplitude distribution of the movable frame at B/L=0.5

The generalized coordinates are taken:

$x_0(t)$ – coordinates of the system center of gravity;

$\psi_0(t)$ – rotation angle of the system in the plane near the center of gravity.

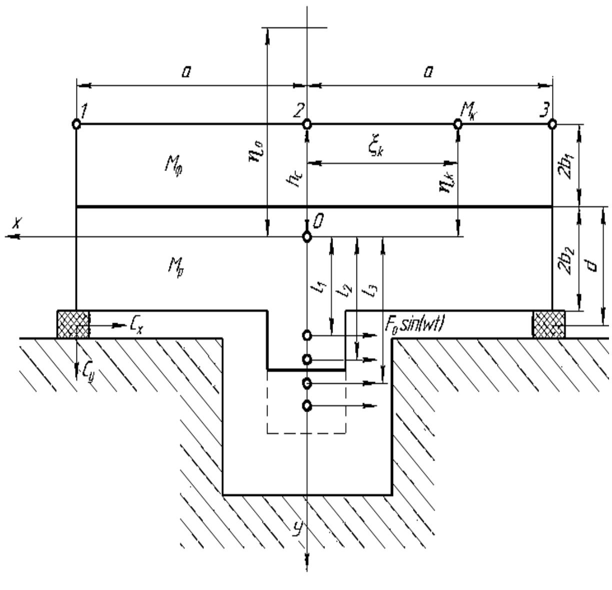

Figure 2 – Scheme of options for applying forced vibrations, relative to the center of mass of the oscillatory system

Neglecting the dissipation of energy in supports and concrete, the differential equations of oscillations of the system are obtained in the form:

$$M_P \cdot \ddot{x}_0 = -2C_x \cdot x_0 - 2C_x \cdot \psi \cdot d + \\ + F_0 \cdot \sin \omega t, \quad (1)$$

$$I_0 \cdot \ddot{\psi} = -2(C_x \cdot d^2 + C_y \cdot a^2) \cdot \psi - \\ - 2C_x \cdot x_0 \cdot d - l_i \cdot F_0 \sin \omega t, \quad (2)$$

where $M_P = M_\phi + M_{PP}$ – mass of the entire system;

M_ϕ – mass of form;

M_{PP} – weight of movable frame;

C_x, C_y – rigidity of point supports in directions of corresponding axes;

l_i – different distances of the point of application of the disturbing force to the center of gravity of the system;

a, d – design parameters.

A partial solution of this system, describing forced vibrations in the resonance constant mode, is:

$$x_0(t) = a_x \cdot \sin \omega t, \quad (3)$$

$$\psi_0(t) = a_\psi \cdot \sin \omega t, \quad (4)$$

where amplitudes of vibration movements are determined by formulas:

$$a_x = \frac{D_x}{D}, \quad (5)$$

$$a_\psi = \frac{D_\psi}{D}, \quad (6)$$

$$D = \omega^4 \cdot M_P \cdot I_0 - \omega^2(2C_x \cdot M_P \cdot d^2 + \\ + 2C_y \cdot M_P \cdot a^2 + 2C_\psi \cdot I_0) + 4C_x \cdot C_y \cdot a^2, \quad (7)$$

$$D_x = F_0[2C_x \cdot d^2 + 2C_y \cdot a^2 - \\ - I_0 \cdot \omega^2 + 2C_x \cdot l_i \cdot d], \quad (8)$$

$$D_\psi = F_0[(M_P \cdot \omega^2 - 2C_x)l_i - 2C_x \cdot d] \quad (9)$$

From the ratios of the values of the main parameters ($M_P, C_x, C_y, I_0, \omega$) of the vibration machine of this type, it follows that in the obtained expressions for the amplitudes of vibration movements, their components are determining their value: $I_0 \cdot M_P \cdot \omega^4$, $F_0 \cdot I_0 \cdot \omega^2$, $F_0 \cdot M_P \cdot \omega^2 \cdot l_i$.

An approximate estimate of amplitude values allows us to conclude that with the removal of the vibration exciter from the center of gravity, the amplitude of the rotary vibration movements increases noticeably, but the amplitude of the horizontal vibration movements slightly decreases.

The increase in coordinates, that characterize the vibrational movements of system points, are determined by equations:

$$\Delta x_k = x_0(t) - \eta_k \cdot \psi(t), \quad (10)$$

$$\Delta y_k = \xi_k \cdot \psi(t), \quad (11)$$

where ξ_k and η_k – constant coordinates, which determine the position of the k-th point in the system, is rigidly connected with the vibrating mechanism. For characteristic points 1, 2 and 3 on the open surface of the form (Fig. 2) are defined as:

$$\eta_1 = \eta_2 = \eta_3 = -h_c, \quad (12)$$

$$\xi_1 = -\xi_3 = a, \quad (13)$$

$$\xi_2 = 0. \quad (14)$$

where h_c – distance to the center of gravity of the system from the open surface of the form and accordingly:

$$\Delta x_1 = \Delta x_2 = \Delta x_3 = x_0 + h_c \cdot \psi(t), \quad (15)$$

$$\Delta y_1 = -\Delta y_3 = a \cdot \psi(t), \quad (16)$$

$$\Delta y_2 = 0. \quad (17)$$

The magnification of coordinate x is zero, that is, horizontal vibration movements are absent at a point that we call "zero" and the coordinate of which we denote η^0. Find the position of this point by putting $\Delta x = 0$, from where:

$$\eta^0 = \frac{x_0(t)}{\psi(t)} = \frac{-I_0 \cdot \omega^2 + 2C_x \cdot l_i \cdot d + 2C_x \cdot d^2 + 2C_x \cdot a^2}{(M_P \cdot \omega^2 - 2C_x) \cdot l_i - 2C_x \cdot d}, \quad (18)$$

As previously called, the magnitude and sign of expressions for a_x and a_ψ are determined by the first components, and therefore it is obvious from equation 18, that $\eta^0 < 0$ and with increasing l_i decreases, that is, with the vibration exciter moving down from the center of gravity, the "zero" point approaches the center of gravity and horizontal vibration movements on the upper surface of the form decrease.

The resulting dependencies can be reduced to a form convenient for calculations. We introduce the following dimensionless coefficients:

$$k_1 = \frac{M_\phi}{M_P}, \quad (19)$$

$$k_2 \frac{b_1}{b_2}. \quad (20)$$

We present $b_1 + b_2 = B$ and express the main characteristics of the vibration machine through these coefficients.

The position of the center of gravity of the machine in relation to the open surface of the form is determined by the distance:

$$h_c = B \cdot \left(\frac{1}{1+k_1} + \frac{k_2}{1+k_2} \right), \quad (21)$$

Moment of inertia of the system correlate with the center of gravity.

$$I_0 = M_P \cdot i^2, \quad (22)$$

$$i^2 = \frac{a^2}{3} + \frac{b^2}{3} \cdot \left[\frac{k_2^2 + 1}{1+k_1} + \frac{3k}{(1+k_1)^2} \right]. \quad (23)$$

Limited to approximate values of vibration movement amplitudes a_x and a_ψ:

$$a_x \approx -\frac{F_0}{M_P \cdot \omega^2}, \quad (24)$$

$$a_\psi \approx \frac{F_0 \cdot l_i}{I_0 \cdot \omega^2} = -\frac{l_i}{i^2} \cdot a_x. \quad (25)$$

Find the increase in coordinates:

$$\Delta x_k = a_x \cdot \left(1 + \frac{l_i \cdot \eta_k}{i^2} \right) \cdot \sin \omega t, \quad (26)$$

$$\Delta y_k = -a_x \cdot \xi_k \cdot \frac{l_i}{i^2} \cdot \sin \omega t. \quad (27)$$

The position of the "zero" point is determined by equality:

$$\eta^0 = -\frac{i^2}{l_i}. \quad (28)$$

Amplitudes of vibration movements of points on the open surface of the mold:

$$a_{1x} = a_{2x} = a_{3x} = a_x \left[1 - \frac{l_i}{i^2} \cdot B \cdot \left(\frac{1}{1+k_1} - \frac{k_2}{1+k_2} \right) \right], \quad (29)$$

$$a_{(1,3)y} = a \cdot a_x \cdot \frac{l_i}{i^2}. \quad (30)$$

The obtained dependencies (Fig. 3) for the vibration system with the following data:

$M_P = 2 \cdot 10^4$ кг; $\quad \frac{M_\phi}{M_P} = 2$;

$2C_x = 9{,}6 \cdot 10^6$ Н/м; $\quad 2C_y = 72 \cdot 10^6$ Н/м;

$\omega = 150$ рад/с; $\quad F_0 = 2 \cdot 10^5$ Н;

$a = 1{,}5$ м; $\quad 2b = 0{,}9$ м.

The results found by the above formulas have good correspondence to natural measurements on several vibration machines with a width of a movable frame $2a \approx 3$м.

Finally, it should be noted that when the vibration exciter is buried under the working surface of the movable frame, it increases the vertical component of vibration displacements near the longitudinal sides of the rigid non-removable frame, increasing the intensity of vibration compaction of the concrete mixture. However, calculations and analytical studies show that the penetration of the vibration exciter by more than 0.6 m under the working surface of a movable formwork with a width of less than 3 m is impractical, since the metal consumption of the vibration machine increases, and the excess vertical component leads to formwork collisions and increased production noise [14].

Selection of the best structural scheme of the vibration machine depending on the specific production conditions and dimensions of the formed reinforced concrete products (Fig. 3).

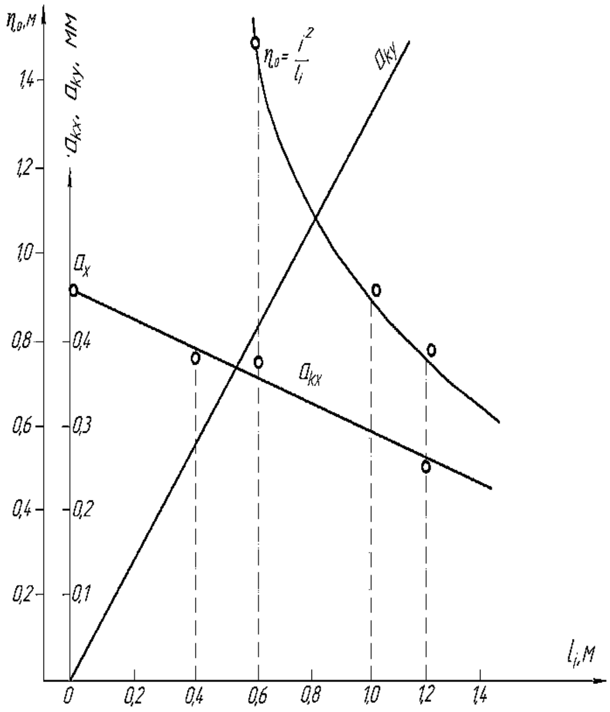

Figure 3 - Dependence of vibration displacement amplitudes at characteristic points 1-3 and position of "zero" point on location of vibration exciter

Conclusions

In this paper, the most rational design schemes of small-sized vibration machines and their optimal dynamic parameters were outlined:

1. When the vibration exciter is located on the vibration machine in the central window of the movable frame and below its working surface, the vibration pattern of the movable frame will be uniform and symmetrical distribution of the displacement amplitudes of the peripheral points of the shape. The vertical component of displacements of the movable frame is noticeable. In this design, the vibration exciter does not protrude above the working surface of the movable frame, which is convenient for conveyor lines. In this case, the central window weakens the cross section of the movable frame, and makes it difficult to access the vibration exciter. It can be recommended for the formation of hollow floor slabs from inactive mixtures.

2. When the vibration exciter is located on the vibration machine at the end of the movable elongated frame and at 100...300 mm above its working surface there is an uneven distribution of displacement amplitudes along the length of the form. Transverse and vertical components are unequal at the ends and smaller in the middle part. Therefor, there is good access to the vibration exciter. Simple and reliable vibration machine design, convenient for open polygons. Recommended for vibration sites and vibration forms that are used for forming long structures from moving mixtures.

3. If the vibration exciter is located on the side and in the middle of the long side of the movable frame, a more even distribution of displacement amplitudes occurs above or below its working surface compared to other cases. Also, the movable frame retains a continuous section in the central part, which contributes to its strength. Good access to the vibration exciter. Asymmetric arrangement of the vibration drive relative to the axis of the vibration platform. Recommended for use on open polygons and for vibration forms.

4. When the vibration exciter is located at the end or at the corner of the equilateral movable frame and raised above its working surface on the calculated value of 400...1200 mm, it is the most distinct multicomponent nature of vibrations of the movable frame and shape with significant vertical components of vibration displacements. There is also good access to the vibration exciter. Conveniently placed in deep pits and open landfills. Simple and reliable vibration machine design. It is recommended for the formation of high volume elements, reinforced concrete pipes, etc.

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Research on modes and operating parameters of construction mixes preparing equipment

Rudyk Rostyslav[1]*, Bidanets Serhii[2]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-8386-977X
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-5346-9545
*Corresponding author E-mail: rostyslavrudyk@nupp.edu.ua

This research paper examines the various modes and parameters of operation of equipment used for preparing mortars in the construction industry. The study emphasizes the significance of ensuring the proper functioning of mixers and mixers on construction sites, as it directly affects the time and energy consumption involved in mortar preparation. The paper discusses different types of mixers, including gravity mixers and concrete mixing buckets, and provides an analysis of their advantages and disadvantages. Additionally, the research presents calculations and formulas for determining the power consumption and energy efficiency of mixers. The findings of the study highlight the necessity for a scientific approach in selecting components based on their energy efficiency in construction site conditions. By considering energy efficiency, construction professionals can optimize the performance of mixers and reduce energy consumption, leading to cost savings and environmental benefits. This research contributes to the existing knowledge in the field and provides valuable insights for decision-making in the selection and operation of mortar preparation equipment in the construction industry.

Keywords: Concrete mixtures, concrete mixer, mortar, preparation, energy efficiency, productivity

Дослідження режимів та параметрів роботи обладнання для приготування будівельних розчинів

Рудик Р.Ю.[1]*, Біданець С.С.[2]

[1]Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[2] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: rostyslavrudyk@nupp.edu.ua

У статті розглянуто різні режими та параметри роботи обладнання, що використовується для приготування будівельних розчинів у будівельній галузі. Ефективне приготування будівельних розчинів має вирішальне значення для своєчасного завершення будівельних проектів і загальної продуктивності галузі. Дослідження підкреслює важливість забезпечення належного функціонування змішувачів на будівельних майданчиках, оскільки це безпосередньо впливає на витрати часу та енергії на приготування розчину. Стаття містить аналіз різних типів змішувачів, які використовуються в будівельній галузі, включаючи гравітаційні змішувачі та ковші для змішування бетону. Кожен тип змішувача оцінюється на основі його переваг і недоліків, враховуючи такі фактори, як простота використання, потужність змішування та вимоги до обслуговування. Результати цього аналізу можуть допомогти фахівцям-будівельникам у виборі найбільш підходящого змішувача для конкретних вимог проекту. Крім того, в дослідженні наведено розрахунки та формули для визначення енергоспоживання та енергоефективності змішувачів. Дослідження також підкреслює важливість врахування енергоефективності при проектуванні та експлуатації змішувачів, оскільки це може призвести до значної економії енергії та екологічних переваг. В результаті досліджень є необхідність наукового підходу до вибору компонентів на основі їх енергоефективності в умовах будівельного майданчика.

Ключові слова: бетонна суміш, бетонозмішувач, будівельний розчин, приготування, енергоефективність, продуктивність

Introduction.

Nowadays, the production of various concrete products in Ukraine requires special attention. Usually, the production of concrete mixtures and mortars takes place at modern enterprises, equipped with highly efficient mechanized means, or directly on the construction site.

In the global construction engineering industry equipment for concrete preparation of various characteristics and purposes is used depending on the characteristics of its further use. However, the importance of the proper functioning of mixers and mixing devices on construction sites is paid with little attention. Therefore, the use of time for the preparation of the finished product and the energy consumption are much higher, compared to the production of similar products in the factory. Due to the limited working space on construction sites, additional equipment is usually required to meet the needs of construction activities.

Review of the research sources and publications.

One of the key aspects of successful mortar preparation is the proper selection of modes and equipment operation parameters. In the modern construction industry, much attention is paid to the efficiency and quality of construction work. Ukrainian [1-4], [10-14] and foreign [16-19] scientists were engaged in the analysis of various structures for the preparation of concrete mixtures and mortars. They were engaged not only in the development of new materials, but also in the search for rational solutions for the process of mixing mortars.

Definition of unsolved aspects of the problem

One of the main problems when mixing mortars on the construction site, which constantly needs to be addressed or improved, is the problem of energy efficiency.

There is a need to investigate the effective use of automation and control systems, which can help in optimizing energy efficiency during the concrete mix preparation process.

Insufficient theoretical grounding of the energy parameters of work processes related to the preparation of concrete mixtures from the point of view of efficient use of consumed power and reduction to a rational level of energy intensity at all stages does not allow the creation of effective technological sets of equipment for various construction conditions. This restrains the development of high-performance technologies for construction work on the construction site.

Problem statement

The purpose of this work is to investigate the modes and operating parameters of equipment for preparing construction mixes and to optimize the construction process with a focus on energy efficiency.

To achieve this goal, it is necessary to analyze the main methods of preparing mortars and methods for determining the energy efficiency of the equipment used for mixing, determine the advantages and disadvantages of such equipment and methods for calculating energy efficiency, determine the further vector of research.

Basic material and results

Using different mixers to prepare concrete mortar directly on the construction site has become a common practice in the construction industry. This opens up opportunities for optimizing the construction process and ensures the high quality of concrete structures. Different types of faucets are used depending on the specific requirements and needs of the construction project.

Mixers on the construction site allows to precisely control the composition of the concrete mixture and consistency, which makes it possible to create rational conditions for a specific construction task. This practice simplifies the process of making concrete, allowing you to quickly adjust and adapt the mixture to changing construction conditions [6].

On-site mixers also help reduce the cost of transporting the finished concrete mix from the plant, which improves production efficiency. They avoid overproduction and store concrete in the required quantities, which helps to save resources.

In general, the use of concrete mortar mixers directly on the construction site is an important component of modern construction [9]. It simplifies the construction process, increases quality control and allows efficient use of resources, ensuring high productivity and reliability of construction projects. Gravity and forced mixers, which differ in the principle of operation, mobility and mixing method, have become widely used.

One of the most common types of equipment for the preparation of concrete mortars on a construction site is a gravity mixer (Fig. 1). In gravity mixers, materials are mixed in a rotating drum with blades fixed on the inner surface. As the drum rotates, the material is captured and lifted by the blades, and then, due to the action of gravitational forces, it moves down.

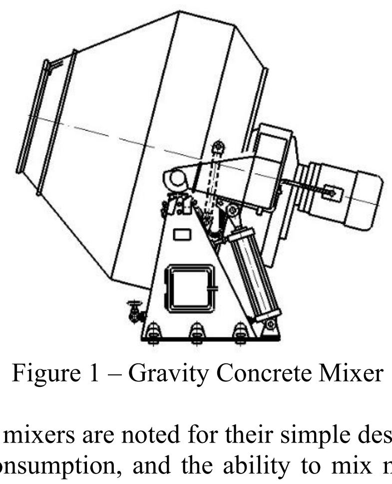

Figure 1 – Gravity Concrete Mixer

Gravity mixers are noted for their simple design, low energy consumption, and the ability to mix materials with large particulate matter. However, they also have their disadvantages, such as the relative duration of the mixing process and the difficulty of achieving complete homogeneity of the mixture when mixing materials that are rigid and have a fine-grained structure.

Concrete mixing buckets are also widely used (Fig. 2). These are special devices designed for mixing concrete, cement mixtures and other building materials directly on the construction site, using the power and mobility of the chassis on which they are installed (tractor, own self-propelled).

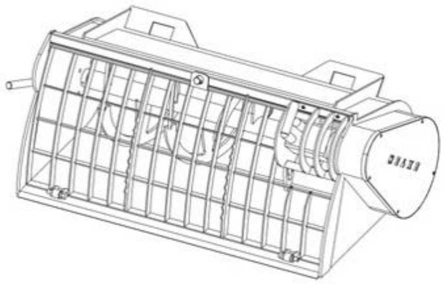

Figure 2 – Concrete mixing bucket

The front loader operator loads the necessary mixing components into the bucket. After that, the bucket rises above ground level and the rotation of the working body inside the bucket begins. This mixing takes place under conditions of high speed and intensity to ensure homogeneous mixing of materials. Due to the mobility of the chassis on which it is installed, it is possible to move the concrete mixture around the construction site at the time of mixing.

The advantages of this equipment are mixing efficiency, quality control and mobility. And the disadvantages are the difficulty of cleaning to avoid contamination of subsequent mixtures and the dependence on an excavator, which is sometimes not suitable for all construction projects.

When comparing these mixers, you need to take into account that they have different designs, mixing times and energy efficiency, and the technical performance of the mixers is determined according to their volume and mixing time:

$$\Pi = \frac{3600 \cdot V_n}{t_c} = 3600 \cdot \frac{V_n \cdot k_{mwb} \cdot k_f}{t_{pr} + t_{pu} + t_{dt}}$$

where, Π – mixer performance, m^3/h;
t_c – cycle time duty, s;
V_n – volume of the finished mixture, m^3;
k_{mwb} – coefficient that takes into account the volume of the mixer's working body (k_{mwb} = 0,92…0,98);
k_f – coefficient filling the faucet body with mortar;
t_{pr} – mix preparation duration, s;
t_{pu} – mix pumping duration, s;
t_{dt} – downtime and maintenance time, s.

Most of the works [10-11] devoted to mixing considered the processes of movement and mixing of building mixtures, the identification of the efficiency of mixing, and the catalyzing of chemical processes. Only a small part of the work relates to the study of the movement and suspensions and other viscoplastic bodies mixing.

In the works of foreign scientists [5], the rational diameter ratio, blade width and mixer body size, as well as the dependence of power and efficiency of mixing on the speed were established. To calculate the power, W, the following formula was proposed:

$$P = 9{,}81 \cdot C \cdot (D + 4H) \cdot \sin(1{,}13\alpha - 12) \cdot \rho^{0,79} \cdot \mu^{0,21} \cdot n^{2,79} \cdot D^{3,58}$$

where C – resistance coefficient;
D – mixing ladle diameter, m;
H – mixing ladle height, m.
ρ, μ – density and viscosity of the medium to be stirred;
n – blade rotation speed;
α – indicator of the degree depending on the mixing conditions.

In research, the equation of energy consumed for mixing is presented in the form of a functional dependence on the criteria of Reynolds and Froude.

Most scientists have come to the conclusion that when determining the power consumption during the mixing of viscous liquids, the most significant influence is exerted by the Reynolds criterion.

The intensity of the mortar mixer action is characterized by the time required to achieve a specific technological result at a constant speed of rotation of the working body or vice versa. According to the work [14], the intensity of mixing can be determined using the angular velocity of the working body ω, rad/s; linear velocity of the working body on the outer diameter, V, m/s; power P, W, which is spent on mixing, which is reduced to a unit of volume or a unit of mass of the mixture; Reynolds' criterion

$$R_e = \frac{\omega \cdot d^2 \cdot \rho}{\eta}$$

where d – diameter of the mixer working body, m;
ρ – density kg/m^3;
η – structured viscosity coefficient, Pa·s.

As mentioned earlier, mixing efficiency is characterized by the amount of energy expended to achieve the desired technological effect. Of the two mortar mixers, the one that achieves a certain technological effect at lower energy consumption will be more efficient. To select the optimal size and operating modes of mortar mixing plants, it is also necessary to apply the mixing efficiency.

In studies, the following formula is provided to calculate power

$$P = \frac{4{,}33 \cdot D^{4,57} \cdot n^{2,78} \cdot \rho^{0,78} \cdot \mu^{0,22}}{10^6}, \text{ Kw}$$

It is clear that in the study of fluid flow in each case it is necessary to take into account the most significant principal factor. In some cases, it is not possible to take into account the Reynolds and Froude criteria at the same time. If the mixer blades are completely immersed in the solution, then the main importance is Re. The forces of gravity will be negligible, so in some cases the Froude criterion can be ignored.

According to the conducted analysis, the method of calculating screw-type mixers was used, the starting point of which is Newton's law. The proposed dependencies for calculating the power of mixers can be presented in the general case

$$P = \frac{\pi^3 \cdot \gamma}{60^3} \cdot \psi \cdot b \cdot n^3 \cdot \left(r_{out}^4 - r_{in}^4\right), \text{Kw}$$

where r_{out}, r_{in} – outer and inner radiuses of the blade, respectively;

γ – indicator of the degree depending on the mixing conditions;

b – blade width.

ψ – initial current phase.

In the study of the main regularities of fluid movement in mixers, the importance of certain components that significantly affect the design power was revealed, namely, the shape of the free surface, the distribution of flow rates, the circulation pattern and the dependence of the above phenomena on the design and kinematic parameters of the mixers. The values of the drag coefficients are set depending on the ratio of the blade size and their number. Therefore, the specific power consumption per unit volume of the mixture is in the ratio

$$P^{/} = \frac{A}{D^m}, \text{Kw/l}$$

where A – constant ratio;

D – mixer blade diameter, m.

Analyzing this expression, it can be concluded that the specific power consumption decreases with an increase in the blade diameter, and therefore the hopper size.

In the study of energy indicators [12], namely, the specific energy consumption of mixers of cyclic forced action, it is proposed to calculate the value by the formula

$$q_e^{/} = \frac{P_e}{V}, \text{W/l}$$

where P_e – power on the mixer drive shaft, W;

V– mixer hopper volume, l.

It has been established that the value of the $q_e^{/}$ has some deviations from the mean. Of particular interest are the unexplored deviations of the magnitude q_e from the average towards a decrease in specific energy consumption. Dependence analysis of mixers power and other parameters of the volume can be used for the predictive calculation of mixers, therefore, it is proposed to use the dependence of the drive power on the volume of the mixer to assess the technical level of existing mixer designs. It has been determined that the technical characteristics of the existing equipment do not take into account a number of design and technological indicators.

According to the studies analysis of the relationship between specific energy consumption $q_e^{/}$ of installed electric motors and mixer capacity V by different types of domestic production. According to the results of the research [12] a dependency graph $q_e^{/} = f(V)$ was obtained, shown in Fig. 3. It was concluded, that by deviation of the $q_e^{/}$ value, gravity cyclic mixers have less than cyclic forced mixers.

Specific energy consumption $q_e^{/}$ of cyclic forced mixers have a significant range of values. This confirms the assumption that there is no unified method for calculating the energy performance of cyclic forced mixers.

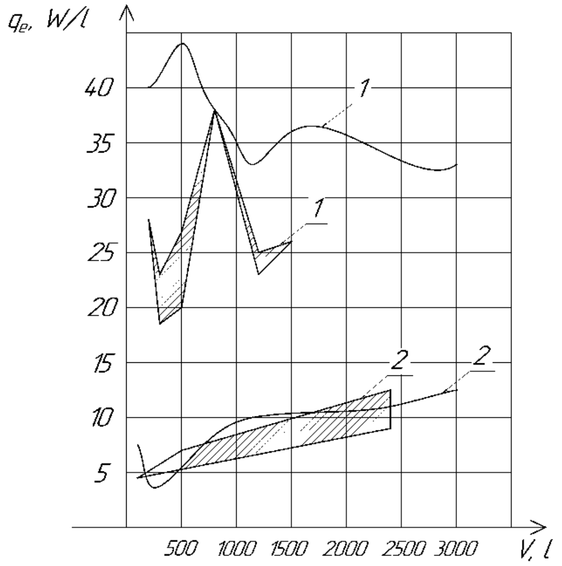

Figure 3 – Dependence of specific energy consumption on forced volume *1* and gravity *2* cyclic mixers $q_e^{/} = f(V)$

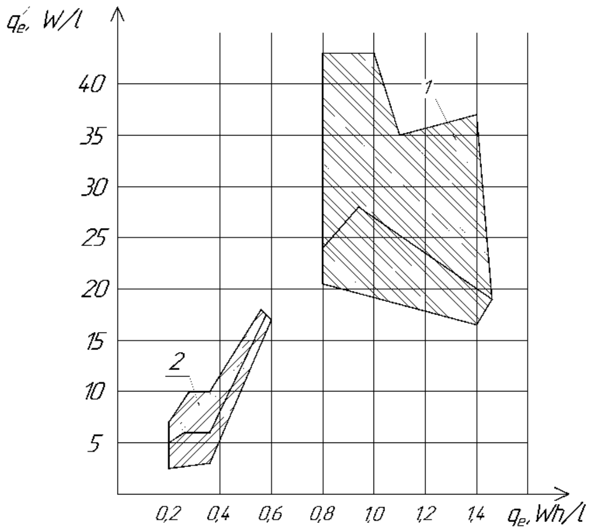

Figure 4 – Dependence of specific energy consumption on the relative power consumption of forced *1* and gravitational *2* cyclic mixers $q_e^{/} = f(q_e)$

Figure 4 shows a graph of dependency $q_e^{/} = f(q_e)$, that is, the specific energy consumption from the relative power consumption, which is determined by the following formula

$$q_e = \frac{P_e}{\Pi}, \text{W/l}$$

where Π – mixer productivity, l/h.

A decrease in specific energy consumption is associated with a decrease in relative power consumption. This allows to assert that it is not enough to know the power of the drive to assess the efficiency of mixers, since energy consumption depends on the power of the electric motor, its efficiency, power reserve factor and mixing time [13].

Most studies show that for concrete mixtures, the energy consumption for mixing depends on the speed of rotation in the first and second powers, for liquids the power indicator is three or four.

There is a need to develop a methodology that includes design features, working bodies, modes of their operation, total energy consumption in the conditions of work on the construction site.

Conclusions

As a result of the research, an analysis was conducted on the main methods of preparing mortars and the energy efficiency aspects of different mixing methods. Promising approaches to enhance the manufacturing process of mortars in the construction industry were identified. Considering the advantages and disadvantages of various mixing methods and their energy efficiency, it can be argued that developing a scientific approach to component selection based on the highest energy efficiency in construction site conditions is both possible and necessary.

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Improving the efficiency of the screw unit of plastering plants

Salnikov Roman[1]*, Rudyk Rostyslav[2]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0009-0001-0408-4358
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-8386-977X
*Corresponding author E-mail: itm.rsalnikov@nupp.edu.ua

The article focuses on enhancing the efficiency of screw units in small-sized plastering installations for pumping mortars within the construction industry. It delves into the analysis of existing plastering unit structures, evaluating their respective advantages and disadvantages. Additionally, the article provides an overview of various mortar pumps and their associated parameters. A key objective of the study is to conduct a comparative analysis of current small-sized plastering unit designs and to elevate the effectiveness of mortar pumping. Mathematical models are presented to determine coefficients that consider the non-uniformity of conditions for the concrete mixture's end, as well as the necessary pressure for optimal filling of the working cylinder with the concrete mixture. Furthermore, the article explores the utilization of innovative technologies and materials to enhance the efficiency and functionality of the screw unit.

Keywords: screw unit, plastering unit, mortar, productivity, pumping, mortar pump

Підвищення ефективності роботи гвинтового вузла штукатурних установок

Сальніков Р. Ю[1*]., Рудик Р. Ю[2]

[1]Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[2] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: itm.rsalnikov@nupp.edu.ua

У статті розглядається критична необхідність підвищення ефективності гвинтових агрегатів у малогабаритних штукатурних установках для перекачування розчинів у будівельній галузі. Проводиться комплексний аналіз існуючих конструкцій штукатурних агрегатів, оцінка їх відповідних переваг і недоліків. Крім того, у статті пропонується ретельний огляд різних типів розчинонасосів і пов'язаних з ними параметрів, що забезпечує цілісне розуміння поточних технологій перекачування розчинів. Основним завданням дослідження є проведення порівняльного аналізу існуючих конструкцій малогабаритних штукатурних агрегатів, основною метою якого є підвищення ефективності процесів перекачування розчину. Це включає в себе детальний аналіз операційних механізмів і показників продуктивності цих підрозділів з метою визначення областей для вдосконалення та оптимізації. У статті також введено математичні моделі, які відіграють вирішальну роль у визначенні коефіцієнтів, що враховують нерівномірність умов кінцевого стану бетонної суміші. Ці моделі допомагають розрахувати необхідний тиск для оптимального наповнення робочого циліндра бетонною сумішшю, тим самим сприяючи загальній ефективності та результативності процесу перекачування. У статті досліджено застосування інноваційних технологій і матеріалів для підвищення ефективності та функціональності шнекового агрегату. Впроваджуючи передові досягнення та матеріали, мета полягає в тому, щоб підвищити продуктивність і експлуатаційні можливості штукатурних установок малого розміру, що в кінцевому підсумку призведе до покращення процесів перекачування розчину в будівельній галузі. Підсумовуючи, стаття є цінним ресурсом для професіоналів, дослідників і зацікавлених сторін у галузі, які прагнуть підвищити ефективність штукатурних установок малого розміру та оптимізувати процеси перекачування розчину в будівництві. Він містить повний огляд поточного стану штукатурних установок і технологій накачування розчину, а також пропонує розуміння можливих областей для вдосконалення та інновацій.

Ключові слова: гвинтовий вузол, штукатурний агрегат, будівельний розчин, продуктивність, перекачування, розчинонасос

Introduction.

Improving the efficiency of the screw unit of small-sized plastering installations for pumping mortars is an urgent problem in the field of construction technology and engineering. Ensuring high-quality and productive operation of these plants is essential for the construction industry, which is constantly developing and improving. Today's construction sector faces a number of challenges, including increased competition, the need to reduce costs and increase productivity. One of the ways to solve these problems is to improve the equipment and technologies used at construction sites. Screw assemblies in small plastering plants are a key component for supplying mortars, and their efficiency can have a significant impact on workflow productivity. However, in order to achieve maximum productivity and quality of work, it is necessary to take into account various aspects, such as the design of the screw assembly, the properties of mortars, the parameters of the working environment and other factors. It is also important to select rational materials and technologies for the manufacture of screw assembly components. In this study, we will investigate various aspects of improving the efficiency of the screw unit of small-sized plastering plants for pumping mortars. The article discusses the types of plastering and finishing works, types of plastering installations and mortar pumps, analyzes the existing designs of plastering units, analyzes their advantages and disadvantages.

Review of the research sources and publications.

Furnishing works in construction make up about 35% of the total labor intensity of works, and they use a wide range of technologies and materials.

Ukrainian scientists were also engaged in the development and improvement of various types of mortar pumps for pumping mortars. Nazarenko I.I. [1], Onyshchenko O.G. [1.3], Yemelyanova I.A. [10-13] Korobko B.O. [7] are the most famous among them.

Publications provide a comprehensive overview of the current state of plastering units and mortar pumping technologies, while also offering insights into potential areas for improvement and innovation. The sources cover a wide range of topics related to the efficiency of screw units in small-sized plastering installations for pumping mortars within the construction industry.

Definition of unsolved aspects of the problem

There is a need for standardized guidelines or industry standards for the design and performance of small-sized plastering plants. The lack of universally accepted standards can lead to differences in efficiency and effectiveness across departments.

There is a lack of comprehensive understanding of the integration of advanced materials, such as high-performance polymers or composite materials, into the design of screw assemblies to improve durability and performance.

There is a need for further research to optimize pumping parameters to achieve the most efficient injection processes.

Addressing these unresolved aspects will contribute to the comprehensive improvement of screw assemblies in small plastering plants, resulting in more efficient and sustainable mortar pumping processes in the construction industry.

Problem statement

Comparative analysis of existing designs of small-sized plastering units, with further increase in the efficiency of pumping mortar.

Basic material and results

Today, two types of solution pumps are used: screw pumps and hose pumps.

Hose solution pumps (Fig. 1, a) allow for a continuous supply of the pumped mixture [4]. The working body of such a pump is a piece of elastic hose along which two or more rollers roll, deforming the hose, completely blocking the passage area under the roller, continuously pushing the solution into the mortar pipeline. The mixture is sucked in due to the elastic properties of the elastic hose. For better recovery of the hose dimensions in cross-section, a vacuum suction circuit is used and the entire mechanism is placed in a sealed chamber. This greatly complicates the design of the pump and its maintenance.

Hose mortar pumps are mainly used for pumping mortars that occupy an intermediate position between plaster mortars and concrete mixtures with a fraction size of up to 7 mm.

The scope of application of hose solution pumps is limited by economic feasibility due to the very short service life (less than 20 hours) of the main working body — the hose. When operating under a vacuum-free suction scheme, the hose quickly loses its elasticity, which leads to the loss of performance of the solution pump.

Screw pumps (Fig. 1, b) are used for pumping plaster mortars. The main features of the pump are uniformity of flow, compactness, simplicity of design and operation and light weight. The pump assembly of a single screw pump includes a cast iron or steel single-head screw with a specific pitch and a rubber cage with an elastic working surface. The propeller receives rotation from the electric motor through a gearbox. The cross-section of a screw is a circle, the center of which is shifted relative to the axis of the screw by an amount of eccentricity. The working surface of the cage is a double-threaded screw with a pitch twice that of a steel thread. Due to this design, when the working surfaces of the screw and the cage come into contact, a closed line is formed, the totality of which limits the closed chambers. During the rotation of the screw, the chambers are filled with the mixture to be transported and move continuously along the axis of the screw from the hopper to the discharge nozzle. Unlike reciprocating pumps, screw pumps do not have valves. The tightness of the chamber is ensured by tension in the connection of the screw with the elastic cage.

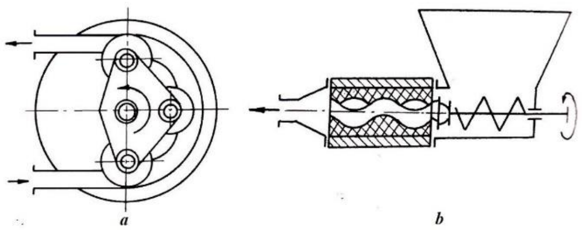


Figure 1 – Diagram of hose (a) and screw (b) solution pumps

Recently, screw solution pumps have become more widely used, but depending on the manufacturer, they may not be economically feasible or have a low capacity. Therefore, it is advisable to improve the existing design.

On construction sites, various plastering units with screw mortar pumps are used, one of which is SO-152 [1]. It provides filtering, feeding and application of plaster mortars to the surface to be treated. The SO-152 unit, complete with a compressor unit, can carry out surface coating by spraying. It consists of two compact main units: a mortar pump and a receiving hopper with a vibrating sieve. Both nodes are connected to each other by a rubber-fabric sleeve with a quick coupling.

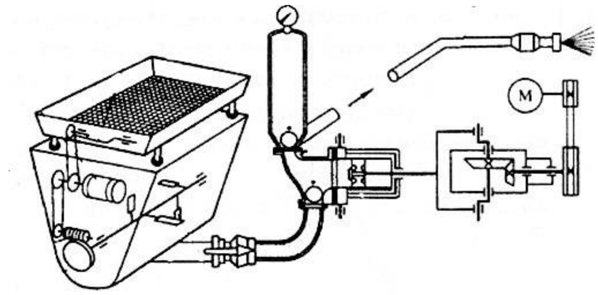


Figure 2 – Diagram of the plastering unit SO-152

The finished solution, delivered to the place of work, is unloaded onto a vibrating sieve. The vibrator provides 50 Hz oscillations to a movable frame with a sieve set at an angle of 5° to the horizontal, for convenient removal of large inclusions, that did not pass through the sieve cell. The solution filtered through a vibrating sieve enters the receiving hopper, and from there through the suction hose to the working chamber of the mortar pump. It is then fed through a pressure solution pump to the nozzle and applied to the treated surface.

The advantages of this design of the plastering unit are compactness for ease of transportation from one workplace to another and the presence of a vibrating screen, which allows you to prepare a mortar with aggregates of certain fractions.

The disadvantage is the division of the structure into two units mounted on independent frames, which leads to an increase in the bulkiness and cost of such equipment. The performance and pressure figures generated by the mortar pump are also insufficient for a wide range of uses of this equipment.

Plastering unit SO-150 is designed for surface application of putty mixtures, primers or water-adhesive paints on treated surfaces. The plaster is applied with a fishing rod using compressed air, and the primer and paint are applied with a pressure pump.

The unit is built on the basis of a screw pump with a loading hopper, a feed hose with a fishing rod and an electrical cabinet. The unit is driven by a two-speed electric motor through a V-belt transmission and a gearbox. At the bottom of the hopper there is a conveyor that mixes the inlet mixture and directs it to the suction part of the pump.

The disadvantage of putty units is their low productivity and unsuitability for supplying slow-moving and dry mixtures.

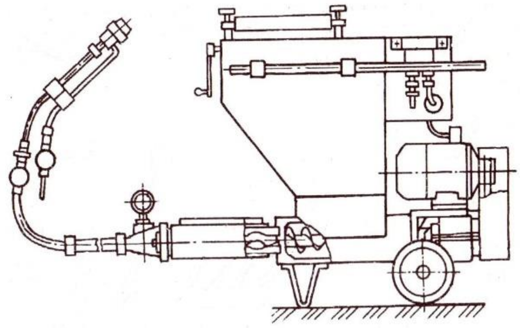


Figure 3 – **Diagram of the SO-150 plastering unit**

Plastering unit SO-154A is designed for the preparation of finishing mortars both from ready-made dry mortars and from its constituent components, which are loaded directly into the unit; transportation of ready-made solutions through pipelines; mechanized application to the work surface [2]. The unit can prepare and transport water-based priming and painting solutions, oils and adhesive putties. It is equipped with a mortar pump, a vibrating sieve, and a device for applying a coloring compound.

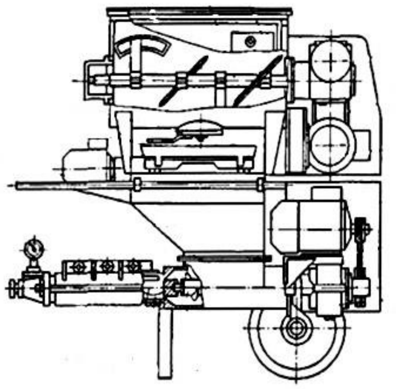
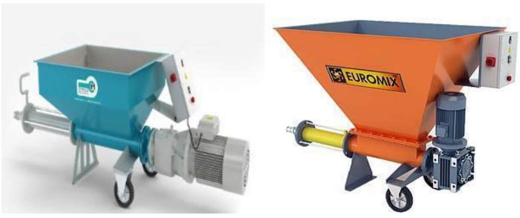


Figure 4 – Diagram of the plastering unit SO-154A

Next to the hopper is an electric motor, from where the movement is transmitted to the blade shaft by means of a V-belt transmission and a worm gearbox. Under the agitator there is a vibrating sieve with a replaceable flat sieve, which is driven by another electric motor of low power. The screw pump, located under the vibrating sieve, consists of a receiving hopper with a screw and a clamp with a screw and clamp at the bottom. The pump drive includes an electric motor, a gearbox and a V-belt drive. There is a pressure gauge on the pump housing.

Screw mortar pumps SO-78 and EUROMIX 400 are used for pumping fine-grained concrete mixtures with aggregate size up to 10 mm. But their disadvantage, as well as the SO-154A plastering unit, is that when working with abrasive mixtures, the fixed elastic clamps and screws of the mortar pump wear out quickly.



a b

Figure 5 – Screw solution pumps:
a) SO-78, b) EUROMIX 400

Universal plastering machine USHM-150 prepares plaster, gypsum, lime-cement and cement-sand mortars from dry components, filters them through vibrating sieves, transports them through mortar pipelines and applies them to the treated surfaces under the influence of compressed air.

Figure 6 – Universal plastering machine USHM-150

The advantages of such an installation include versatility. The disadvantages include the small volume of the working chamber of the mixer, increased power consumption and overall dimensions, weight.

Plastering machine T-101 based on a screw pump is a mobile small-sized high-performance machine of continuous and cyclic action, working with ready-made dry mixes [2]. It is designed for the preparation and application of plaster mortars on prepared treated surfaces.

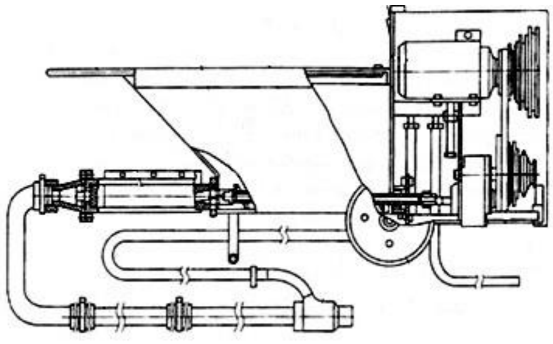


Figure 7 – Plastering machine T-101

The disadvantage of the plastering machine is the impossibility of preparing the plaster mortar directly in the hopper from individual components, which significantly reduces the scope of its application. Stepped speed adjustment is time-consuming and takes time to change the position of the drive belt on the pulleys.

The PFT G4 plastering machine is used for kneading, feeding and applying mortars to vertical and horizontal surfaces [3].

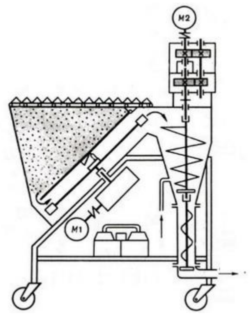


Figure 8 – Diagram of the PFT G4 plastering machine

PFT G4 prepares and injects mortars from dry components, which significantly reduces its versatility on the construction site. The receiving hopper has a capacity of 150 litres and must be constantly replenished with the components of its chamber.

The PFT ZP 3 XL MIX unit (Fig. 9) is used for the preparation and delivery of mortars to construction sites. Plaster or masonry mortar prepared in the built-in mixer is supplied directly to the facility. The capacity of the pump is adjusted depending on the concentration of the solution. The unit can be switched on and off using the remote control.

With small volumes of work or a significant distance from the mortar plant to the construction site, it is recommended to use plastering and mixing plants with mortar pumps and plastering units [4]. In this case, the preparation of mortar is carried out directly at the construction site, which significantly reduces the consumption of working materials.

Figure 9 – Plastering station
PFT ZP 3 XL MIX

The disadvantage of plastering stations is that gravity mixers are inefficient for plaster lime-sand mixtures, have low productivity, limited transportation range and high cost.

The PFT SWING L screw mortar pump has a short service life of the screw feeder, is unsuitable for supplying slow-moving concrete mixtures and has a high cost.

Figure 10 – Screw Solution Pump
PFT SWING L

The pressure generated by the screw can be determined at the distance to which the mixture is supplied under the pressure of the working piston of the pump with the suction valve open. When calculating the parameters, air resistance was not taken into account, because the frontal air resistance at speeds of 5 m/s is insignificant, and the change in velocity for a jet with a diameter of 45 mm and the density of the mixture from 2300 to 2500 kg/m^3 will be less than 1 [4]. At the same time, the unit of the mortar concrete pump, including a loading hopper with a screw and with a suction valve body, is considered at a height of 1 m (Fig. 11).

The velocity of the concrete mixture flow jet (m/s) discharged through the open suction valve can be determined by the Torricelli formula [10]:

$$v = k_{c.m.} \cdot \sqrt{2gH_{c.m.}} \tag{1.1}$$

where H – height of the column of concrete mixture that creates overpressure, m;

$k_{c.m.}$ – a coefficient that takes into account the non-identity of the conditions for the end of the concrete mixture;

g – acceleration of gravity.

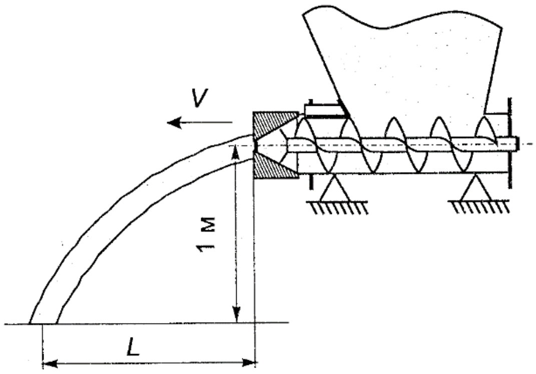


Figure 11 – Diagram of a loading hopper with a screw shaft and a stirrer

As a result of mathematical processing of experimental data, taking into account the factor of mobility of the concrete mixture P_1, a second-order mathematical model was obtained, which allows to determine the coefficient $k_{c.m.}$, which takes into account the non-identity of the conditions for the end of the concrete mixture [8].

$$k_{c.m.} = [8,185 - 0,590P_1 + 0,113P_1^2] \cdot 10^{-2} \tag{1.2}$$

Using Torricelli's formula and the conditions of the experiment in the presence of forced loading of the machine, it is also possible to determine the required pressure that ensures the maximum filling of the working cylinder with concrete mixture, using the dependence:

$$P_w = \frac{L^2 \cdot g \cdot \rho}{k_{c.m.} \cdot 2H \cdot 2} = \frac{L^2 \cdot g \cdot \rho}{k_{c.m.} \cdot 4H} \tag{1.3}$$

where: $k_{c.m.}$ – a coefficient that takes into account the non-identity of the conditions for the end of the concrete mixture;

L – the distance to which the jet of concrete mixture is supplied, m;

ρ – mixture density, kg/m^3.

The presence of forced loading when using slow-moving concrete mixtures makes it possible to ensure a denser filling of the working cylinder with the mixture, therefore, to achieve a higher volumetric coefficient of efficiency, as well as to ensure the operation of the pump, compared to the existing ones, with increased productivity. The change in the productivity of a mortar concrete pump with forced loading depending on the mobility of the concrete mixture is evidenced by the data shown in the figure 12.

The issue of increasing the efficiency of the screw unit of small-sized plastering installations for pumping mortars is quite relevant and important for the construction industry, because it can have a positive effect on the quality and timing of construction, as well as reduce the cost of labor and materials [9].

One of the important factors is also to conduct research on the geometry of the propeller, which determines the direction and speed of movement of the pumped material. It depends on the diameter of the screw, the pitch and the angle of inclination of the tooth, which, with the right calculations, can ensure maximum fluid flow with minimal energy losses due to friction.

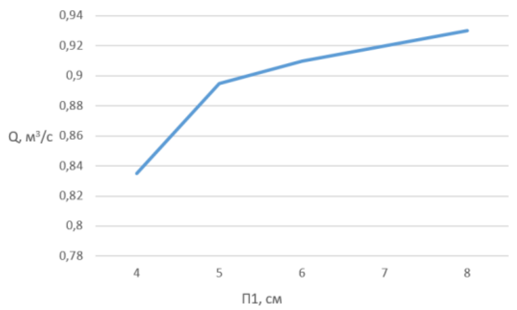


Figure 12 – Dependence of the performance of a forced-loading mortar pump on the mobility of the concrete mixture

The use of automatic control systems will ensure optimal parameters for pumping mortars, depending on their characteristics and operating conditions of the screw unit. Wireless data transmission and screw control systems can also be used, which will provide more accurate and efficient control of the pumping process.

The use of these technologies makes it possible to provide more accurate and efficient control of the process of pumping mortars, reduce the cost of energy supply of the screw unit, increase its service life and reduce the cost of maintenance. In addition, the use of innovative technologies makes it possible to increase the safety of the screw unit and reduce the risk of accidents.

Conclusions

An analysis of existing structures for pumping mortars and other mortars using screw assemblies and their technical characteristics was carried out and the main problems and shortcomings were identified.

To improve the operation of the unit, first of all, it is proposed to use screw assemblies made of polymeric materials, which will ensure greater strength and wear resistance of the elements of the unit, as well as reduce its weight and energy supply costs.

Maintaining the correct operation of the unit will reduce the loss of solution and ensure better pumping of components. This can be ensured by adjusting the speed of rotation of the unit, pressure and temperature of the solution.

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The improved soil base model for the calculation of the combined raft pile foundation with the structural nonlinear behavior of the elements

Samorodov Oleksandr[1*], Tabachnikov Serhii[2], Dytiuk Oleksii[3], Bondar Oleksandr[4]

[1]O.M. Beketov National University of Urban Economy in Kharkiv; https://orcid.org/0000-0003-4395-9417
[2]O.M. Beketov National University of Urban Economy in Kharkiv; https://orcid.org/0000-0002-2619-8612
[3]O.M. Beketov National University of Urban Economy in Kharkiv; https://orcid.org/0000-0001-8363-6132
[4]O.M. Beketov National University of Urban Economy in Kharkiv; https://orcid.org/0009-0006-8468-6805
*Corresponding author E-mail: osamorodov@ukr.net

The paper considers and theoretically justifies the improved model of the soil base for the combined raft pile foundation (CRPF) to consider the nonlinear behavior of the elements "after" and "before" the connection between the raft and the piles (structural nonlinearity) to calculate the stress-strain state using the finite element method in present-day calculation packages. Using the improved model makes it possible to qualitatively simulate the behavior of the CRPF with the structural nonlinearity in the behavior of its elements. The simulation and numerical calculation of the base-CRPF system was performed using a specific example and it was found that the application of the proposed model with consideration to the structural nonlinearity of the behavior of the foundation elements reduces the moment forces in the raft to 15% in comparison with the application of the full load at once and the behavior of the raft with the permanent connection between the raft and the piles

Keywords: soil base, model, combined raft pile foundation, methodology, stress-strain state

Удосконалена модель грунтової основи для розрахунку комбінованого плитно-пальового фундаменту з конструктивної нелінійністю роботи елементів

Самородов О.В.[1*], Табачніков С.В.[2], Дитюк О.Є.[3], Бондар О.П.[4]

[1, 2, 3, 4] Харківський національний університет міського господарства ім. О.М. Бекетова

*Адреса для листування E-mail: osamorodov@ukr.net

У статті пропонується та теоретично обґрунтовується удосконалена модель грунтової основи комбінованого плитно-пальового фундаменту для врахування нелінійної роботи його елементів «до» та «після» з'єднання плити та паль (конструктивна нелінійність) для розрахунку методом скінченних елементів напружено-деформованого стану у сучасних розрахункових комплексах. Використання удосконаленої моделі дає змогу якісно моделювати процес поведінки КППФ з конструктивною нелінійністю роботи його елементів. Результатом є отримання надійних результатів щодо напружено-деформованого стану системи «основа – фундамент – споруда». На конкретному прикладі виконано моделювання та чисельний розрахунок системи «основа – КППФ» із використанням лінійно-пружної моделі грунту та нелінійної моделі Мора-Кулона. Аналіз отриманих даних показує, що різниця у результатах складає не більше 2%. За критерій оцінки впливу запропонованої комбінованої моделі грунтової основи при розрахунках різних фундаментів прийнято суму згинальних моментів уздовж плити $\Sigma|M_x|$. Встановлено що врахування 2-х етапного формування НДС КППФ із застосуванням запропонованої моделі зменшує моментні зусилля у плиті на 2-му (останньому) етапі до 15% у порівнянні з прикладанням одразу повного навантаження і роботою плити у якості ростверку з постійним з'єднанням плити та паль (один етап). За результатами розрахунків встановлено, що при сприйнятті плитною частиною 100% навантаження та інших рівних умовах моментні зусилля у плиті завжди менші ніж у випадку з'єдання паль з плитою, що відбуваєтья через відсутність значної концентрації зусиль у кутових та периферійних палях у разі роботи плити як ростверку

Ключові слова: грунтова основа, модель, комбінований плитно-пальовий фундамент, методика, напружено-деформований стан

Introduction

In modern geotechnics, with the advances of information technology and the availability of powerful software packages for the calculation of the entire base-foundation-building (BFB) system, one of the main research areas is the development, improvement and research of soil base models to ensure adequate interaction between the components of the system during the construction and operation of structures (buildings).

It is generally known that to obtain reliable and valid results of the stress-strain state calculation for the foundation designs in the BFB system, a model of the soil base with appropriate parameters should be chosen that is close to the behavior of the actual soil medium by two criteria: distribution capability and deformability of the foundations of buildings.

Review of the research sources and publications

Back in the last century, the model of the soil base in the form of a continuous linear elastic layer was widely used in engineering calculations of bases and foundations, as it was provided by the national building code [1, 2] and required only setting the thickness H of the layer (compressible thickness) and the stress-strain properties of the soil (the total strain modulus E and Poisson's ratio v). Furthermore, this analytical model had no constraints in plan. Today, with the expansive growth of information technology, when simulating and performing numerical calculations of the BFB system in the powerful calculation packages such as SOFiSTiK, ABAQUS, Plaxis, SCAD, Lira and others, the three-dimensional formulation generally uses a soil base model in the form of a *continuous layer of finite distribution capability* (Fig. 1) [12-22] (the concept is introduced for the first time), which, in addition to the vertical strain constraints at a certain depth H, also has the horizontal strain constraints at a certain distance from the load in plan ($L_x \times L_y$).

These boundary conditions for the model are based on the fact that under the action of external loads on the soil base a spatial stress-strain region is formed, beyond which the soil strains can be neglected, since the additional load at the boundaries of the soil mass does not exceed the structural strength of soil [3]. In addition, any patterns of soil straining under loads, including time patterns, can be specified for the model itself. For two-dimensional formulations (plane strain) the model is well-known as the model of a continuous layer of finite width.

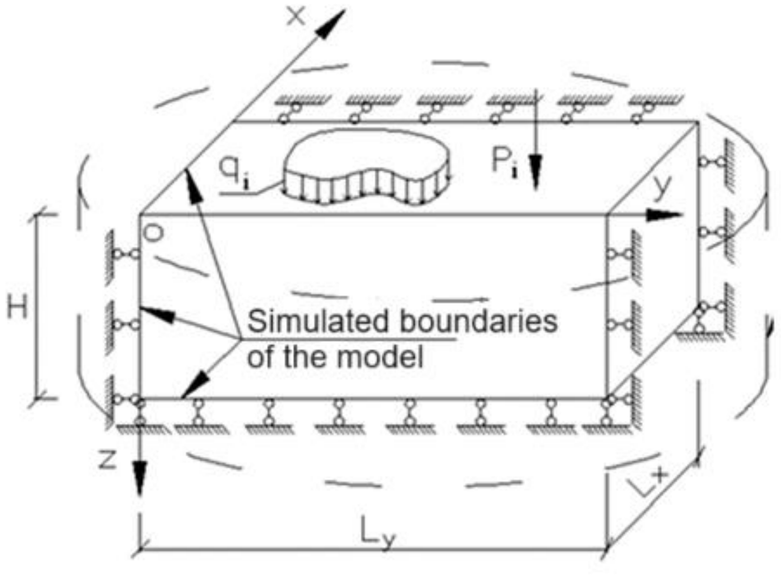

Figure 1 – Soil base model in the form of a continuous layer of finite distribution capability (for three-dimensional problems)

Definition of unsolved aspects of the problem

The major drawback of the existing approaches to simulating the interaction between the building and the soil base using classical models is that it is impossible to incorporate the structural nonlinearity of the behavior of the BFB system, particularly for a new type of high-performance large-size combined raft pile foundations for multistory and high-rise buildings [4, 22], where no contact between the piles and the raft is observed at the first stage of loading. A utility model of a combined raft pile foundation (CRPF) [1] (Fig.2) has been patented, which consists of the raft *1* and the piles *2* with the diameter d, with the gap *3* with the height Δ being provided between the raft and the piles. For the technological convenience of ensuring that no contact is made between the raft and the pile heads within the concrete bed *4*, the gap under the raft can be filled up with a low-modulus material. The soil base is designated as *5*.

Problem statement

The purpose of this work is to improve and theoretically justify the soil base model and the methodology for identifying its parameters to calculate a CRPF in the BFB system.

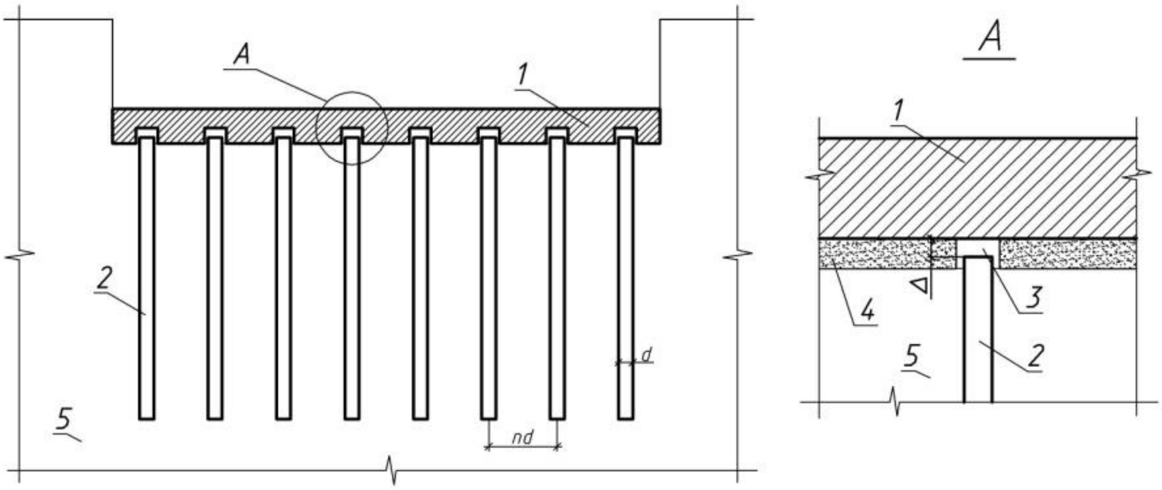

Figure 2 – General arrangement of a combined raft pile foundation (CRPF)

Basic material and results

To represent a soil base as a linear strain medium under conditions of a single load application, which does not result in significant growth of the regions of the ultimate stress state ("unstable" regions), it is required to ensure the normative condition [1, 2]:

$$p \leq R \,, \tag{1}$$

where p is the average pressure under the bottom of the foundation, kPa;
R is the design resistance of the soil of the foundation base, kPa.

Since this paper considers large-size combined raft pile foundations, the average pressure under the bottom of the raft of the foundation does not generally exceed the design resistance of the soil of the base, that is to say it is appropriate to adopt the linear strain law for the soil base under load, which was proposed by N. Gersevanov [6] and V. Florin [7].

Following the previous solutions to test problems on various interactions between the raft and the piles in present-day calculation packages (SOFiSTiK, PLAXIS), we propose an improved model of the soil base for the CRPF and a methodology for simulating the base-CRPF subsystem to incorporate the structural nonlinearity of the behavior of the CRPF, that is, the behavior of the foundation elements "before" and "after" the connection of the piles to the raft.

An improved model of the soil base in the form of a combination of a continuous linear strain layer of finite distribution capability and a Winkler-Fuss layer is shown in Fig. 3.

The methodology for simulating the base-CRPF subsystem includes the stages as follows:

1. We simulate the soil base of the CRPF with the physical and mechanical properties of soil layers and model dimensions such as compressible thickness $H_{p_{pl}}$ and overall dimensions $L_x \times L_y$ in plan, and corresponding vertical and horizontal strain constraints on the boundaries of the model.

2. We simulate the interaction between the soil base and a single pile separately (or using a built model). Based on the calculations and results of soil tests with piles at the construction site, we iteratively determine the connection stiffness G_p under the lower end of a single pile. In this case, the connection stiffness G_p of a single pile can be either linear or nonlinear (for example, bilinear). To determine the stiffness of piles in the pile field, we should consider their interaction; therefore, the stiffness G_{pf} under the lower ends of the piles will be equal to:

$$G_{pf} = G_p \cdot \zeta \, [\text{kN/m}],$$

where G_p is the stiffness of the connection under the lower end (bottom) of a single pile, kN/m;
ζ is the coefficient of transition from the settlement of a single pile to the settlement of the pile field, units. We take the normative value of $k = 0.2$ or when justified, the value of $k = 0.25 \div 0.33$ can be taken [8].

3. We simulate a CRPF with no contact between the raft and the piles with the gap Δ between them.

4. We simulate special inserts with the thickness Δ between the raft of the foundation and the piles, the stiffness of which should be not less than that of the foundation elements (by convention, "concrete" inserts). The "concrete" inserts should provide a connection between the raft of the foundation and the piles at the stage of calculation "after" the connection to the raft.

Next, we simulate the superstructure with the appropriate effective, wind and other loads on it to obtain a model of the entire base-CRPF-building system (Fig. 3).

To calculate the structural nonlinearity of the combined raft pile foundation, the main calculation steps are as follows:

– We determine the stress-strain state of the **raft** of the foundation **"before"** the connection to the piles. It is determined for the part of the vertical load p_{pl}, which is taken by the raft of the foundation **"before"** the connection to the piles;

– We determine the stress-strain state of the **raft** of the foundation **"after"** the connection to the piles to find the most unfavorable combination of loads on it. It is determined for the additional (effective) vertical load p_{ad} after developing the stress-strain state at the previous stage.

To investigate the effect of the proposed model of the soil base on the stress-strain state of the CRPF, it is proposed to consider a simple example of calculation with the initial data of an actual construction project in a two-dimensional formulation:

– The overall normative vertical average load under the raft of the combined raft pile foundation is $p_{tot}=p_{pl}+p_{ad}=167$ kPa;

– The gap between the raft and the piles is $\Delta=0.05$ m=5.0 cm;

– The soil base takes the average vertical load under the raft of $p_{pl}=119$ kPa (approximately of the weight of the total building volume) "before" the connection to the piles (Stage 1);

– The soil base takes the additional average vertical load under the raft of $p_{ad}=48$ kPa (effective load) "after" the connection to the piles (Stage 2);

– The linear stiffness under the ends of the piles is G_{pf} =32000 kN/m, which is determined from numerical iterative calculations of the interaction between the soil mass and the single pile under the action of a vertical force $F = 1200$ *kN* on the single pile with the stiffness under the lower end of $Gp = 160000$ *kN/m* (determined iteratively) and its settlement ≈ 5 *mm*, which corresponds to the results of field tests of soils with bored piles [10].

The conditional calculation patterns of the base-CRPF system are shown in Figs 4 and 5.

a)

b)

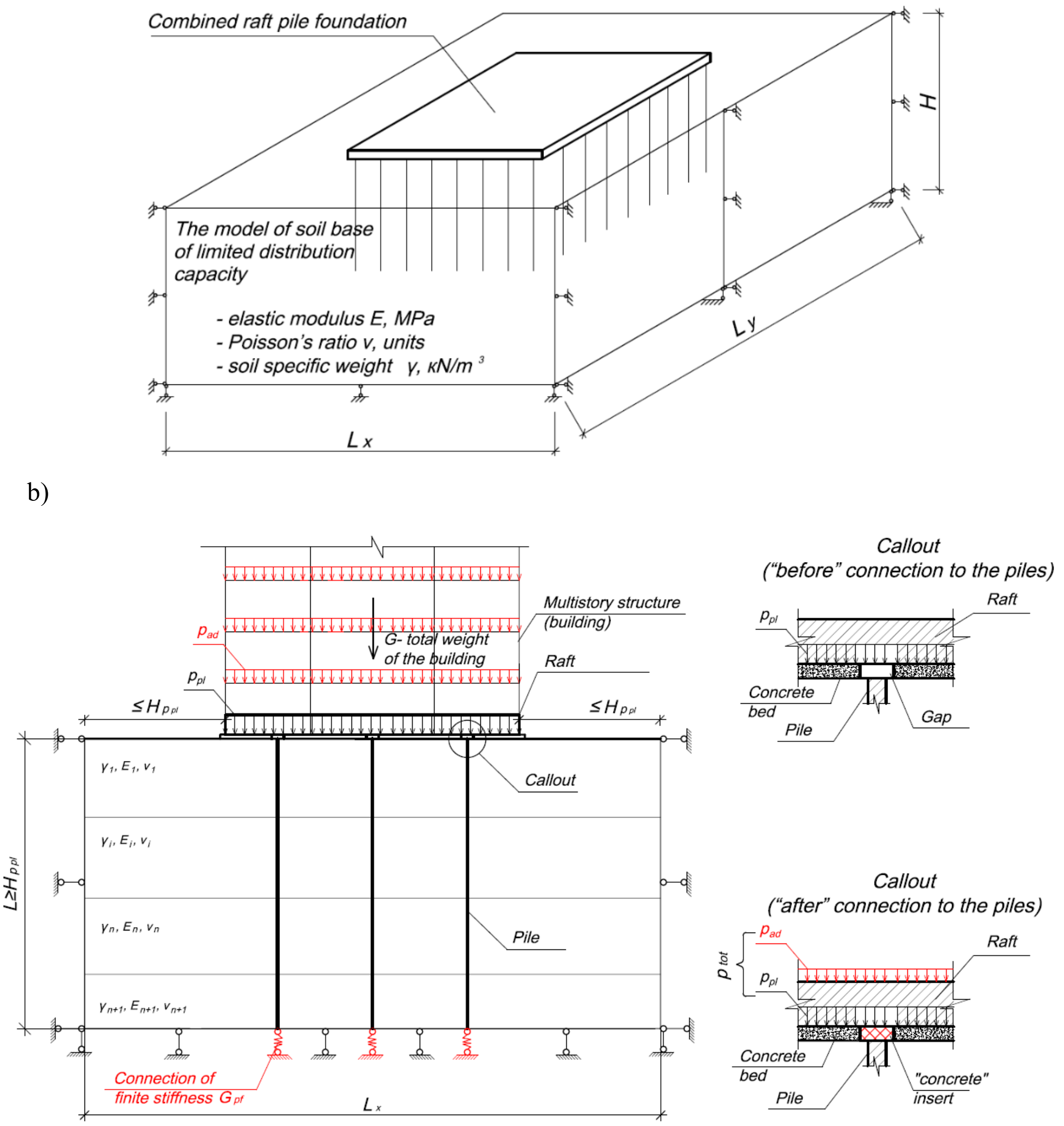

Figure 3 – General arrangement of an improved model of the soil base for the CRPF: a) Three-dimensional view of the base-CRPF subsystem; b) View of the base-CRPF-building system with the specific locations of the connections of finite stiffness G_{pf} under the bottom of the piles.

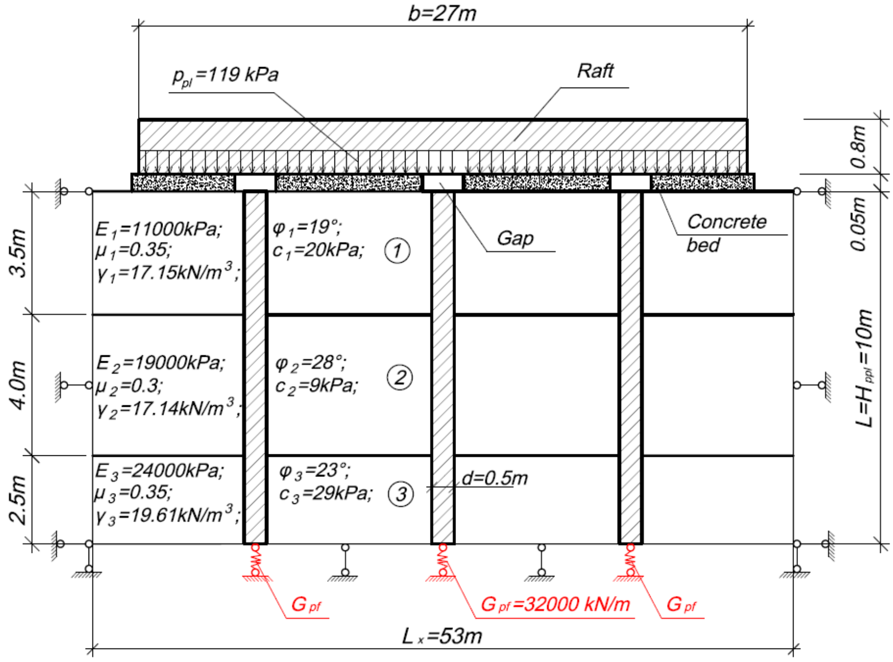

Figure 4 – Conditional calculation pattern of the base-CRPF system "before" the connection to the piles (Stage 1).

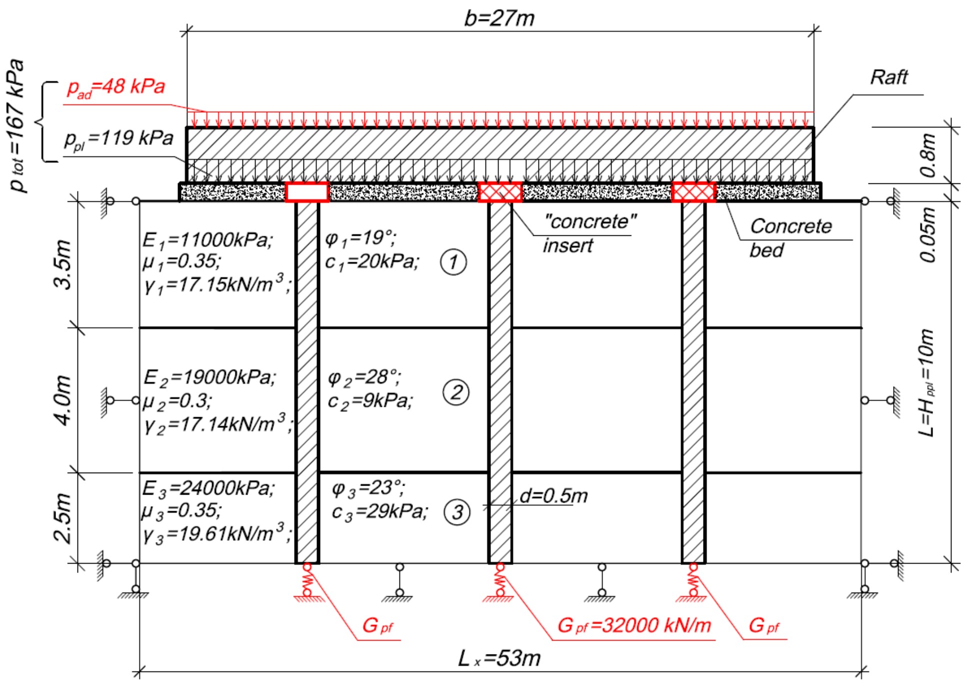

Figure 5 – Conditional calculation pattern of the base-CRPF system "after" the connection to the piles (Stage 2).

To investigate the performance of the proposed model of the soil base, a finite element model of the base-CRPF subsystem, which consists of a soil base and a combined raft pile foundation, was created using the PLAXIS 3D package according to the calculation patterns of Figs 4 and 5 (Fig. 6) [11].

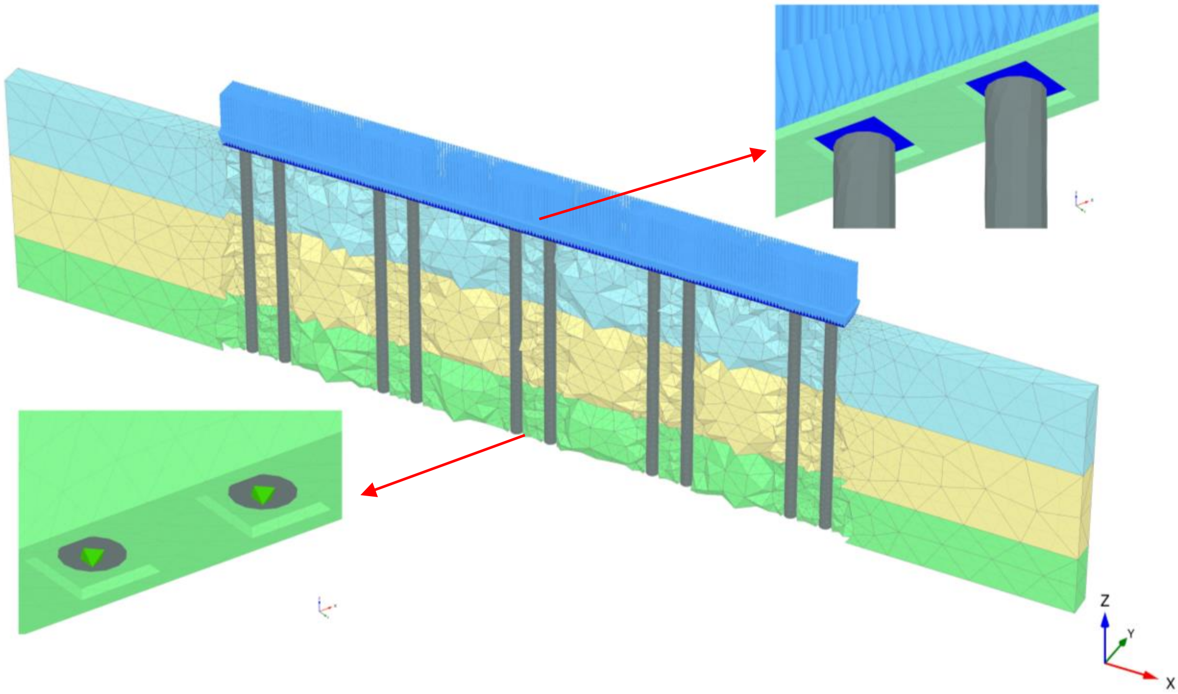

Figure 6 – General view of the base-CRPF system in a two-dimensional formulation.

The soil base and piles were simulated using a linear-elastic material model which is based on Hooke's law for isotropic elasticity and represented by solid finite elements with consistent stress-strain properties such Young's modulus (elastic modulus) E in kN/m^2 and Poisson's ratio v in units.

The raft is simulated by plate finite elements using an elastic material model with the parameters as follows: specific weight γ in kN/m^3, elastic modulus E in kN/m^2, and Poisson's ratio v in units.

Fixed-end anchor elastic elements with the elastic modulus E (kN/m^2), cross-section A (m^2), and thickness $^{\Delta}$ (m), that is, with the linear stiffness of $Gpf=E{\cdot}A/\Delta=32000\ kN/m$, are used as the connection of finite stiffness under the lower ends of the piles.

A two-row arrangement of the piles with the spacing *3d* at a distance of *6.0 m* between the rows was adopted.

The load is assumed to be evenly distributed over 1 (one) running meter of the raft.

Fig. 7 below shows the results of the preliminary simulation of the interaction between the soil base and the single pile to determine iteratively the connection stiffness G_p under the bottom end of the single pile. Iterative calculations were performed for both the linear-elastic model and the nonlinear Mohr-Coulomb model for soil. The difference was not more than 2%.

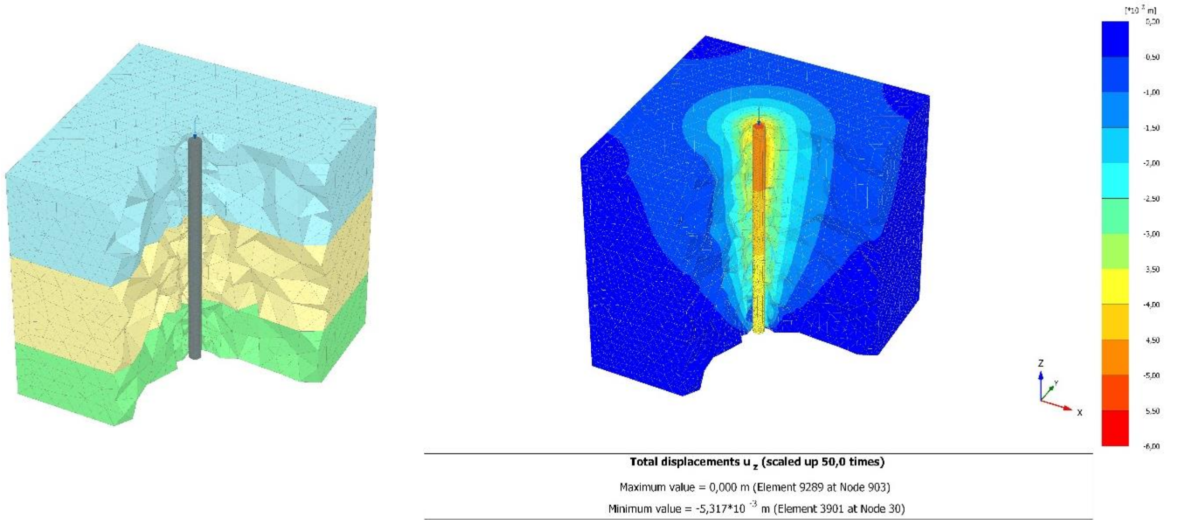

Figure 7 – General view and straining of the base-single pile system.

Fig. 8 shows the bending moment curves along the raft of different foundations:
- CRPF (2 stages) L-E model: calculation pattern for the base-CRPF system "after" the connection to the piles (Stage 2), where the soil base is simulated using a linear-elastic material model;
- CRPF (2 stages) M-K model: calculation pattern for the base-CRPF system "after" the connection to the piles (Stage 2), where the soil base is simulated using the nonlinear Mohr-Coulomb material model;
- RPF L-E model: calculation pattern for the base-RPF system with the full load p_{tot} being applied and the behavior of the raft as a raft with the permanent connection between the raft and the piles, where the soil base is simulated using a linear-elastic material model;
- RPF M-K model: calculation pattern for the base-RPF system with the full load p_{tot} being applied and the behavior of the raft as a raft with the permanent connection between the raft and the piles, where the soil base is simulated using the nonlinear Mohr-Coulomb material model.

The criterion for evaluating the effect of the proposed combined model of the soil base in the calculation of various foundations is the sum of the bending moments along the raft: $\Sigma|M_x|$, kN·m (Fig. 9).

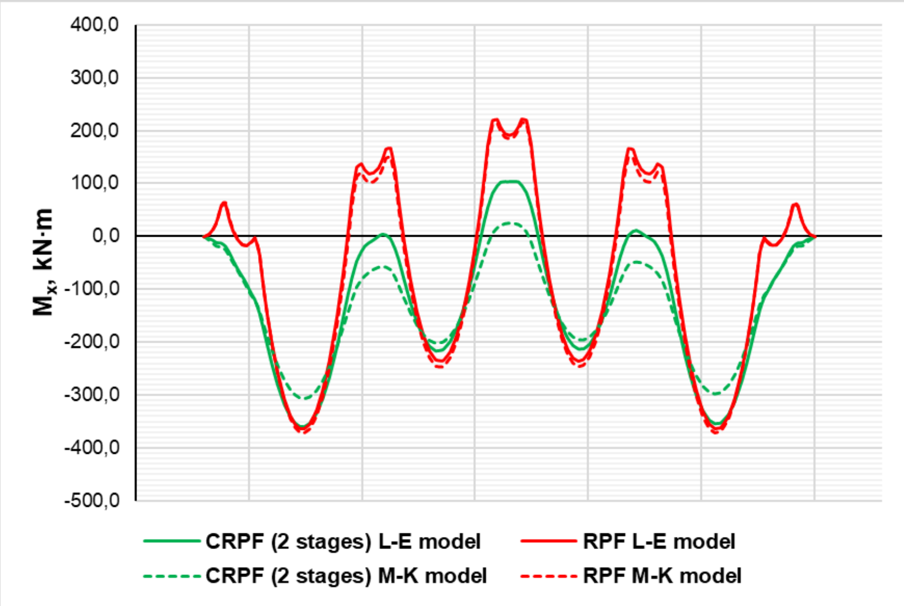

Figure 8 – Bending moment curves M_x along the raft, kN·m

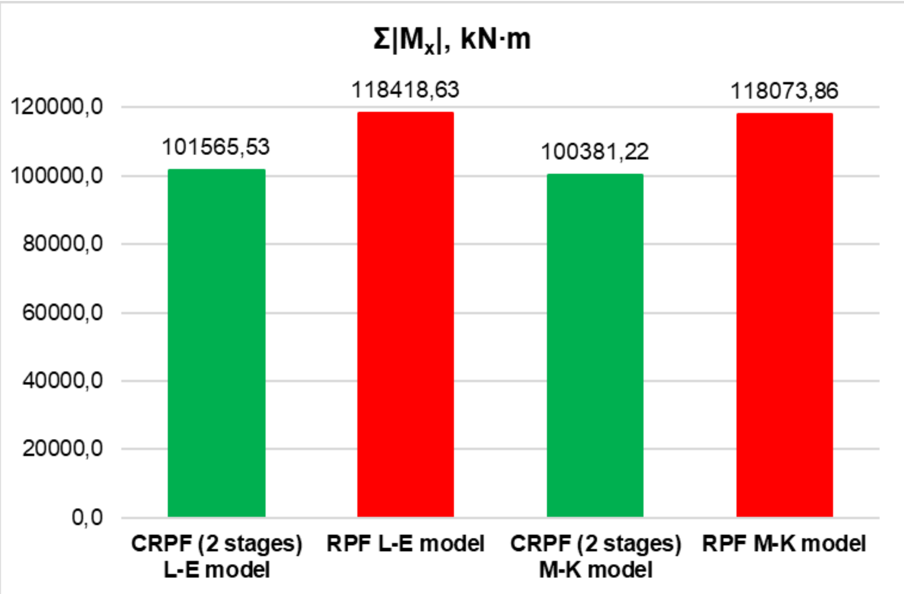

Figure 9 – Sum of the bending moments along the raft: $\Sigma|M_x|$, kN·m

It should be noted that the calculation of a 2-stage development of the stress-strain state of the CRPF reduces the moment forces in the raft at the 2nd (last) stage to 15% in comparison with the application of the full load $p_{tot}=p_{pl}+p_{ad}=167\ kPa$ and the behavior of the raft as a raft with the permanent connection between the raft and the piles.

The analysis of the stress-strain state of the combined raft pile foundation at different stages of the interaction with the proposed soil base model helps to confirm the physical significance of this structural nonlinearity of the behavior of the foundation elements. It should be noted that in this case there is no point in comparing the stress state of the raft when using other soil base models since this is the only available model now that can qualitatively simulate the behavior of the CRPF with the structural nonlinearity in behavior.

Conclusions

The conducted investigations suggest the conclusions as follows.

1. A soil base model in the form of the combination of a continuous linear strain layer of finite distribution capability and a Winkler-Fuss layer was improved and theoretically justified. A methodology for simulating the base-CRPF subsystem was developed to determine the stress-strain state of the CRPF in present-day calculation packages. In this respect, the improved model is capable to qualitatively simulate the behavior of the CRPF with the structural nonlinearity in the behavior of its elements, raft and piles, as shown in a specific example.

2. Numerical studies of the model's impact on the distribution of bending moments in the raft of various foundations were conducted, which showed a decrease in moment forces in the raft of up to 15% when considering the structural nonlinearity of the foundation elements in comparison with the application of the full load p_{tot} at once and the behavior of the raft as a raft with the permanent connection between the raft and the piles.

3. The results of the calculations of separately performed test tasks show that when the raft takes 100% of the load and other conditions are equal, the moment forces in the raft are always less than in the case of the pile-raft connection, which makes the physical significance owing to the absence of a significant concentration of forces in the corner and peripheral piles in case the raft behaves as a raft.

4. The improved combined model may also be used to calculate classical piled raft foundations to reduce the concentration of forces in the corner and peripheral piles, which requires further research into the proposed soil base model.

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The influence of the arrangement scheme of vertical soil-cement elements of the soil base reinforcement on their joint work with the strip stamp

Vynnykov Yuriy[1], Razdui Roman[2*]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0003-2164-9936
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-5819-6056
*Corresponding author E-mail: romanrazduy@gmail.com

The characteristics and parameters for modeling the soil base under the strip stamp with variable parameters of the vertical soil base reinforcement are given. Variants of soil-cement element placement with varying reinforcement ratio are presented. Differences in graphical results are shown on the example of longitudinal and transversal cross. Graphs of dependences of pressures on the soil base according to numerical modeling using HSM model and volumetric soil elements on the reinforcement ratio for different variants for of the arrangement scheme of SCE are shown. The effective zones of soil work of strip foundations (stamps) under the considered soil conditions for each of the options for placement of SCE have been identified

Key words: vertical soil base reinforcement, vertical soil-cement element, reinforcement ratio, soil-cement soil base, tray experiment, finite element method, settlements, weak soil base, strip stamp, numerical simulation

Вплив розміщення в плані вертикальних ґрунтоцементних елементів армування основи на їх спільну роботу зі стрічковим штампом

Винников Ю.Л.[1], Раздуй Р.В.[2*]

[1, 2] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: romanrazduy@gmail.com

Наведено характеристики та параметри для моделювання напружено-деформованого стану (НДС) основи, армованої вертикальними ґрунтоцементними елементами (ҐЦЕ), під стрічковим штампом при варіативних параметрах вертикального армування основи. Для моделювання методом скінченних елементів (МСЕ) у просторовій постановці (2D) використано вже добре апробовану модель ґрунту ізотропного ущільнення (Hardening soil model) і спосіб задання ҐЦЕ об'ємними елементами з відповідними характеристиками за моделлю лінійно-еластичної поведінки. Створено сітку скінчених елементів, для якої прийнятий допустимий рівень щільності. Представлено варіанти розміщення ҐЦЕ в плані при варіюванні відсотку армування від 0% до 39,7%. Показано відмінності у графічних результатах на прикладі повздовжніх та поперечних перерізів при відсотку армування 7,1%; 10,8%; 16,4%. Показано графіки залежності тисків на основу при чисельному моделюванні із використанням моделі ізотропного ущільнення ґрунту та об'ємних елементів від відсотку армування при різних варіантах розміщення ҐЦЕ в плані при різних значеннях осідання центру штампу. Виокремлено ефективні зони роботи стрічкових фундаментів (штампів) при розглянутих ґрунтових умовах для кожного із варіантів розміщення ҐЦЕ як у лінійній, так і в нелінійній (пружно-пластичній) стадіях роботи основи. Визначено, що до 7% армування ефективно армування, при якому відстань від центру ҐЦЕ до грані штампу складає 1,5 їх діаметри, в діапазоні 7…40% – варіант армування із співпадінням зовнішніх граней елементу армування та фундаменту (штампу), а при більшому відсотку армування – можливий вихід зони армування за межі розміщення фундаменту (штампу). Винесення елементів армування в плані за бічну грань штампу (третій їх варіант розміщення) не дає суттєвого ефекту, оскільки більшу частину навантаження сприймає саме центральний ряд ҐЦЕ

Ключові слова: вертикальне армування основи, вертикальний ґрунтоцементний елемент, відсоток армування основи, ґрунтоцементна основа, лоткове дослідження, метод скінченних елементів, осідання, слабка основа, стрічковий штамп, чисельне моделювання

Introduction

The need to improve the natural soil base under conditions of weak soils is quite obvious because with low characteristics the probability of the development of supernormal deformations of the soil base of buildings increases, which may cause the need to calculate the settlements of the soil base with methods of nonlinear soil mechanics, including, with usage of software complexes [1, 3, 4]. One of the methods of ground improvement is the reinforcement of the soil massif with vertical soil-cement elements (SCE) which are used for a whole range of needs, in particular, the reinforcement of foundations under strip foundations.

Review of the research sources and publications

The following materials are a continuation of a series of studies [7, 8, 9] on determining the effectiveness of using SCE for reinforcing the bases of strip foundations. In previous works the results of tray [7] and field studies [8] were presented and the optimal method of determining SCE and soil base for calculation by the finite element method (FEM) [9] was determined for the soil conditions specified in the study.

Definition of unsolved aspects of the problem

The effectiveness of reinforcing the soil bases of strip foundations with a low modulus of soil deformation using SCE has already been repeatedly proven [9]. However, the issues of effectiveness of SCE reinforcement and the dependences of foundation settlements on foundation pressure [2], including depending on the reinforcement ratio, as well as the influence of the arrangement scheme of SCE under the strip foundation on their work as a system have not yet been sufficiently studied.

Problem statement

A reliable method of solving such problem is to compare the settlements of a natural experiment with its numerical simulation. Therefore, based on the results of past works [7, 9], the goal is the FEM simulation of the soil-cement base under variable reinforcement parameters while preserving the dimensions of the tray, stamp, diameter and depth of the SCE for evaluating the effect of placing elements in the plan under the stamp, analyzing the results and determining the best option for their placement.

Basic material and results

The hardening soil model was used to FEM modelling in a spatial setting. To perform numerical simulations of stamp studies in the tray, the same characteristics of the tray, soil base, soil-cement, and reinforcement ratio as in the tray study [7, 8] were chosen (Table 1). The dimensions of the calculation area in the plan were 580×530 mm, the depth – 560 mm. The depth of the reinforcement from the base surface was 100 mm, the diameter of the elements was 6 mm. A rectangular steel stamp with a plan size of 420×35 mm is modeled by a plate element. The selected hardening soil model behavior and the determination of SCE by volume elements was chosen as the most correct according to the results of previous studies [5, 6, 8]. At the same time, the reinforcement ratio varied from 0 to 39.7% (that is, from the unreinforced base to the filling of the massif area by SCE under stamp in a staggered order with a step of two SCE diameters between the centers of the elements in each of the directions). SCEs were modeled by volumetric elements. Excavation of soil for the installation of a buffer crushed stone cushion, SCE installation, filling of wells with soil-cement, installation of a cushion, stamp and gradual loading were gradually taken into account. SCE were modeled as a volumetric soil bodies with appropriate characteristics with a *linear elastic* behavior model.

The following assumptions and parameters are used in the calculations. The iterative procedure provided for: a relative error equal to 0.05; the maximum number of iterations does not exceed 60; the maximum number of steps in each phase is 250. The density level *fine* was set for created mesh.

Table 1 –Characteristics set for the soil model with modeling the stress-strain state system "soil-cement soil base - rigid strip stamp"

Element	ρ, g/cm^3	E_{oed}, MPa	E_{ur}, MPa	φ, °	c, kPa	υ
Soil paste	1,85	0,7	3,5	0	15,8	0,35
Crushed stone	2,00	40	-	40	1,0	0,25
Soil-cement	2,00	300	-	-	-	-

Three variants of modelling based on the arrangement scheme of SCE under strip stamp are presented.

The first variant was performed similarly to the tray experiments, when a gap of one diameter of the SCE remained between the side faces of the SCE and the stamp. The maximum reinforcement ratio was 16.4%, which corresponds to two diameters between the centers of the elements in the plan (Fig. 1).

The second option is to place the outer edge of the SCE on the outer edge of the stamp. At the same time, the reinforcement ratio ranged from 0 to 39.7% (Fig. 2).

The third variant is to place the inner face of the SCE behind the outer face of the stamp (that is, when the SCE protrude beyond the dimensions of the stamp in plan on each side). The reinforcement ratio ranged from 7.1 to 39.7%, since at a lower percentage of reinforcement, each row of SCE placement along the stamp had less than three elements, that is, the condition was accepted that at least one SCE in the row was under the stamp (Fig. 3).

According to the results of FEM modeling in fig. 4–6, a–b shows the longitudinal and transversal cross-sections of the settlements of the base at the value of the settlements of the center of the stamp of 4 mm at the reinforcement ratio of 7.1%, respectively in fig. 4–6, c–d at 10.8%, in fig. 4–6, d–e at 16.4%.

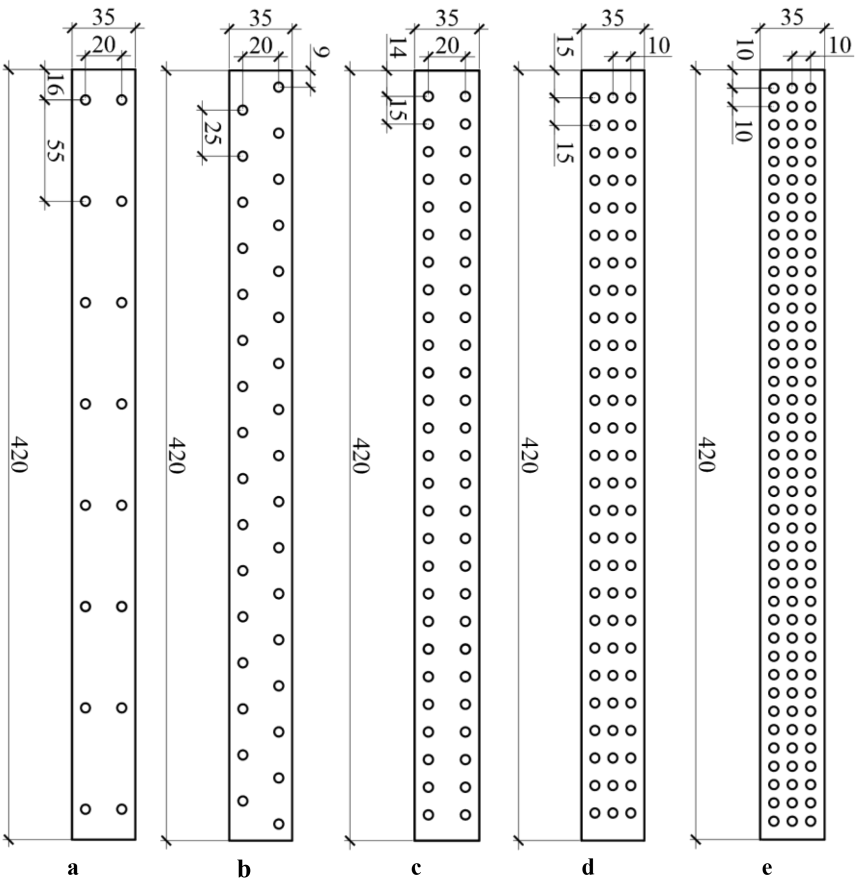

Figure 1 – The first variant of the arrangement scheme of SCE under strip stamp:
a – 2,1%; b – 4,4%; c – 7,1%; d – 10,8%; e – 16,4%

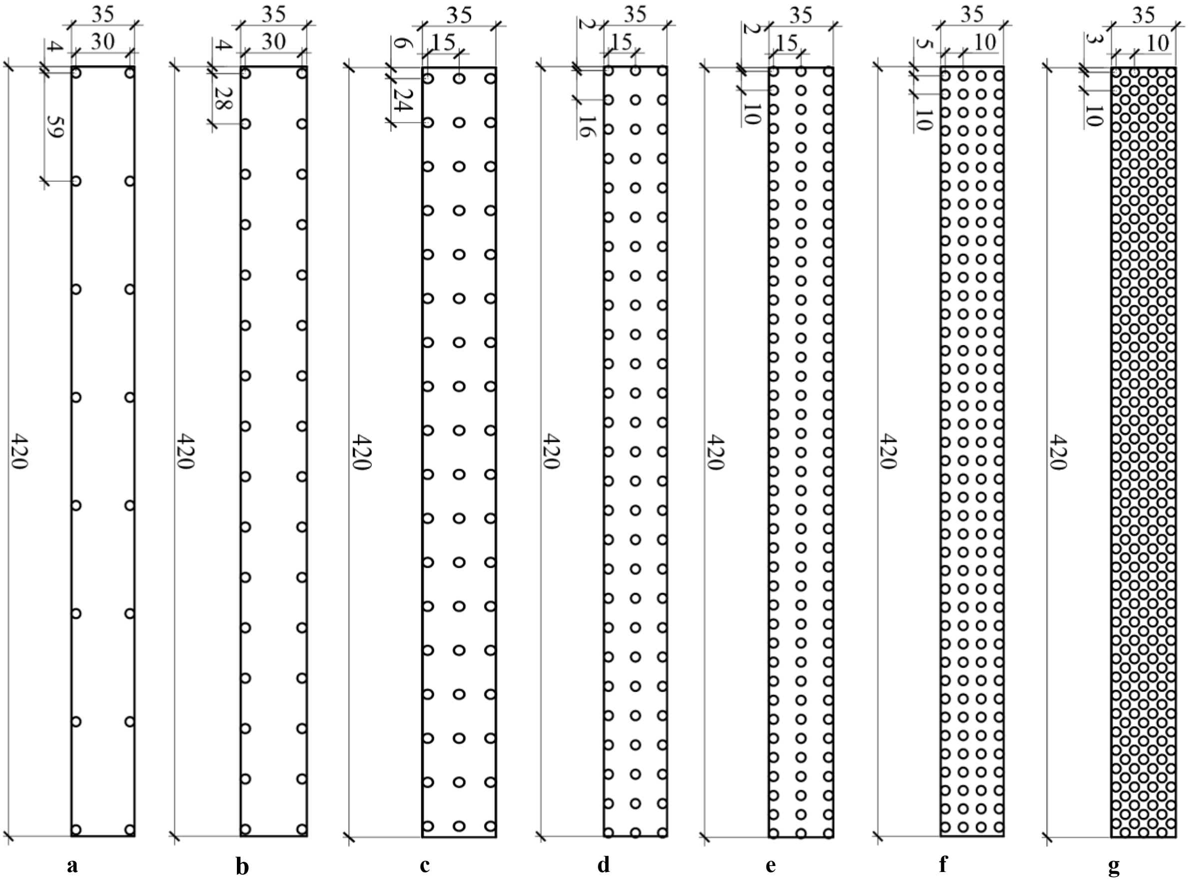

Figure 2 – The second variant of the arrangement scheme of SCE under strip stamp:
a – 2,1%; b – 4,4%; c – 7,1%; d – 10,8%; e – 16,4%; f – 22,4%; g – 36,7%

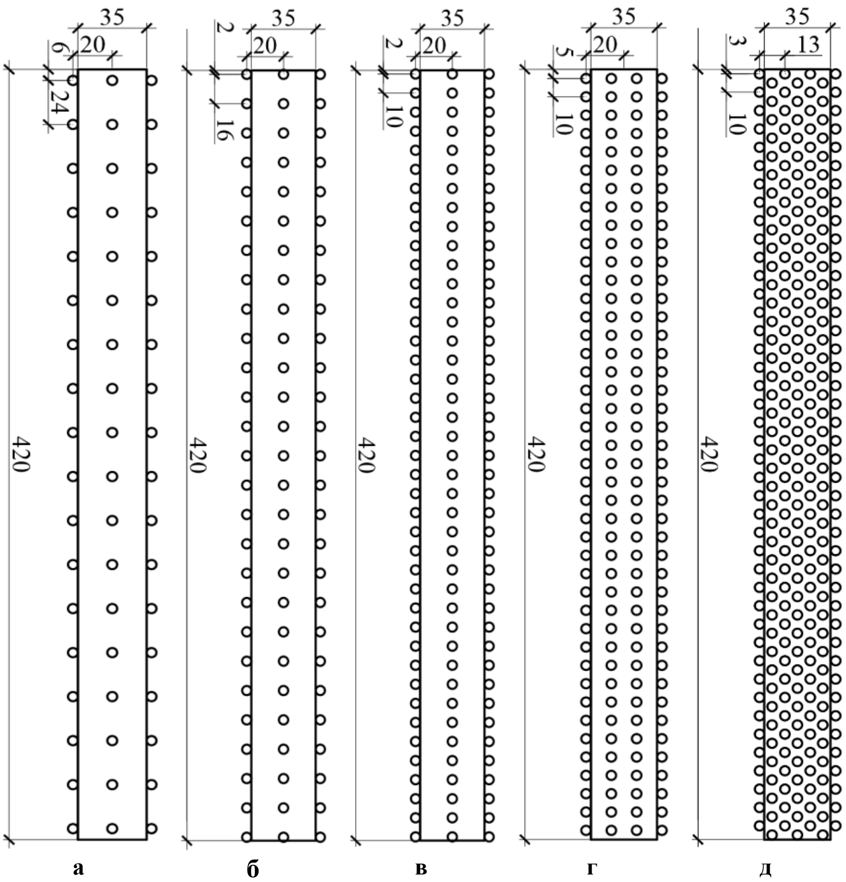

Figure 3 – The third variant of the arrangement scheme of SCE under strip stamp:
a – 7,1%; b – 10,8%; c – 16,4%; d – 22,4%; e – 36,7%

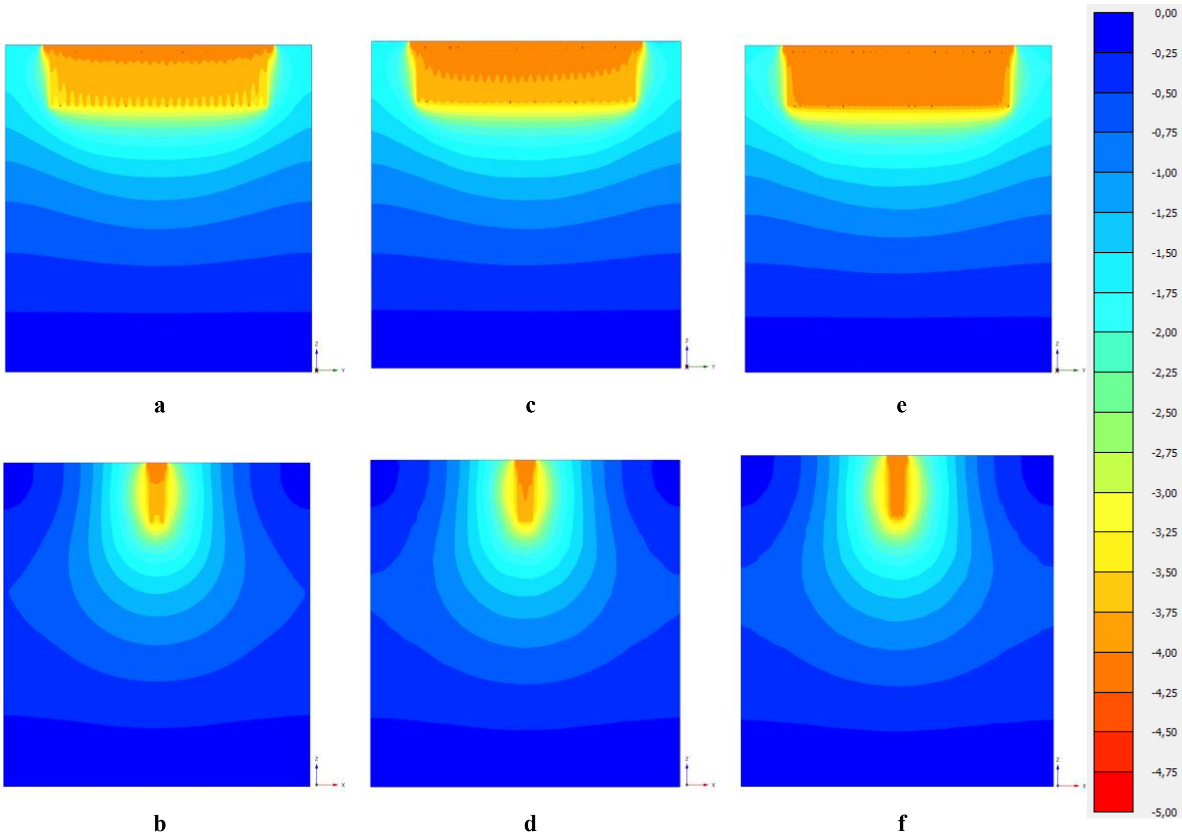

Figure 4 – Vertical longitudinal and transversal cross-sections of soil base settlements according to the results of FEM simulation (with a 4 mm settlement in the center of the stamp) for the first variant of the arrangement scheme of SCE at: a, b – 7,1%; c, d – 10,8%; e, f – 16,4%

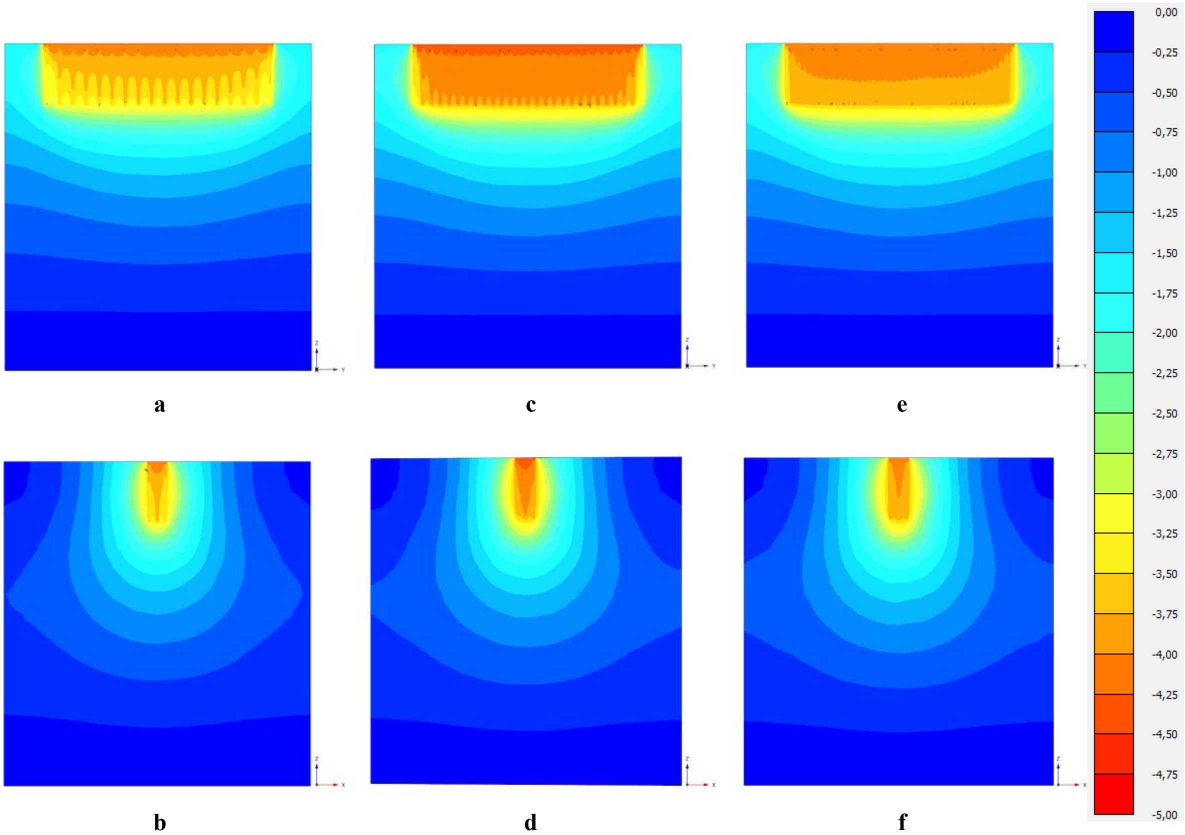

Figure 5 – Vertical longitudinal and transversal cross-sections of soil base settlements according to the results of FEM simulation (with a 4 mm settlement in the center of the stamp) for the second variant of the arrangement scheme of SCE at: a, b – 7,1%; c, d – 10,8%; e, f – 16,4%

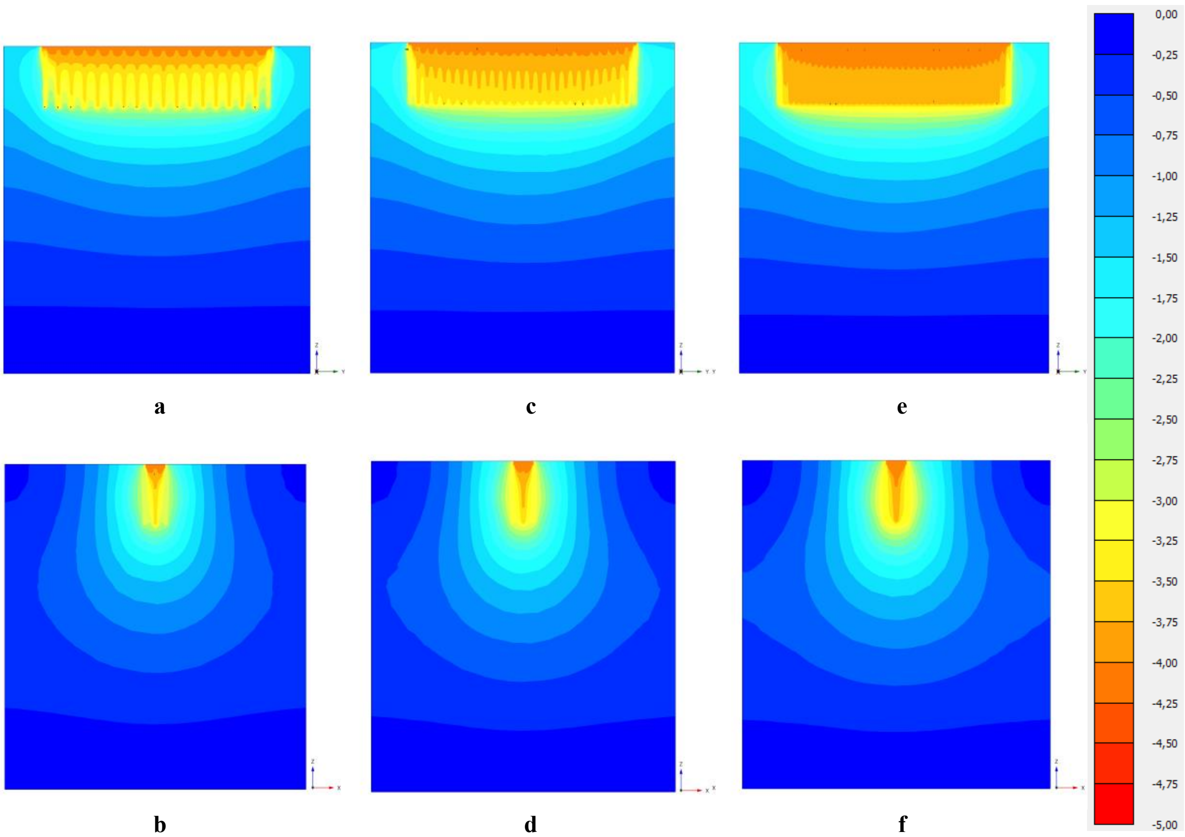

Figure 6 – Vertical longitudinal and transversal cross-sections of soil base settlements according to the results of FEM simulation (with a 4 mm settlement in the center of the stamp) for the third variant of the arrangement scheme of SCE at: a, b – 7,1%; c, d – 10,8%; e, f – 16,4%

These cross-sections demonstrate that under these conditions with reinforcement up to 16.4% the soil base can be considered as reinforced by individual SCEs, while at 16.4% and more it can be considered as a continuous reinforced array. Carrying out the reinforcement elements in the plan beyond the side face of the stamp (the third variant of their placement) is not effective, since most of the load is perceived by the central row of the SCE.

In order to compare the effectiveness of the placement of elements in the plan under the stamp, graphs are given that demonstrate what pressure was transmitted to the soil base for all options for placement of SCE depending on the reinforcement ratio with the same settlements of the stamp (Fig. 7).

The graphs are given for different values of soil base settlements: 4 mm; 6 mm; 8 mm; 10 mm. The listed values of settlements were chosen in such a way that for all percentages of reinforcement of the experimental foundation, settlements were analyzed for both linear and non-linear stages of soil work.

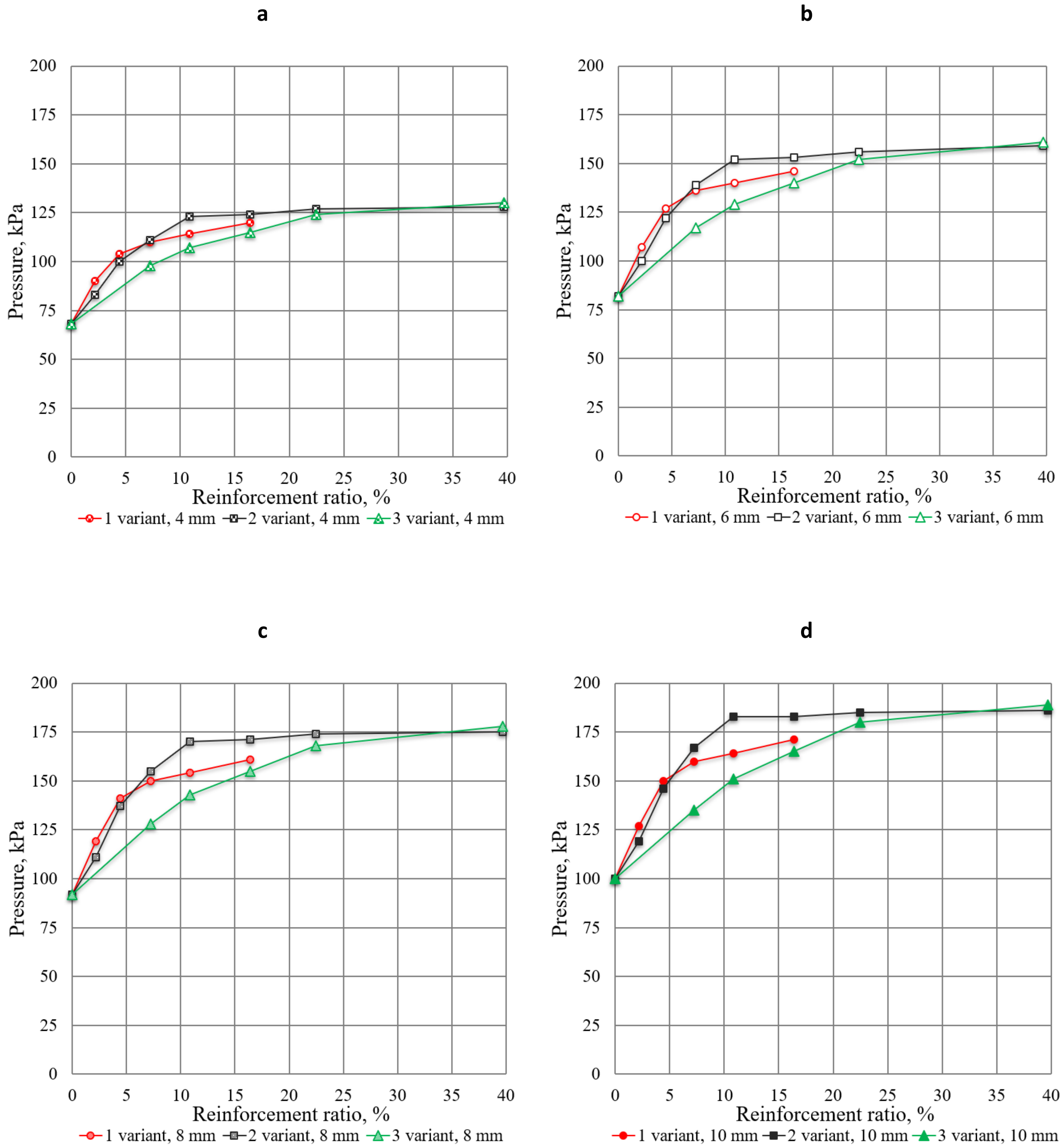

Figure 7 – The graph of dependences of pressures on the soil base according to FEM modeling using hardening soil model and volumetric soil elements on the reinforcement ratio for different variants of the arrangement scheme of SCE in the plan at values of settlement of the center of the stamp: a – 4 mm; b – 6 mm; c – 8 mm; d – 10 mm

Therefore, analyzing the obtained cross-sections and curves on the graphs of the dependences of the pressures on the base from the reinforcement ratio of SCE with the parameters of the soil base, strip stamp and constant depth of base reinforcement specified in the study, the following generalizations are possible.

1. When placing 2 elements in each row of reinforcement (up to the reinforcement ratio of 7.1%), the first arrangement scheme is the most effective, when all elements are placed under the stamp, and the distance from the center of the SCE to the edge of the stamp is 1.5 their diameters.

2. When placing more than two elements in each row of reinforcement (7.1% reinforcement ratio and more), the second arrangement scheme is the most effective, when all elements are located under the stamp, and the distance from the center of the SCE to the edge of the stamp is 0.5 of their diameters.

3. With high reinforcement ratio of the soil base (39.7%), when the elements are located closer than 1.5 of their diameters from each other, the placement of elements becomes effective, in which the base is also reinforced behind the side faces of the stamp (in the conducted studies, the distance from the center of the SCE to the outer face of the stamp is 0.5 diameters).

4. We also note that the generalizations formulated above generally correspond to different pressures on the soil base, both in linear and non-linear (elastic-plastic) stages of the base's work.

Conclusions

Thus, we can summarize the following from the results obtained in this work.

1. The effective zones of work of strip stamps are identified under the considered soil conditions both in linear and non-linear (elastic-plastic) stages of operation of the base

2. It was determined that up to 7% of reinforcement is effective when the distance from the center of the SCE to the edge of the stamp is 1.5 their diameters, in the range of 7...40% - the reinforcement option with the coincidence of the outer faces of the reinforcing element and the foundation (stamp) and with a greater reinforcement ratio – possible placement of the reinforcement zone outside the foundation placement (stamp).

3. The obtained statements based on the graphs of the dependences of the pressures under the strip stamps on the soil base from the reinforcement ratio have a satisfactory convergence with the graphic cross-sections of the soil base settlements.

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Ensuring the reliability of corrosion and mechanical resistance of pipelines and steel structures of oil and gas complexes

Zyma Oleksandr[1*], Steblianko Valeriia[2], Pahomov Roman[3], Pavlo Mytrofanov [4]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-7484-7755
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-0289-9342
[3] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-9169-8296
[4] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0003-4274-1336

*Corresponding author E-mail: zymaae@gmail.com

The article addresses the issue of ensuring the reliability and durability of steel structures used in oil and gas complexes. Attention is drawn to the need for research and improvement of scientific, technical, and technological developments in the field of corrosion-mechanical resistance of metal structures. The article describes the results of experimental research aimed at analyzing the causes and mechanisms of metal strength loss during operation, and proposes a method for predicting the residual working life of structures. The obtained results make a significant contribution to the development of technical and design measures to enhance the efficiency and reliability of oil and gas complexes

Keywords: destruction, corrosion, steel structures, mechanical stability, degradation

Забезпечення надійної корозійно-механічної стійкості трубопроводів та сталевих конструкцій нафтогазових комплексів

Зима О.Є.[1]*, Стеблянко В.С.[2], Пахомов Р.І.[3], Митрофанов П. Б.[4]

[1] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[2] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[3] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[4] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: zymaae@gmail.com

Стаття присвячена аналізу факторів для забезпечення надійності сталевих конструкцій та трубопроводів, які використовуються у нафтогазових комплексах. Проаналізовано протиріччя та невизначеності у сучасних науково-технічних й технологічних розробках щодо забезпечення надійної корозійно-механічної стійкості й тривалості сталевих конструкцій нафтогазових комплексів та інших оболонкових металоконструкцій відповідального призначення. Звертається увага на необхідність дослідження та вдосконалення науково-технічних та технологічних розробок у галузі корозійно-механічної стійкості металевих конструкцій. В статті описані результати експериментальних досліджень, що спрямовані на аналіз причин та механізмів втрати міцності металу у процесі експлуатації. Отримали подальший розвиток розробки та застосування ефективних методів моніторингу та діагностики, зокрема використання ефекту коронного розряду для виявлення дефектів діелектричних покриттів. Виявлені недоліки методів оцінки працездатності конструкцій та їх залишкового ресурсу вказують на те, що у сучасний період особливо важливими є розрахункові методи, які базуються на критеріях тріщиностійкості, що чутливі до змін структури металу під час тривалої експлуатації, особливо в умовах корозійно-активних технологічних середовищ при змінних динамічних навантаженнях. Пропонується метод прогнозування залишкового робочого ресурсу конструкцій, що дозволяє систематично впливати на умови їх експлуатації для оптимізації роботи. Проведений аналіз може стати важливим внеском у розробку технічних та конструкторських заходів для підвищення ефективності та надійності нафтогазових комплексів.

Ключові слова: руйнування, корозія, сталеві конструкції, механічна стійкість, деградація

Introduction

Modern scientific and technical and technological developments in relation to providing of reliable corrosivemechanical firmness and duration of steel constructions of oil and gas complexes and other thecal metallic constructions of the responsible setting, that is subject to Government service of mountain supervision and industrial safety of Ukraine, contradiction and vagueness educed. Absent reasonable recommendations are for practical application with the aim of providing of corrosive-mechanical firmness of constructions that function in technologically aggressive environments at variable temperature-barometric terms and loading.

There was a necessity of system study of reasons, terms and mechanisms of corrosivemechanical damages of equipment with the protracted term of exploitation that will allow substantially to promote operating reliability of industrial equipment. Experimental researches find out reasons and grounded the mechanisms of loss of durability of metal with the increase of term of that causes his degradation, especially during the protracted exploitation in corrosive environments. Methods of foresight of remaining working (accident free) resource of metallic constructions that allow purposefully to regulate them the operating state was analyzed. It gives possibility in good time to apply technical and designengineering measures for the increase of terms of exploitation of such constructions. The got results of experimental tests of metallic standards of the different setting create a base for the comparative analysis of steels on the different parameters of firmness to the cracks. The article is devoted to the analysis of modern anti-corrosion materials that are used to protect the structures of oil and gas-bearing complexes. Various compositions and properties of these materials are considered, as well as their effectiveness in preventing corrosion damage to metal elements. The main advantages and areas of application of modern anti-corrosion materials in the oil and gas industry, in particular in the production, transportation and storage of petroleum products, are outlined. The possibilities of their improvement and the prospects of their use in the future for the most effective protection of the infrastructure of oil and gas complexes from corrosion were also studied. The results of the analysis will allow to deepen the understanding of modern opportunities and trends in the field of anti-corrosion materials to ensure the long-term and reliable functioning of the oil and gas infrastructure.

Review of the research sources and publications

Many domestic and foreign researchers have studied the problems of crack resistance and brittleness of metals used in aggressive environments with hydrogen sulfide impurities in oil and gas fields. The analysis of scientific sources shows that existing methods of calculating the durability of pipelines and tanks used both in Ukraine and abroad usually provide for independent consideration of corrosion fatigue and creep processes, although in reality these phenomena often occur simultaneously in various combinations. This issue has been studied, in particular, by such scholars as: S. Maksymov, S. Polyakov, S. Nesterenko, V. Panchenko, and O. Stepova.

Definition of unsolved aspects of the problem

The methodology for analyzing and assessing the reliable corrosion and mechanical resistance of pipelines and steel structures of oil and gas complexes is actively developing, so the development of new and improvement of existing approaches, models and methods for ensuring reliable corrosion and mechanical resistance of pipelines and steel structures and their computer implementation remain an urgent task for our country.

Problem statement

Description of analytical methods for ensuring reliable corrosion and mechanical resistance of pipelines and steel structures of oil and gas complexes.

Basic material and results

Today, the main task is to maintain and increase hydrocarbon production. This goal can be achieved in two ways: by developing new fields and increasing hydrocarbon production from existing wells. It is important to note that maintaining and increasing hydrocarbon production is associated with technological operations in the well, which often include the use of killing fluids. The main purpose of these fluids is to avoid fluid leakage and preserve the primary filtration and capacitive characteristics of the productive reservoir. There are different types of damping fluids depending on their composition, but the most common are fluids based on polymeric structuring agents and inorganic salts [1].

The use of polymeric chemicals makes it possible to obtain structured process fluids with high rheological characteristics. However, most polymers have low thermal stability and low resistance to microbial degradation. This leads to a loss of structural and rheological properties of such process fluids under the influence of thermobaric conditions in the wellbore. In addition, the destruction of polymeric components can cause contamination of productive formations and a decrease in well production rate. Alternative options for such fluids are process fluids based on inorganic salts. These fluids are either naturally occurring (formation water with known mineralization) or artificially produced (inorganic salt brines of appropriate composition and concentration). Such fluids have advantages, including the ability to widely adjust their density, minimal impact on rock volume, and preservation of the original properties of productive formations. They are also characterized by low freezing point and high thermal stability. The disadvantages include high fluid consumption for killing due to the lack of an impermeable screen (filter casing) on the well walls and absorption of the solution by the pores of productive formations [2].

In addition, the use of produced water as a killing fluid can cause microbiological corrosion due to the presence of sulfur-reducing, thione and other types of bacteria in produced water, depending on its composition [3]. For this reason, it is common to use killing fluids of artificial origin, which are thoroughly cleaned of excess mechanical impurities that may be a clogging agent in the productive formation before use.

The problems of crack resistance and brittleness of metals operating in aggressive environments with hydrogen sulfide impurities in oil and gas fields have been studied by many domestic and foreign researchers [5].

The analysis of scientific sources shows that existing methods for calculating the strength of pipelines and tanks used both in Ukraine and abroad usually involve independent consideration of corrosion, fatigue and creep processes, although in reality these phenomena often occur simultaneously in various combinations. In addition, the analysis of existing methods of non-destructive testing of metal damage and degradation shows their limited effectiveness in assessing the service life of industrial equipment. Thus, the identified shortcomings of methods for assessing the performance of structures and their residual life indicate that in the modern period, calculation methods based on crack resistance criteria that are sensitive to changes in the metal structure during long-term operation are especially relevant, especially in conditions of corrosive technological processes and environments with variable dynamic loads. In addition, in today's challenging conditions for the oil and gas industry, when the renewal of physically and morally obsolete fixed assets is limited by financial circumstances, it is important to maintain and extend the service life of industrial equipment, including metal structures and pipelines, by increasing the overhaul interval.

Thus, the development and use of modern crack resistance criteria in regulatory and technical documents that take into account hydrogen sulfide degradation of the metal will allow for a more accurate prediction of the residual life of steel during long-term operation. Most of the corrosion inhibitor is located in the water plug of the gas-liquid flow. Thus, a condensed liquid with organic acids and water containing a minimal amount of inhibitor can accumulate in the upper part of the pipeline. This can cause a corrosion process [4]. Corrosion inhibitors dissolved in liquid water can accumulate for a month before passing through the pipeline. Whereas condensate, moving at the speed of the gas phase, can form only during its passage through the pipeline at any point where the temperature and pressure conditions favor condensation.

In situations where the gas phase is not moving fast enough to ensure that the upper part of the pipe is wetted with water droplets containing the corrosion inhibitor from below, corrosion of the upper part of the cylindrical pipe occurs. Therefore, it is necessary to ensure either a constant injection of the inhibitor into such pipelines or to use cleaning pistons to distribute the corrosion inhibitor from the bottom of the pipe to the top. For this purpose, polymer balls, gel pistons and pistons with special corrosion inhibitor sprays are used. To predict such conditions, analytical models for predicting this type of corrosion are used [10]. Controlling erosion and corrosion requires determining and evaluating the relative impact of flow-accelerated corrosion or erosion on corrosion. Only then can measures be taken to prevent these phenomena.

According to I. Chudyk, if the main cause is accelerated corrosion caused by damage to the protective coating, there are two options: take measures to prevent damage to the coating or accept the damage to the coating and apply methods to control the corrosion process [11].

If the main cause of failure is the erosion of the metal layer (usually the lower part of the inner surface of the structure), it is necessary to find the optimal solution for the pipeline structure and system and the right choice of material [6]. Determining the type of erosion-corrosion process is often not a difficult task. Erosion-corrosion, which occurs from the single-phase flow of water or solid particles in suspension, is characterized by the presence of various features such as smoothed grooves, piercing grooves, shallow pits and depressions with a characteristic horseshoe-shaped profile, often with an orientation along the flow [15].

One of the characteristic features of an aggressive environment is the appearance of isolated spots on the metal surface, which can then develop into a normal rough surface [8]. In the presence of cavitation and an aggressive environment in the form of impacts of liquid droplets, damage begins in the form of deep pits with sharp edges that can combine into a honeycomb structure. The corrosion atlas [7] and reference books on corrosion identification and control contain images of various manifestations of corrosion-erosion with descriptions of control methods and examples of their application. Compared to oil wells, gas and gas condensate wells show a higher level of corrosion activity from the very beginning of operation.

This is because all natural gas fields produce a certain amount of water and also contain additional natural gas components that, condensing in the gas stream as the temperature and pressure drop, dissolve in water and make it corrosive. Most underground hydrocarbon deposits do not actually contain dissolved oxygen in their fluids. This is a favorable factor, since it is known that even a small amount of oxygen, even at the level of billions of volume fractions in the gas-liquid mixture of the flow, significantly enhances corrosion processes. At the same time, carbon dioxide (CO2) and hydrogen sulfide (H2S) can be present in different concentrations in the flows of raw materials from both oil and gas fields [9]. In-situ corrosion in the absence of oxygen depends on the concentration of CO2 and H2S in the downhole flows. The terms "sweet corrosion", which describes corrosion caused by CO2, and "sour corrosion", which indicates problems with H2S, are used to distinguish which of these two gases prevails in a particular area [7].

Other factors that affect the rate of corrosion processes in pipelines include temperature, pressure, fluid flow pattern on the metal surface, and impurities in the aqueous phase of the fluid [14].

In general, corrosion "attacks" have different characteristics that can cause uneven zones of metal loss along the inner surface of the pipe. The erosion-corrosion process is the result of a combination of an aggressive chemical environment and high fluid velocity along the inner surface of the pipe. This can occur due to the rapid movement of the flow near a stationary object or due to the rapid movement of the object in a stationary flow. It is generally accepted that there is a relationship between erosion-corrosion rates and flow turbulence. While flow structure can lead to serious corrosion problems due to its high velocity, erosion-corrosion per se is not observed in straight pipelines where there are no mechanical impurities.

However, when the flow pattern changes, such as in a hydraulically rough pipe or nozzle, liquid droplets or gas bubbles collide and generate shock waves that destroy the protective surface film. Particulate matter can cause accelerated attacks by removing the protective mineral or corrosion inhibitor film. However, flow regime maps do not reflect the effects of mechanical impurities such as sand, corrosion products or scale, which are known as erosion-corrosion accelerators.

In the mechanics of fracture of metal structures, the critical stress intensity parameter is widely used to assess the toughness of the metal, which characterizes the metal's resistance to crack opening and propagation. Its threshold (critical) value during tests in corrosive environments is denoted by Kssc, MPa·m1/2. Fatigue cracks in the samples were grown using a TsDMpu-10 hydraulic pulsator (Germany) at a loading frequency of 10-15 Hz and a cycle asymmetry factor of r=0.1-0.2. Tests to determine the Ki parameter were carried out at the UME-10 installation according to the standard method described in [14], both in air and in a corrosive solution with H2S (NASE method). The material for the study was pipe steel, the characteristics of which are given in Tables 1 and Table 2.

Table 1 – Steel brands and their purpose

Steel brands	**Purpose**	Heat treatment
10 20 20K 09g2s 17g1s VST3SP	Machine-building metal structures, oil and gas, metallurgical, chemical, agricultural, utility and other industries	Normalization

Table 2 – Chemical composition of steels

Steel brands	**Chemical composition of steels,%**							
	C	Si	Mn	P	S	Cr	Ni	Cu
10	0.12	0.30	0.55	0.035	0.035	0.15	0.10	0.10
20	0.20	0.30	0.55	0.035	0.035	0.15	0.10	0.10
20K	0.22	0.35	0.65	0.3	0.03	0.12	0.12	0.10
09g2s	1.12	0.37	1.80	0.025	0.025	0.08	0.05	-
17g1s	0.19	0.60	1.21	0.03	0.03	-	0.30	0.30
VST3SP	0.12	0.27	0.40	0.04	0.04	-	-	-

It was found that the samples of all steels withstood the full test cycle, in particular, none of the five samples of each series failed within 480 hours. At the same time, the analysis of the corrosion fatigue curves led to the following conclusions:

1) steel grades 10, 20, 20K and VX3sp have poor resistance to long-term alternating loading, in particular, after 10-15 years of operation, the ultimate long-term strength reaches stresses (150-220 MPa), the lower yield strength for these steels is 230-260 MPa, and the threshold (critical) stresses in the supports are 125-160 MPa. At the same time, 09G2S and 17G1S steels meet the requirements of the NACE standard (Standard MP-01-75-96), in particular, the σpore values are 250-262 MPa.

The results of calculating the ratio σpor/σt(σ0.2) for all grades of steel that were subjected to experimental research are shown in Table 3. The analysis of the data in Table 3 shows that the ratio σпор/σт(σ0.2) is exactly 0.86 (steel 09Г2С) and 0.89 (steel 17Г1С), i.e. these two grades of steel meet the requirements of the technical conditions of NACE, and therefore can be recommended for use in the manufacture pipes that are intended for operation in chemically aggressive environments that contain hydrogen sulfide;

2) based on the obtained experimental results, a diagram of the susceptibility to hydrogen sulfide cracking of unexploited steel grades: 10 was constructed; 20; 20K; 09G2S; 17G1C; VSt3sp. Shaded area - steels with high corrosion resistance against SCRN.

Table 3 – Threshold stresses and ratio σpor/σт(σ0.2) steels

Steel brands	Class characteristic	σpor MPa	σpor / σt(σ0.2)
10	ferritic	150	0,68
20	ferritic	145	0,51
20K	ferritic	160	0,66
09g2s	pearly	250	0,86
17g1s	pearly	262	0,89
VST3SP	ferritic	125	0,56

t was found that the samples of all steels withstood the full test cycle, in particular, none of the five samples of each series failed within 480 hours. At the same time, the analysis of the corrosion fatigue curves led to the following conclusions: 1) steel grades 10, 20, 20K and VX3sp have poor resistance to long-term alternating loading, in particular, after 10-15 years of operation, the ultimate long-term strength reaches stresses (150-220 MPa), the lower yield strength for these steels is 230-260 MPa, and the threshold (critical) stresses in the supports are 125-160 MPa. At the same time, 09G2S and 17G1S steels meet the requirements of the NACE standard (Standard MP-01-75-96), in particular, the σ_{pore} values are 250-262 MPa.

The results of calculating the ratio σpor/σt(σ0.2) for all steel grades that were the subject of experimental studies are shown in Table 3. Analysis of the data in Tab. 3 shows that the ratio σpor/σt(σ0.2) is exactly 0.86 (09G2S steel) and 0.89 (17G1S steel), i.e., these two steel grades meet the requirements of the Classifier of Economic Activities, and therefore can be recommended for use in the manufacture of pipes intended for use in chemically aggressive environments containing hydrogen sulfide; 2) based on the experimental results, a diagram of the susceptibility to hydrogen sulfide cracking of unexplored steel grades was constructed: 10; 20; 20K; 09G2S; 17G1S; VSt3sp. The shaded area shows steels with high corrosion resistance against SCRH.

Conclusions. The study and analysis of the problem of ensuring reliable corrosion and mechanical resistance of steel structures of oil and gas facilities is extremely important in the context of preserving and extending the service life of industrial equipment and pipelines. This study identified the main factors affecting corrosion and mechanical resistance, including the chemical composition and service life of the material, device features, and parameters of process media.

An important step in solving this problem is to improve the methods of monitoring the condition of structures and introduce advanced technologies into oil and gas production practice. One of the most promising areas is the development and application of effective monitoring and diagnostic methods, in particular, the use of the corona discharge effect to detect defects in dielectric coatings.

Given the growing activity of corrosion processes in the hydrocarbon industry, it is important to strengthen corrosion prevention and protection measures to ensure the reliability and durability of equipment and facilities of oil and gas complexes.

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Analysis of the calculation of support nodes bolted connections of cantilevered steel-reinforced concrete posts

Zakomirnyi Dmytro[1]*, Semko Oleksandr[2]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/ 0009-0005-9803-0324
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-2455-752X

*Corresponding author E-mail: dvz-@ukr.net

In order to reduce steel consumption in the installation of support nodes of cantilevered pipe reinforced concrete advertising structures, the optimal ratio of the base plate size and the diameter of the support node anchor bolts of an existing advertising structure was calculated. The analysis of the calculations revealed the total cost dependence of the support node and anchor bolts on the overall node dimensions and the anchor bolts diameter. With an increase in the size of the support node, the cost of the support node metal increases much faster than the cost of the anchor bolts decreases. For more efficient use of materials, it is necessary to reduce the size of the node and increase the diameter of the anchor bolts accordingly. As a result of the research and calculations, the most efficient support node was determined. The savings in the total cost of such a node is 8.9% compared to the existing support node of the studied advertising structure.

Key words: wind load, support node, bolted connection, cantilever construction.

Аналіз розрахунку болтових з’єднань опорних вузлів консольних сталезалізобетонних стійок

Закомірний Д.В. [1]*, Семко О.В.[2]

[1, 2,] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: dvz-@ukr.net

З метою оптимізації витрат сталі при влаштуванні опорних вузлів консольних трубобетонних рекламних конструкцій було розраховано оптимальний варіант співвідношення розміру опорної пластини та діаметру анкерних болтів опорного вузла. Для розрахунку діаметру та перерізу анкерних болтів було пораховано навантаження на вузол обпирання рекламної конструкції для п’яти різних значень вітрового тиску. Проаналізовано вплив зміни розміру опорної пластини консольної конструкції та відповідно відстань між анкерними болтами на розрахункові напруження в анкерних болтах для п’яти вітрових районів України. В результаті аналізу розрахунків було виявлено залежність загальної вартості опорного вузла та анкерних болтів від габаритних розмірів вузла та діаметра анкерних болтів. При збільшенні розмірів опорного вузла вартість металу опорного вузла зростає значно швидше ніж зменшується вартість анкерних болтів. Для більш ефективного використання будівельних матеріалів необхідно зменшити габаритні розміри опорного вузла і відповідно збільшити діаметр анкерних болтів. Для кожного вітрового району існує оптимальне співвідношення розміру бази, товщини бази та діаметру анкерних болтів. В результаті проведених досліджень та розрахунків існуючої рекламної конструкції з рекламним щитом розміром 6,0м на 3,0м що розміщено на висоті 4,0м (у м. Полтава) найбільш ефективним виявився вузол обпирання з габаритним розміром бази колони 500х500мм в комбінації з анкерними болтами діаметром 36мм. Економія загальної вартості такого вузла становить 8,9% в порівнянні з вартістю існуючого вузла обпирання досліджуваної рекламної конструкції. Подальше зменшення габаритних розмірів вузла обпирання веде до збільшення загальної вартості вузла обпирання за рахунок збільшення діаметрів та відповідно і вартості анкерних болтів.

Ключові слова: вітрове навантаження, опорний вузол, болтове з’єднання, консольна конструкція.

Introduction

The support nodes of cantilever structures serve to properly transfer forces and moments from the metal structure of the post to the structure foundation. Most often, bases with traverses are used, where the traverses serve as additional elements that contribute to the uniform loading of the base plate.

The peculiarity of cantilever nodes is the high torque moment acting on the nodes and the relatively low vertical load, unlike the support nodes of industrial buildings, where the nodes perceive high vertical loads from the weight of the supporting structures and the payload of the building.

In cantilevered structures, the connection between the column and the foundation must be rigid, i.e., ensuring that the column base is connected to the foundation without turning the column in relation to the foundation.

Cantilever support nodes are widely used in advertising structures throughout Ukraine and are most often installed on free-standing reinforced concrete foundations.

More than seventeen thousand cantilever advertising structures have been installed in Ukraine. Given the large number of existing advertising structures and the constant installation of new ones, this task is urgent, as cases when the support units do not withstand the design loads are not at all rare.

a)

b)

Figure 1 – Advertising structures that did not withstand the load (a, b).

And since advertising structures, for greater commercial effect, are mostly placed in places with large crowds of people or a large flow of cars, the reliability of such structures is very important.

Examples of advertising structures that failed to withstand the load (see fig. 1).

In most of the cases analyzed, it is the cantilever structure's support node that fails to withstand the load.

Review of the research sources and publications

Ensuring the reliability and failure-free operation of buildings and structures depends to a large extent on the standardization of wind loads. To correctly calculate the forces acting on a structural support node, it is necessary to calculate the wind load on a cantilevered structure.

The issue of calculating wind pressure on structures is covered in the work of Pichugin S.F. [1]. The wind zoning of the territory of Ukraine takes into account the significant territorial variability of the wind load. The territorial zoning of the territory of Ukraine according to the characteristic values of the wind load includes five territorial districts with calculated characteristic values from 0.4 to 0.6 kPa. The lowest wind loads are observed in the central and northwestern regions of Ukraine, as well as in Zakarpattia. The highest wind loads are realized in the Carpathians, Prykarpattia and coastal areas.

The methodology of administrative-territorial zoning of climatic loads on building structures based on the establishment of a single design value for a certain administrative region is described in the work of Pashinsky V.A. [2].

The methodology for determining loads and impacts on building structures based on the data of a local network of weather stations is covered in the work of Pashinsky V.A. [3], where the methodology for determining loads and impacts on building structures at a given local weather station is improved by introducing reserves that take into account the random scatter of data from the nearest weather stations.

Foreign researchers have also covered the issues of calculating the wind load on cantilever advertising structures. In particular, the article “Wind Loads on Solid Signs” [4] calculates the wind load taking into account the overall dimensions of the advertising structure, the height of placement above the ground with the use of correction factors. The calculation of wind loads on buildings and structures is described in [5-6].

A parametric analysis of wind effects on tall buildings according to European, American, and Australian standards was conducted in work “A parametric analysis of wind effects on tall buildings according to European, American, and Australian standards” [7]. The calculation of wind loads takes into account various factors, including wind speed, effective wind speed, orographic factors, dynamic factors, load gust factors, and shape factors. All of these factors vary slightly in different design codes. The impact results are compared using computer programs to find out the similarities and differences in the different design approaches.

Examples of calculating bolted joints for strength depending on the forces in the bolts and the tensile strength of the bolts are given in the textbook Steel Structures in Construction [8].

An increase in the safety margin of threaded connections operating under variable loads is highlighted in the work by Nevdakha Y.A., Pyrogov V.V., Nevdakha N.A., Oleinichenko L.S., Vasylkovsky M.O. [9]. When calculating the ultimate working load acting on a bolt, which varies according to a pulsating cycle for a tightened threaded connection, the conditions of no fracture and no opening of the joint are determined, and the relationship between the safety margin of the bolt and the value of the initial tightening is revealed, which is of great practical importance. The correct choice of the initial tightening value, ceteris paribus, provides the highest safety margin, which is a condition for reliable operation of the bolted joint.

Foreign researchers have also highlighted the problem of calculating bolted connections of the cantilever structure's support node. The calculation of the bolted connection of the end cantilever beam is presented in the article Bolted Connection of an End-Plate Cantilever Beam: The Distribution of Operating Force [10], which presents an alternative method for calculating the distribution of operating forces on bolts and the calculation results were also confirmed by measurements of actual forces in the bolts. The problem of calculating bolted connections of the column support node is also considered in the article “Tensile Behavior of Asymmetric Bolted Square Hollow Section Column Splices” [11].

Modeling of bolted connections is also discussed in other articles [11-12].

Definition of unsolved aspects of the problem

The reliability of an advertising structure largely depends on the reliability of the support node. Calculating all the loads acting on the support node and determining the optimal ratio between the calculated overall dimensions of the support node and the diameter of the anchor bolts is the key to efficient use of building materials and ensuring the standard service life of the cantilever advertising structure.

Problem statement

The purpose of the study is to optimize the size and types of cantilever support nodes and calculate their performance depending on the type of the nodes usage and the load on the nodes for the most rational use of building materials and labor while maintaining the bearing capacity of the support node throughout the entire standard service life of the structure.

Basic material and results

A large number of advertising structures in the region were studied and it was found that most of the existing supporting units of advertising structures have similar dimensions and fundamental solutions. According to the calculations, the total number of existing cantilever advertising structures (billboards) located in Poltava is more than 350.

The general view of the advertising structure accepted for further research is shown in Figure 2.

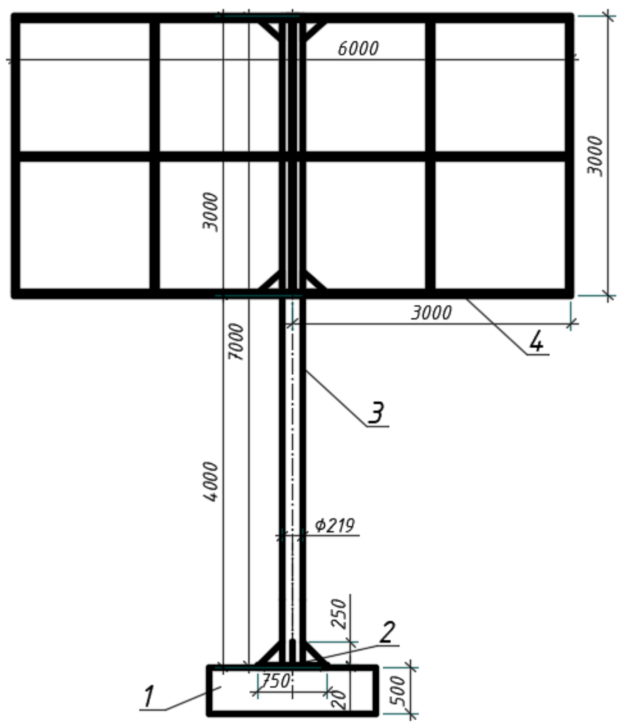

Figure 2 - General view of the cantilever advertising structure.
1 – supporting structure, 2 – supporting node of the advertising structure, 3 – stand, 4 – advertising board.

According to the analysis of the sizes and types of existing structural bases, it was found that more than half of the cantilever structures have the same size and design scheme of the support nodes, as shown in Fig. 3.

a)

b)

Figure 3 - The most common support nodes (a, b).

For further study and demonstration of the calculation methods, the most common support node in the form of a column base measuring 750x750 mm with a base plate thickness of 20 mm was chosen. The studied advertising structure stand is made of a steel pipe with a diameter of 219x8 mm. For rigidity, the assembly has four stiffeners with a thickness of 8 mm each.

The design scheme of the studied node is shown in Figure 5.

The anchor bolt was chosen as one of the most common among the studied support nodes, with a metric thread M27, with a total length of 1000 mm, of which 200 mm is used to secure the base, 400 mm is buried in the concrete foundation and 400 mm is bent at an angle of 90 degrees to securely fix the anchor bolt in the foundation. The most common height of the foundation slab in the studied advertising structures is 500 mm, and the overall dimensions of the foundation itself are 1800×2200 mm.

To calculate the diameter and cross-section of the anchor bolts, the load on the support node of the advertising structure was calculated for five different wind pressure values.

The wind load is a variable load for which two design values are established: the limit and operational design values. The limit design value of the wind load is calculated according to formula 9.1 of DBN B.1.2-2:2006 "Loads and Impacts" [14]:

$$W_m = \gamma_{fm} \cdot W_0 \cdot C$$

where, γ_{fm} – reliability factor of the designed wind load limit value, determined according to 9.14 [14]. γ_{fm} = 0,82;

W_0 – characteristic value of wind pressure, determined according to 9.6 [14]. W_0 = 400 Pa;

C – coefficient is determined according to formula 9.3 [14].

$$C = C_{aer} \cdot C_h \cdot C_{alt} \cdot C_{rel} \cdot C_{dir} \cdot C_d$$

where, C_{aer} – aerodynamic coefficient;

C_h – height coefficient of the structure, determined according to Table 9.02 [14], adopted for the II type of terrain;

C_{alt} – geographic altitude coefficient, determined according to 9.10 [14];

C_{rel} – relief coefficient, determined according to 9.11 [14];

C_{dir} – directional coefficient, determined according to 9.12 [14];

C_d – dynamic coefficient, determined determined according to 9.13 [14];

The coefficient C for the stand element and for the billboard will be fundamentally different, so we divide the structure into two parts. Part I is the stand, and part II is the billboard. Determine the wind load for each part separately. Division of the structure for calculation into parts I and II (see Fig. 4).

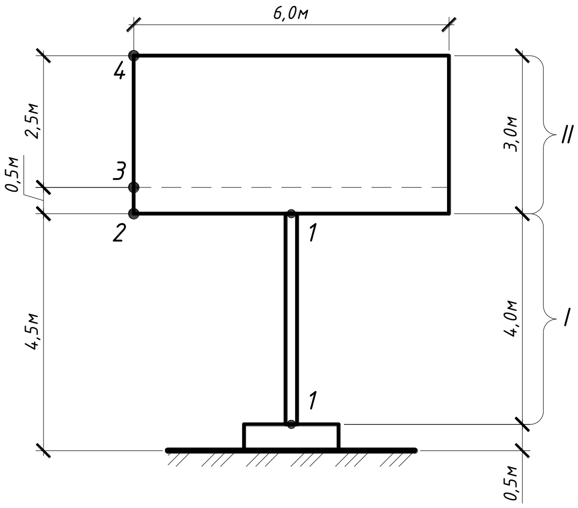

Figure 4 - Division of the structure into parts I and II. Points of determination of the building height coefficient C_h.

Wind load for part of the structure I (stand).

Determine the value of the coefficient C_I.

$$C_I = C_{aer} \cdot C_{h1} \cdot C_{alt} \cdot C_{rel} \cdot C_{dir} \cdot C_{d1}$$

were, C_{h1} = 1,2; C_{alt} = 1; C_{rel} = 1; C_{dir} = 1.

C_d – the dynamic coefficient is taken according to the graph shown in Fig. 9.8 [14]. Since the graph data are not available for such a structure (diameter 0.22 m, height 4.5 m), the value of 1.2 is taken; the dynamic coefficient is taken according to the graph shown in Fig. 9.8 [14]. Since the graph data are not available for such a structure (diameter 0.22 m, height 4.5 m), the value of 1.2 is taken;

C_{aer} – the aerodynamic coefficient for a round pipe in the plan is in the form of Cx – drag coefficient and is determined according to Annex I, Figure 14 [14].

$$C_x = k \cdot C_{1\infty}$$

where, k is determined according to Table 1 of Scheme 13 of Annex I [14];

$C_{1\infty}$ is determined according to the graph in Annex I, Figure 14 [14].

Determine k:

To determine k, we need to find the value of λ_e and λ.

λ_e is determined according to Table 2 of Figure 13 and is equal $\lambda_e = 2\ \lambda$, where $\lambda = L/b$.

$$L = 4 \text{ m},\ b = 0.22 \text{ m}$$

$$\lambda_e = 2 \cdot (4 \div 0{,}22) = 36.4$$

By interpolating the values from Table 1 of Figure 13, we determine that k = 0.86.

Determine $C_{1\infty}$:

To determine the value of $C_{1\infty}$ from the graph, it is necessary to find the value of Reynolds number Re using the formula in the table of Scheme 12a of Annex I [14].

$$\mathrm{Re} = 0{,}88 \cdot d \cdot \sqrt{W_0 \cdot k(z) \cdot \gamma_{fm}} \cdot 10^5$$

where, d = 0.22 m (diametr);

$k_{(z)} = C_{h1} = 1{,}2$; $\gamma_{fm} = 0.82$; $W_0 = 400$ Pa.

$$\mathrm{Re} = 0{,}88 \cdot 0{,}22 \cdot \sqrt{400 \cdot 1{,}2 \cdot 0{,}82} \cdot 10^5 = 3{,}84 \cdot 10^5$$

According to the graph of Figure 14 [14], we find the value of $C_{1\infty}$, which is 0.45.

We ignore the value of Λ, since in this calculation the range of determination from the graph does not depend on the specified indicator.

Thus, the drag coefficient Cx is equal

$$C_x = 0.86 \cdot 0{,}45 = 0.387$$

Now we calculate the coefficient C_I:

$$C_I = 0.387 \cdot 1{,}2 \cdot 1 \cdot 1 \cdot 1 \cdot 1{,}2 = 0.557$$

Calculate the wind pressure on the stand

$$W_1 = 0.82 \cdot 400 \cdot 0.557 = 183 \text{ Pa}$$

Wind load for part of the structure II (billboard)

Taking into account the height of the billboard above the ground, the billboard structure is divided into three points (#2, #3, #4, see Fig. 4) to more accurately determine the wind load.

$$C_i = C_{aeri} \cdot C_{hi} \cdot C_{alt} \cdot C_{rel} \cdot C_{dir} \cdot C_d$$

where, $C_{alt} = 1$; $C_{rel} = 1$; $C_{dir} = 1$;

i – the number of the point for which the calculation is performed

C_d – is determined according to Figure 9.8 [14] and is equal to 1;

$$C_{h2} = .2;\ C_{h3} = 1.2;\ C_{h4} = 1.35;$$

C_{aer} – has the form C_e and is defined in Annex I, Scheme 1. This coefficient takes into account drag pressure (C^+_e) and wind pressure (C^-_e) and will have the same value for all points, namely C^+_e=0.8, C^-_e= -0.6.

We calculate the coefficient C_i for each of the points, taking into account drag and wind pressure:

$$C^+_2 = 0.8 \cdot 1.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 0.96$$

$$C^-_2 = -\ 0.6 \cdot 1.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = -0.72$$

$$C^+_3 = 0.8 \cdot 1.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 0.96$$

$$C^-_3 = -\ 0.6 \cdot 1.2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = -0.72$$

$$C^+_4 = 0.8 \cdot 1.35 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 1.08$$

$$C^-_4 = -\ 0.6 \cdot 1.35 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = -0.81$$

Since the actual movement of the structure due to drag and wind pressure is in the same direction and to reduce the number of calculations, we add these two coefficients for each of the points. The calculations show that the values of the coefficients C for sections 2 and 3 are identical, so we further assume the values at these points to be equal.

$$C_{2,3} = C^+_{2,3} + |C^-_{2,3}| = 0.96 + 0.72 = 1.68$$

$$C_4 = C^+_4 + |C^-_4| = 1.08 + 0.81 = 1.89$$

Calculate the wind pressure on the billboard:

$$W_{2,3} = 0.82 \cdot 400 \cdot 1.68 = 551 \text{ Pa}$$

$$W_4 = 0.82 \cdot 400 \cdot 1.89 = 620 \text{ Pa.}$$

Thus, the maximum calculated value of wind pressure on the billboard W_m is 585.5 Pa.

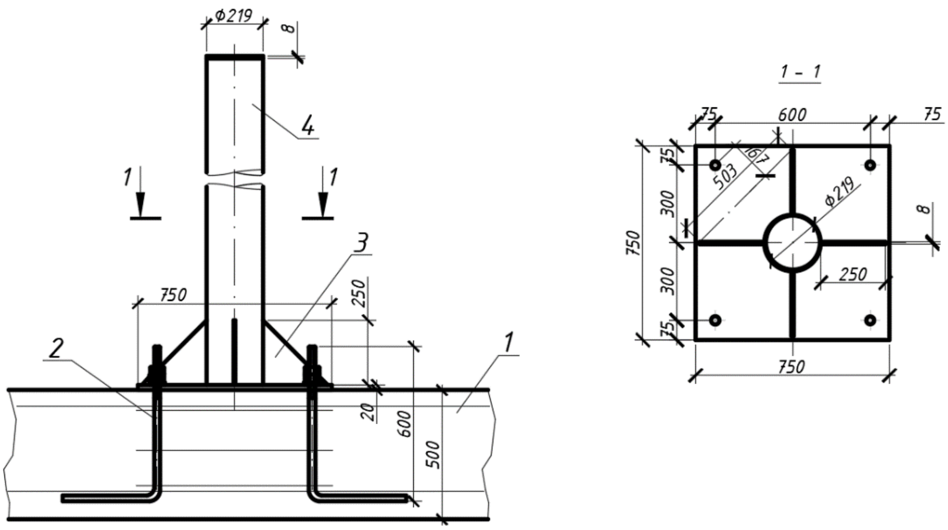

Figure 5 - Design scheme of the studied support node:

1 – supporting structure, 2 – anchor bolt, 3 – supporting node of the advertising structure, 4 – stand.

The dimensions of the base plate in the plan depend on the design requirements for placing the column cross-section, traverses and stiffeners on the plate. The slab works as a plate on an elastic base that absorbs the pressure from the column and the traverses.

The thickness of the slab was determined based on its bending behavior in the areas between the traverses. The thickness of the base slab was calculated using formula 11.1 of DBN B.2.6-198:2014 [15]:

$$\delta_n = \sqrt{\frac{6 \cdot M_{\max} \cdot \gamma_n}{R_y \cdot \gamma_c}}$$

The maximum and minimum stresses in the base plate of the support node are determined by the formula:

$$\sigma = N/A \pm M/W$$

The length of the compressed zone of the slab is calculated by the formula:

$$c = (\sigma_{max} / (\sigma_{max} + |\sigma_{min}|)) \cdot L$$

The distance from the equidistant compressed zone to the center of the bolts of the tensile zone is:

$$y = L - c/3 - e \quad [8].$$

The force in the tensile anchor bolts is determined by the formula:

$$Z = (M - N \cdot a) / y$$

The following condition must be observed:

$$z / (n \cdot S) \leq R_{ba} \cdot 0{,}8$$

The tensile resistance of anchor bolts (R_{ba}) is taken from Table D6, Annex D, DBN B.2.6-198:2014 [15].

At the next stage, we calculated the loads acting on the support node of the advertising structure and, accordingly, on the bolted connections, depending on the location of the advertising structure in different wind regions of Ukraine. The calculated values of the loads of the existing advertising structure located in different wind regions of Ukraine are shown in Table 1.

Table 1. Calculated load values of an existing advertising structure located in different windy regions of Ukraine.

Windy region	Wind pressure characteristic value W_0, Pa	Maximum design value of wind pressure on a billboard W_m, Pa	Moment at the bearing node, kN*cm	Forces in tensile bolts, kN
1	400	585,5	6171,0	106,14
2	450	658,7	6941,0	120,24
3	500	731,8	7712,0	134,35
4	550	805,0	8484,0	148,49
5	600	878,2	9255,0	162,61

Rigid column bases should have at least four anchor bolts, which prevents the column from turning on the support after the bolts are tightened.

At the next stage of the research, the size of the column base was reduced and increased, and the loads acting on the support node of the advertising structure were calculated to determine the optimal ratio. In total, eight variants of the size of the support nodes were calculated for five windy regions of Ukraine.

The effect of changing the size of the base plate of the structure and, accordingly, the distance between the anchor bolts on the calculated stresses in the anchor bolts for five windy regions of Ukraine was analyzed.

The results of calculations of the base size changing effect and, accordingly, the change in the force in the anchor bolts for the third wind region of Ukraine (Poltava) are shown in Table 2.

As a result of the calculations, the following dependencies were noted: with an increase in the overall size of the base and, accordingly, an increase in the distance between the anchor bolts, the stress in the anchor bolts decreases, which means that their diameter decreases, but the total weight of the support assembly increases and, consequently, its cost.

Given that the cost of anchor bolts per unit weight is one and a half times higher than the cost of metal structures per unit weight of the support node, there is an optimal ratio of base size, base thickness, and anchor bolt diameter for each wind region.

The analysis of the calculations revealed the dependence of the total cost of the support node and anchor bolts on the overall dimensions of the assembly and the diameter of the anchor bolts.

The verification calculation of the bearing capacity of the existing support node under study (type 5), column base size 750x750 mm, and anchor bolt diameter 27 mm) showed that the anchor bolts with a diameter of 27 mm used in this assembly cannot withstand the design load for the third wind area. The force in the anchor bolts is 1.6% greater than the design resistance of the anchor bolts. It was proposed to increase the size of the column base to 800x800 mm (type 6) - in this case, the force in the anchor bolts is less than the maximum resistance.

Table 2. Estimated values of loads and cost of different sizes of the advertising structures supporting nodes.

Indicator	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node	Dimensions of the support node
Overall size of the support node base	mm	400x400	500x500	600x600	700x700	750x750	800x800	900x900	1000x 1000
Distance between anchor bolts	mm	250x250	350x350	450x450	550x550	600x600	650x650	750x750	850x850
Force in two stretched bolts	kN	285,25	215,84	173,66	145,31	134,35	124,94	109,61	97,64
Resistance to stretched bolts, 2 pcs	kN/cm^2	12,73	13,23	10,64	12,95	14,64	13,61	11,94	13,83
Weight of the support node with anchor bolts	kg	120,34	104,04	110,40	118,32	121,87	126,87	133,37	147,63
Cost of the support node with anchor bolts	UAH	15923	13411	14115	14413	14514	15069	15791	17151
Percentage of anchor bolt cost in the support node cost	%	46,55	40,56	38,54	26,18	20,71	19,95	19,03	13,88
Percentage of anchor bolt weight in the total weight of the support node	%	36,23	30,76	28,99	18,76	14,51	13,94	13,26	9,48
Anchor bolts design diameter	mm	42	36	36	30	27	27	27	24
Cost of anchor bolts	UAH	7412	5440	5440	3774	3006	3006	3006	2380
Cost of the support node without anchor bolts	UAH	8511	7971	8675	10639	11508	12063	12785	14771
Design thickness of the column base	mm	40,3	28,9	20,5	16,3	15,8	14,4	12,1	10,3
Accepted thickness of the column base	mm	40,0	30,0	25,0	20,0	20,0	16,0	14,0	12,0

After analyzing the results of research and calculations of different sizes of the column base, we can conclude that the existing support assembly (type 5), which costs 14514 UAH, is not optimal in terms of material efficiency (see Fig. 6).

As the size of the support node increases, the cost of the support node metal increases much faster than the cost of the anchor bolts decreases.

For more efficient use of materials, it is necessary to reduce the node size and increase the diameter of the anchor bolts accordingly.

As a result of the analysis and calculations, the most effective was the support node type 2, the overall size of the column base is 500x500 mm in combination with anchor bolts with a diameter of 36 mm. The cost of such a unit is UAH 13411.

The savings in the total cost of such a node is 8.2% compared to the existing support node (type 5).

A further reduction in the overall dimensions of the bearing node leads to an increase in the total cost of the bearing node due to an increase in the cost of anchor bolts.

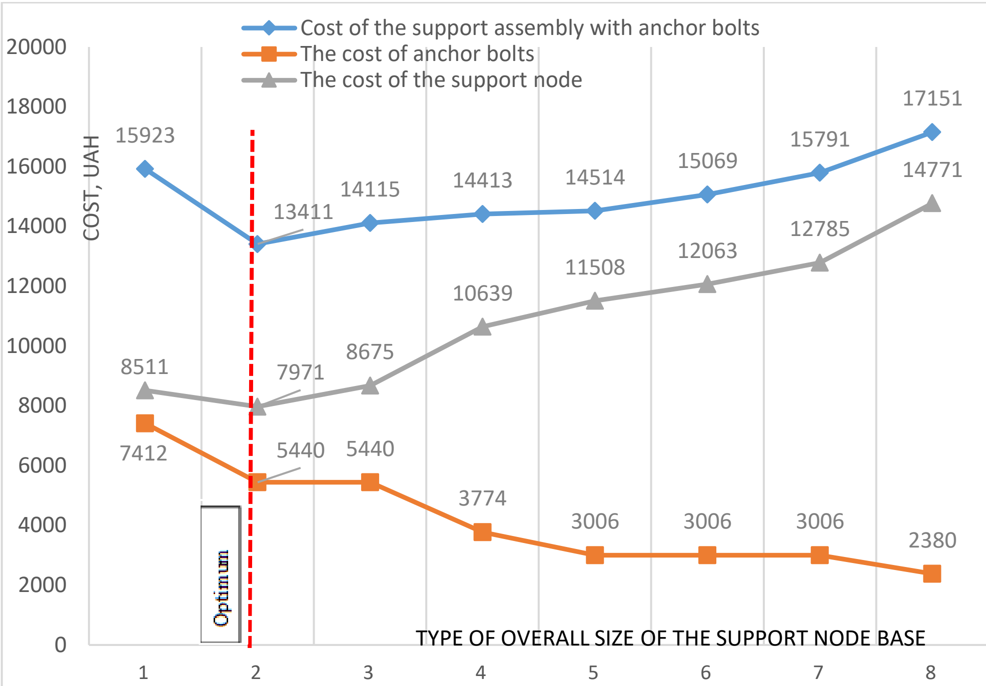

Figure 6. Dependence of the the support node cost on the support node base size and anchor bolt diameters for the third wind region of Ukraine.

Conclusions

For each wind region, there is an optimal ratio of base size, base thickness, and anchor bolt diameter. As a result of the calculations, and analysis of the graphs presented in Figure 6, the most efficient support node for Poltava was proposed. The savings in the total cost of such a node is 8.9% compared to the cost of the existing support node of the studied advertising structure.

In particular, in our opinion, filling the advertising structure's stand with concrete has relatively low financial costs, but it can significantly improve the bearing capacity of the support node, and therefore the bearing capacity of the cantilever structure as a whole, which will positively affect the reliability of the node and may increase its failure-free time.

If the destroyed tubular advertising structures that were destroyed due to the failure of the support node had been filled with concrete, half of the node failures could have been avoided.

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Retrospective analysis of wall waterproofing structures to determine the main directions of the relevant restoration work

Oleksandr Semko[1], Olena Filonenko[2]*, Yurin Oleg[3], Nataliia Mahas[4], Viktor Rudenko[5], Tetiana Ilchenko[6]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-2455-752X
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-8571-9089
[3] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-9290-9048
[4] Slovak University of Technology in Bratislava https://orcid.org/0000-0002-4459-3704
[5] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-7821-8147
[6] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-5034-3955
*Corresponding author E-mail: olena.filonenko.pf@gmail.com

The rationality of foundation and plinth construction largely depends on soil moisture, which is influenced by groundwater levels, precipitation, site grading, the quality of near-wall paving, and the use of hard landscaping. To determine effective structural solutions that prevent plinth dampness, a retrospective analysis of plinth designs across different historical periods was conducted. The study covers the mid-19th century to the present — a timeframe marked by major socio-economic changes and technological progress. The analysis revealed that before 1953, domestic construction lacked mandatory waterproofing standards due to the absence of mass-produced materials. Since 1956, with the shift to industrial construction, standardized waterproofing methods using mass-produced materials were introduced. Today, particularly in the context of reconstruction and restoration, local waterproofing challenges require tailored, site-specific solutions. The study underscores the importance of adapting historical experience to modern construction needs, ensuring effective moisture protection of wall foundations and plinths.

Keywords: waterproofing; foundation; plinth; historical buildings

Ретроспективний аналіз конструкцій гідроізоляції стін для визначення основних напрямів відповідних реставраційних робіт

Семко О.В.[1], Філоненко О.І.[2]*, Юрін О.І.[3], Магас Н.М.[4], Руденко В.В.[5], Ільченко Т.М.[6]

[1, 2, 3, 5, 6] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[4] Словацький технічний університет в Братиславі
*Адреса для листування E-mail: olena.filonenko.pf@gmail.com

Раціональність конструктивного рішення фундаментів і цоколів будівель залежить від кількості вологи у ґрунті. На неї впливають: рівень ґрунтових вод, атмосферні опади, якість вертикального планування прибудинкової території, якість виконання будівельних робіт при формуванні вимощень у пристінній частині будинків та наявність твердих покриттів у благоустрої прибудинкової території. Для визначення раціональних конструкційних рішень, що перешкоджають зволоженню цокольних частин будинків було проведено ретроспективний аналіз варіантів конструкцій цоколів будинків у різні часові періоди. Розлянуто період з середини Х1Х століття до наших часів, адже у цей період відбулося у будівництві ряд змін, пов'язаних з соціально-економічними перетвореннями у суспільстві та значний науково-технічний прогрес. Внаслідок ретроспективного аналізу конструкцій гідроізоляції прифундаментних частин стін встановлено, що до 1953 року у вітчизняній практиці будівництва була відсутня обов'язкова вимога влаштування такої гідроізоляції через відсутність масового виробництва відповідних матеріалів. З 1956 року з переходом будівництва на індустріальну основу, були напрацьовані як типові варіанти гідроізоляції стін з використанням матеріалів, що масово вироблялися. В сучасних умовах практики будівництва, особливо у таких напрямках як реконструкція і реставрація, необхідно використовувати індивідуальний підхід для вирішення локальних проблем гідроізоляції стін будинків.

Ключові слова: гідроізоляція; фундамент; цоколь; історичні будівлі

Introduction

When surveying buildings, special attention should be paid to the part of the walls that are in the zone of the greatest influence of moisture and temperature - the plinths of buildings. After all, it is located in the zone of active moisture during rains, since part of the liquid precipitation from the roof of the buildings, even with organized drainage, overflows beyond the roof and falls on the pavement near the wall and splashes moistens the plinth from the outside. The plinth also receives some of the water that runs off the wall surface during slanting rains. Another factor of moisture can be improper planning of the territory where the house is located. If the ground surface slopes towards the house, excessive moisture accumulates near the wall, both on the soil surface and below the surface, which also contributes to the moistening of the plinth. The above options for moisturizing can be called surface contact.

Another option for moistening is capillary moistening. The plinth is located directly on the foundation, which is immersed in the ground to its full height. The humidity of the foundation depends on the amount of moisture in the soil, as well as the properties of the materials of these parts of the house, namely, porosity, which create conditions for the movement of moisture towards the basement. The rationality of the design of foundations and basements depends on the amount of moisture in the soil. And it is influenced by the groundwater level, rainfall, the quality of the vertical layout of the adjacent territory, the quality of construction work in the formation of blind areas in the wall part of the buildings and the presence of hard coatings in the improvement of the adjacent territory.

In buildings that are more than 100 years old, the foundations and basement are made of brick, so they are constantly wet. Over time, this has led to frost damage to the relevant structures.

To determine rational structural solutions that prevent moisture in the basement of buildings, it is worthwhile to conduct a retrospective analysis of the options for building basement structures in different time periods. The period from the middle of the nineteenth century to the present day is appropriate, since during this period a number of changes occurred in construction related to socio-economic transformations in society and significant scientific and technological progress.

Review of the research sources and publications

The problem of waterproofing building structures has been known for a long time [1] and is constantly being studied. Moisture and water in building structures are the subject of numerous studies [2-3]. The issue of waterproofing is important for the preservation of historic buildings [4-6]. The results obtained in such studies are used to develop practical recommendations for waterproofing building structures [7-8].

Definition of unsolved aspects of the problem

The restoration of historic buildings does not pay attention to the causes of moisture in the brickwork of the foundations and plinths, which results in frost damage to the bricks from the outside and mold formation inside the walls. Therefore, repair measures include only the replacement of the interior and exterior finishes of the wetting wall sections. This leads to their repeated destruction over a larger area.

Problem statement

The purpose of the publication is to investigate the specifics of the operation of historic buildings through a retrospective analysis of the design options for building basements in different time periods and to identify the main measures to restore waterproofing in their foundation zone.

Basic material and results

Since the mid-nineteenth century, three types of objects have been used in urban development on the territory of Ukraine, which at that time was part of the Russian Empire: mass housing, "elite" housing, and public buildings. Poltava was not spared from this practice of construction. The first two groups of objects listed above were different in terms of their functional features and materials used in their construction. Mass housing was small in size and had compact space-planning solutions. Such houses were built using a wooden rack and beam system with the frame filled with clay-sand mortar or clay concrete. Sometimes adobe was used. This is evidenced by the large number of old one-story houses in Poltava with this construction solution (Fig. 1).

Near such housing, as a rule, there are " lordly" houses, near which even outbuildings such as carriage sheds, barns, and cellars have been preserved. The second type of housing is structurally different from mass housing. The foundations, plinths, and the outer layer of the exterior walls are made of brick. The inner layer of the outer walls is made of wooden beams, approximately 200x200 mm in size. Attic floors in both types of houses are wooden (Fig. 2).

The third type of buildings, public buildings, built from the mid-nineteenth to the early twentieth century, have brick walls with lime mortar. Brick was then used in the construction of foundations, basements, and the bulk of not only the exterior and interior walls, but often in the construction of floors in the form of vaults and staircases based on arched structures. A striking example of such solutions is the Cadet Corps building in Poltava (Fig. 3).

The bricks made during the period under consideration differed from those used in modern construction practice. Thus, its dimensions were as follows: thickness was 67 mm; width - 134 mm (two thicknesses without a seam); length - 268 mm (two widths without a seam) [9].

Figure 1 - Residential buildings using a wooden frame with clay-sand mortar or clay concrete filling

Figure 2 - Residential buildings with brick walls and foundations

Figure 3 - Public building with brick walls and foundation

The brick-making technology also differed from the modern one. For example, clay was frozen and soaked for 3-4 days. This was followed by kneading the clay, and then forming bricks in wooden molds by hand-packing [9]. According to N. Fadeev [9], this technology of brick making using prolonged soaking of clay and its kneading before molding contributed to a decrease in the water permeability of bricks. A tangential proof of this is the practice of preserving damage to such garden and park objects as retaining walls, stairs by pouring crushed clay into cracks to prevent water and debris from entering the damage sites, as well as well-known recommendations for creating waterproofing layers near the foundations of crushed clay. In order to obtain indisputable evidence of the possibilities of using ancient bricks to protect walls from capillary moisture, it is necessary to study in the future the change in brick properties depending on the peculiarities of its manufacturing technology.

When inspecting the structures of the ground parts of the walls of all the above types of buildings built before the 30s of the twentieth century, it was found that there is no horizontal waterproofing between the foundations and the basement parts of buildings using special waterproofing materials. Obviously, there is a functional need for waterproofing, but there are no appropriate construction solutions using special waterproofing materials. Or this problem was partially solved by using bricks with high resistance to water penetration.

In professional literature sources of different years of publication, the theory of using horizontal waterproofing in the ground part of the walls of buildings is given a different amount of attention. For example, in the 1930 edition of the manual for technical schools authored by N. Fadeev [9], in the section on masonry work, the performance of work in the construction of brick walls is considered in detail. But there is no information about the waterproofing device. The figures showing a section of the outer wall do not show the location of the waterproofing. One could conclude that the issue of moisture protection of building walls is not addressed. However, the section on building adobe walls focuses on the installation of waterproofing: "If there is a possibility of soil dampness, which is especially harmful to adobe, then a layer of roofing felt, birch bark, or other similar material is laid on the foundation under the walls themselves." To protect the adobe wall from rain and snow water, it is not recommended to use a protruding plinth. It is recommended to build a wall of adobe so that its plane coincides with the plane of the foundation or plinth. From this we can conclude that in the practice of construction until the 30s of the twentieth century, the influence of moisture on the wall structure, namely its basement, was taken into account, but to protect against it, wall and foundation materials with minimal hygroscopicity at that time were used.

As for the mass housing, it was protected from moisture in the ground part of the walls by using "pryzby", which was a thickening of the lower part of the wall to a height of 500-600 mm (Fig. 4). The "pryzba" traditionally protruded 400-500 mm from the wall plane and served as a pavement that diverted rain and snow water from the adobe walls and as insulation for the ground part of the wall. This element of the house is an element of folk national architecture, so the peculiarities of their design solutions are not discussed in detail in the professional literature, since the methods of folk construction are not a component of the formation of the ideology of construction industrialization, which had already begun at the time under consideration.

Figure 4 – Residential building with a "pryzba"

Since the 30s of the twentieth century, significant changes in all areas of construction activity have begun. A system for standardizing the parameters of building materials was created. Thus, the governing bodies of the national economy decided to standardize the dimensions of bricks: length - 250 mm, width - 120 mm, height - 65 mm [9]. New building materials appeared with their detailed descriptions in the professional literature, especially after 1945. Taking into account the peculiarities of the historical period, a large amount of reference literature is published, for example, reference books [10], [11]. Regulatory documents are being adopted, such as the "Technical Specifications for the Performance and Acceptance of Construction Works" [12] and the like.

In the reference literature of 1950 [10], it is recommended to use various types of roofing material for waterproofing. The reference book of 1955 [11] also lists roofing felt as a waterproofing material with different markings and recommended purposes. A common feature of both of these publications is that neither of them contains recommendations for the use of rolled waterproofing in walls. Only as a roofing material for roofs.

Strict requirements for the installation of protection against soil moisture of foundations and ground parts of walls appeared simultaneously with the introduction of technical conditions for the performance and acceptance of construction work, which were adopted in 1953 [12]. The section "Works on the Installation of Waterproofing" in the part "Waterproofing of Walls" contained a list of mandatory works to protect walls and pillars from capillary moisture.

Cement-sand mortar (with a ratio of at least 1:2) in the upper part of the foundation or in the lower part of the wall; coatings based on black binders; cast asphalt, rolled materials in one layer or in several layers, interconnected with bitumen (black) binders "with significant soil moisture" were recommended as waterproofing materials.

The technical conditions strictly limited the location of horizontal waterproofing in exterior walls - not lower than 10 cm from the level of the pavement or sidewalk. For interior walls - not lower than the upper level of preparation for floors [12].

Since 1956, construction in Ukraine has been in a state of maximum industrialization, meaning that all types of architectural and construction activities were clearly regulated. Information and regulatory professional publications were centralized. Construction according to standard projects developed by central research and design and experimental institutes gained significant momentum. In parallel with the development of unified and standardized space-planning solutions, unified options for protecting the foundations and basements of buildings were developed, based on two main structural solutions - the use of coating waterproofing with hot bitumen in 2 times, as well as the use of rolled waterproofing of two layers of roofing material in various variations. Such waterproofing options were presented in almost all textbooks and manuals for the professional training of architects and builders.

This put an end to the use of ambiguous options for waterproofing the ground parts of the walls of buildings, the volume of construction of which, due to industrialization based on the unification and typification of design, construction, production of building materials and structures, reached huge volumes in the 60s-80s of the last century. An example is the emergence of such neighborhoods as Almaznyi, Polovky, Levada, Sady-1, Sady-2, and Ognivka in Poltava during this period. During this period, Poltava's development was actually divided into two parts:

1) the old city, created by the buildings of the nineteenth and first half of the twentieth century.

2) the new city, created by the buildings of the 60s and 90s of the twentieth century.

The current state of the old city's buildings is often more than 100 years old, and therefore requires survey work and recommendations to overcome the functional and structural deficiencies identified during the survey. The specialists of Department of Construction and Civil Engineering of National University "Yuri Kondratyuk Poltava Polytechnic" carry out such works. One of such works was the study of the possibility of a new material for waterproofing a wall in a nineteenth-century building. In such cases, the use of traditional solutions is not appropriate. There is a need to use individual approaches based on the latest achievements in the production of building materials, structures, and technologies.

Individual approaches to solving professional problems in construction have become especially relevant in terms of the operation of existing housing stock, public and industrial buildings, because buildings built in the early twentieth century have been under the influence of external and internal factors, with the active influence of anthropogenic factors, i.e., those related to human activity, throughout their operation.

One of the most common problems in old buildings is excessive moisture in the ground part of the walls. To solve this problem, a group of specialists from the above-mentioned department investigated the effectiveness of using the injectable liquid "AQUAMAT-F" [13] to protect against moisture in the foundation part of the wall in a nineteenth-century building. To do this, the wall was perforated in the foundation part of the wall, and a waterproofing liquid was injected into the wall under minimal pressure through the resulting holes, which reduced the wall's moisture content by half. The absence of waterproofing in the wall used in the experiment is quite logical, since, as has already been proven by retrospective analysis, in the nineteenth and early twentieth centuries there were no reliable waterproofing materials, but at the beginning of the twenty-first century there is already a whole palette of waterproofing materials that have already become traditional, and new ones are emerging.

The method of hydrophobic injection is not effective for thick walls (over 1000 mm), for walls with a heterogeneous structure (voids) and for dense bricks. Under such conditions, the historical method of drying the foundations of the central building of National University "Yuri Kondratyuk Poltava Polytechnic" was restored, namely the method of installing external ventilation screens (tunnels). To install a ventilation screen that drains the underground part of the wall, a ditch has to be dug along the building, the bottom of which is 15 cm below the basement floor level. At the bottom of the ditch, a concrete foundation for the retaining wall is arranged. At a distance of 20 cm from the outer wall of the building, a retaining wall 30 cm thick is arranged. A channel 15 cm wide and 20 cm deep is punched in the masonry wall of the building. The channel starts 10 cm above the floor level. The channel needs to be insulated. Longitudinal section in Fig. 5, cross sections of the ventilation duct are shown in Fig. 6.

It is recommended to plaster the plinth to a height of 80 cm with a system of sanitizing plasters, for example, Ceresit WTA.

Works on the installation of the "sanitizing plaster system" shall be performed according to the following technology:

1) Prepare the substrate (remove old plaster, perform a depth of approximately 20 mm of masonry joints (which crumble and crumble) and antifungal treatment, primer the surface to strengthen the substrate and bind dust residues;

2) Apply a semi-finishing coat to the surface of the walls to increase the strength of the plaster bond with the substrate. The semi-spray should cover approximately 50% of the surface area of the substrate in the form of a grid, about 5 mm thick.

3) Apply a layer of plaster, leveling and grouting. After the plaster has hardened and dried (not earlier than 28 days), the finishing coating (facade silicate paint) can be applied.

4) Clean the area 2 m wide from the wall from bio-contamination, arrange a concrete blind area 1.2 m wide with a slope of 0.05%.

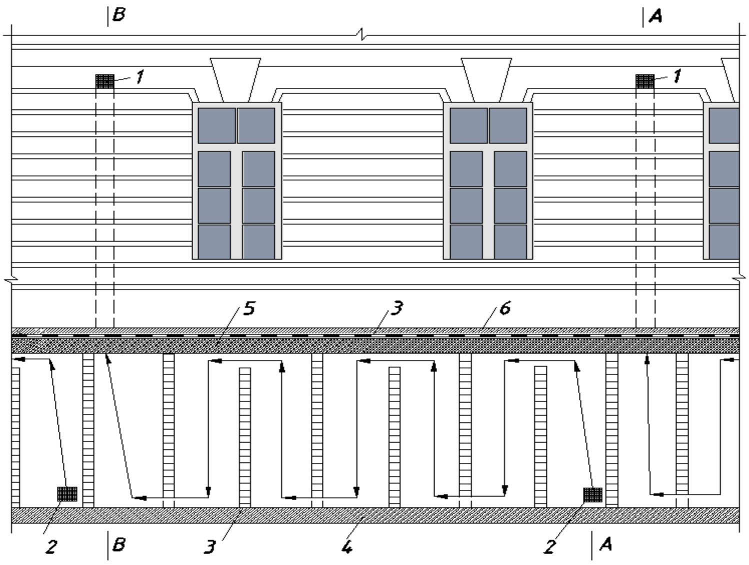

Figure 5 – Figure 6 - Longitudinal section of the ventilation duct

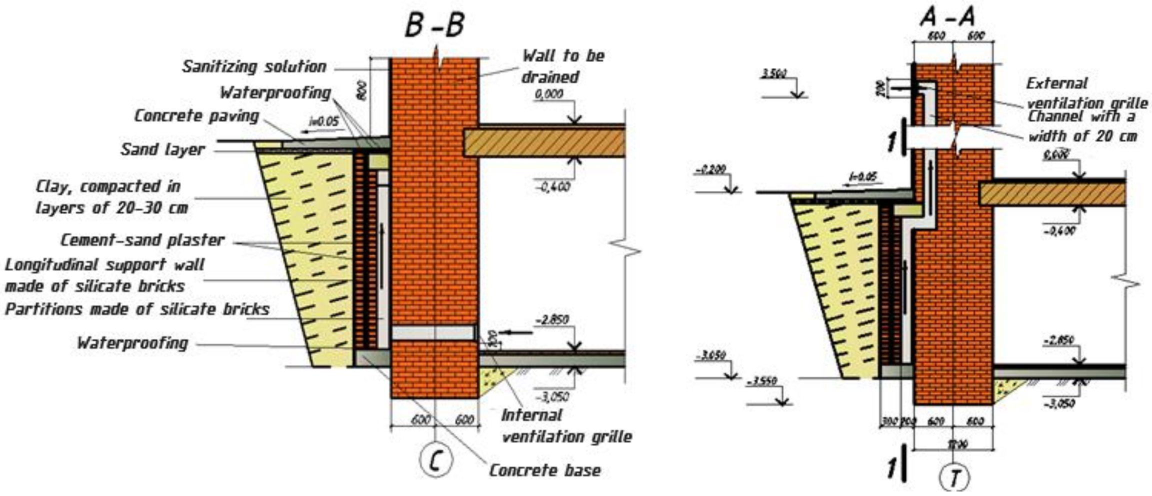

Figure 6 – Cross sections of the ventilation duct

Conclusions

As a result of a retrospective analysis of waterproofing structures at the foundation parts of walls, it was found that until 1953, there was no mandatory requirement for such waterproofing in domestic construction practice due to the lack of mass production of appropriate materials. Since 1956, with the transition of construction to an industrial basis, waterproofing of walls using mass-produced materials has been developed as a standard option. In modern conditions of construction production, covering such areas as restoration, it is necessary to use an individual approach to solve local problems of waterproofing the walls of buildings.

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Applied problems of penetration of sedimentary rocks

Zotsenko Mykola[1], Vynnykov Yuriy[2*], Novokhatniy, Valeriy[3], Zyma Oleksandr[4], Aniskin Aleksej[5]

[1] National University «Yuri Kondratyuk Poltava polytechnic» https://orcid.org/0000-0003-1886-8898
[2] National University «Yuri Kondratyuk Poltava polytechnic» https://orcid.org/0000-0003-2164-9936
[3] National University «Yuri Kondratyuk Poltava polytechnic» https://orcid.org/0000-0001-8107-7912
[4] National University «Yuri Kondratyuk Poltava polytechnic» https://orcid.org/0000-0001-7484-7755
[5] University North, Varazdin, Croatia https://orcid.org/0000-0002-9941-1947
*Corresponding author E-mail: vynnykov@ukr.net

A number of topical applied problems on studying the physical and mechanical characteristics of sedimentary rocks using the already sufficiently tested high-speed penetration method are considered, such as: the influence of tip sizes on the value of the static probing index of sands; the influence of the surface quality of conical tips on the results of penetration and probing; improvement of the tip for penetrating rocks with anisotropic properties. New practical possibilities of using the equations of the relationship between the physical properties of rocks and their mechanical parameters, in particular, the specific resistance to penetration or the penetration index, to generalize the results of experiments are shown.

Keywords: sedimentary rock, penetration, penetration tip, penetration index, specific penetration resistance, relationship, rock skeleton density, anisotropy.

Прикладні задачі пенетрації осадових гірських порід

Зоценко М.Л.[1], Винников Ю.Л.[2*], Зима О.Є.[3], Аніскін А.[4]

[1, 2, 3] Національний університет «Полтавська політехніка імені Юрія Кондратюка»,
[4] Північний університет, Вараждин, Хорватія
*Адреса для листування E-mail: vynnykov@ukr.net

Розглянуто ряд актуальних прикладних задач з дослідження фізико-механічних характеристик осадових гірських порід із застосуванням вже достаньо апробованого швидкісного методу пенетрації, зокрема: вплив розмірів наконечників на величину показника статичного зондування пісків; вплив якості поверхні конічних наконечників на результати пенетрації та зондування; удосконалення наконечника для пенетрації порід з анізотропними властивостями. Показано нові практичні можливості використання рівнянь взаємозв'язку між фізичними властивостями гірських порід і їх механічними параметрами, зокрема питомим опором пенетрації чи показником пенетрації, для узагальнення результатів експериментів. Зокрема. доведено. що застосовуючи метод пенетрації та маючи значення щільності-вологості, в будь-якому елементі масиву осадових гірських порід можливо визначити необхідну характеристику. Шляхом кореляційного аналізу однозначно встановлено повну незалежність величини показника зондування від розмірів гладких конічних наконечників для піску кварцевого, крупного, малого ступеню водонасичення в широкому діапазоні зміни його щільності. Експериментально встановлено, що опір ґрунту занурення ідеально шорсткуватих наконечників одного діаметра практично не залежить від кута розкриття конуса. Наведено наочні приклади, що показують високу ефективність і достовірність використання рівняння взаємозв'язку між фізичними і механічними параметрами гірських порід при вирішенні різних емпіричних завдань досліджень. Розроблено та запатентовано «Наконечник для пенетрації ґрунтів з анізотропними властивостями» та «Спосіб визначення коефіцієнта анізотропії ґрунту методом пенетрації», які дають можливість підвищити достовірність оцінювання напружено-деформованого стану масивів масивів гірських при використанні в їх моделі фізичних співвідношень ортотропного чи трансверсально-ізотропного середовища.

Ключові слова: осадова гірська порода, пенетрація, наконечник для пенетрації, показник пенетрації, питомий опір пенетрації, щільність скелету гірської породи, взаємозв'язок, анізотропія.

Introduction

The penetration method, together with probing, composite testing, and rotary sectioning, is traditionally referred to as the so-called high-speed methods for studying the physical and mechanical properties of sedimentary rocks (soils).

It is based on the slow immersion of a conical tip into the rock to a depth *h*, which should not exceed the height of the cone h_k. When conducting penetration tests in the laboratory, the load is usually transferred in stages, while recording the depth of the tip immersion. The duration of exposure of each individual load stage is taken to be the same (usually 1-2 minutes) [1].

The generalized parameters of these penetration studies were obtained by V.F. Razorenov on the basis of solutions to the axisymmetric problem of the theory of limiting equilibrium [2]. In particular, for cohesive sedimentary rocks (clay, loam, sandy loam), this indicator is the ratio of the penetration force *P* to the square of the cone immersion depth, which is called the specific penetration resistance *R*, MPa.

Practice has shown that the main advantage of penetration studies of homogeneous sedimentary rocks is the so-called invariance condition of the results obtained, i.e., complete independence from the applied force and the corresponding depth of the cone immersion, and, taking into account the constants of the tips used, independence from the angle of their opening. Consequently, in this case, the results of the study do not depend on the means of recording the penetration resistance and the design of the penetrometers themselves [3].

Review of the research sources and publications

The method of penetration testing of rocks, in particular, is recommended for:

– quantitative assessment of changes in the state and mechanical properties of various sedimentary rocks under any type of external impact on them (compaction, moistening, drying, freezing, thawing, etc.). The effect of the impact is determined by the ratio of the values of the specific resistivity of penetration R/R_0 (or penetration indices U/U_0) obtained before and after the impact [4];

– control of the results of mechanical tests of rocks performed by traditional methods [5];

– identifying the relationship between physical condition indicators and strength characteristics of sedimentary rocks [6, 7].

In the current practice of penetration testing of sedimentary rocks, several quite popular areas can be identified. First of all, the equipment for penetration and static rock probing and the methods of processing and interpreting the results of these studies continue to be improved [8, 9].

Another modern trend in the penetration studies of sedimentary rocks, to the development of which the specialists of National University "Yuri Kondratyuk Poltava Polytechnic" (NU "Poltava Polytechnic") made a significant contribution, is the comprehensive substantiation of the equations of the relationship between the physical and mechanical properties of soils for certain types of rocks that have constant, so-called, indicative characteristics (e.g. plasticity number, mineralogical composition, structural features, etc. etc.) based on the results of generalization of numerical experimental data [10-12].

Thus, the general relationship equation of the form (1) has already been well tested for solving applied problems of determining the physical and mechanical characteristics of both cohesive and non-cohesive sedimentary rocks.

The general relationship equation in this case is as follows

$$\lg\frac{R}{R_0} = W_R\frac{1}{e_0} + \frac{\rho_w}{\rho_s}\cdot\frac{1-M_{kpf}}{1/e_0} - W\frac{M_{kpf}}{1/e_0} - \frac{\rho_w}{\rho_d}\cdot\frac{M_{kpf}}{1/e_0}, \quad (1)$$

where *R* – specific penetration resistance, MPa;

R_0 = 1 MPa;

W_R – moisture content of water-saturated rock at R_0 = 1 MPa;

$$M_{kpf} = 1 - \frac{1/e_0}{1/e}; \quad (2)$$

$1/e_0$ and $1/e$ – are the angular coefficients of the linear equations, respectively, for the case of complete water saturation of the rock and under the condition of constant moisture;

ρ_w – water density (1 g/cm^3);

ρ_d – density of dry soil (or soil skeleton).

Thus, having equations of the form (1) for specific types of sedimentary rocks, defined as a certain engineering and geological element, it is possible to determine the corresponding values of: specific resistance to penetration, R; modulus of deformation, E; angle of internal friction, φ; specific adhesion, *c*, based on their known values of the porosity coefficient (*e*) and moisture content (*W*).

And using similar expressions obtained from equation (1) [10, 11], it is possible to determine the mechanical properties of the rock based on the known values of the specific resistance to penetration, *R*, and the moisture content, *W*: *E*; φ; *c*.

It should also be noted that the methodology for assessing the physical and mechanical properties of sedimentary rocks using the relationship equation (1) has been repeatedly tested in the study of compaction zones in various piles and foundations [10].

A number of publications [13-15] are devoted to the interpretation of the results of penetration tests of sedimentary rocks on the sea shelf.

Recently, the use of penetration studies to evaluate the anisotropic properties of sedimentary rocks has also gained some popularity [16, 17]. Thus, the definition of the coefficient of anisotropy of the mechanical characteristics of the rock as the ratio of the values of the specific resistance to penetration at a certain angle to the plane of isotropy to the same parameter, but at a zero angle, has been tested.

Definition of unsolved aspects of the problem

However, the application of the equation of the form (1) is possible to solve a number of other relevant phenomenological problems of studying the physical and mechanical properties of sedimentary rocks.

Problem statement

Therefore, the purpose of the work was to expand the scope of applied problems for studying the physical and mechanical parameters of sedimentary rocks using a sufficiently tested high-speed penetration method. Some of them will be considered below.

Basic material and results

Influence of tip sizes on the value of the sands probing index.

When developing a general methodology for static probing of sands, this issue is of some interest.

The experimental studies were carried out in the laboratory at the laboratory probing unit LZU-1 designed by National University "Poltava Polytechnic".

The sand studied was quartz, coarse, homogeneous, air-dry with a SO_2 content of 98.7%.

In the tray, the sand was given six values of its skeleton density ρ_d = 1.50, 1.52, 1.55, 1.60, 1.64, 1.67 t/m^3.

The density of sand was achieved for the loose state by pouring through a funnel, and for the dense state by surface and deep vibration with loading.

The probing was carried out with smooth conical tips with an angle between the base and the vertical of α = 15°.

The tips of five different sizes were used with cone base diameters α = 2.9, 3.5, 3.9, 4.5, and 5.0 cm.

In all cases, the ratio of the cone diameter to the rod diameter $dc/dsh \geq 1.8$ was maintained. The tip immersion rate in the rock did not exceed 0.25 m/min.

For each experiment, the probing index *V* was determined [11].

Each value of this indicator corresponded to a certain value of rock density, $1/\rho_d$.

To summarize the test results, they were presented in the coordinates "inverse of the dry soil density, $1/\rho_d$ - logarithm of the probing index, *lgV*".

This graph is shown in Fig. 1.

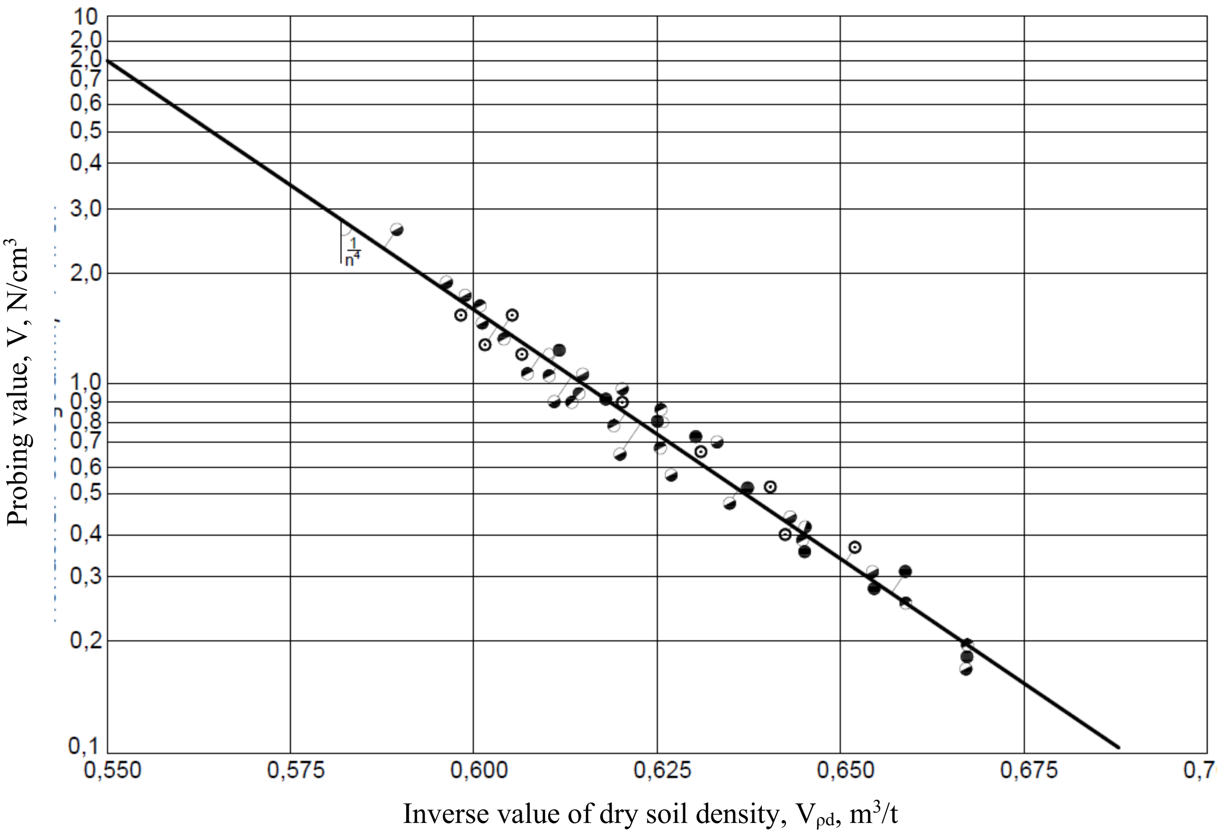

Figure 1 – Results of sand probing with tips of different sizes

Interpreting it in accordance with equation (1), we obtain the linear equation (3)

$$\frac{1}{\rho_d} = 0.886 - 0.0716\lg\frac{V}{0.1}, \qquad (3)$$

with the correlation coefficient r = 0,99.

Thus, as a result of the correlation analysis, the complete independence of the value of the probing index, V, from the size of smooth conical tips for quartz sand, coarse sand, and sand with a low degree of water saturation in a wide range of changes in its density was unequivocally established.

Influence of tapered tip surface quality on penetration and probing results.

Studies by many experts point to the influence of the surface quality of the conical tip on the results of penetration and probing.

It is customary to use a polished metal cone for these tasks [11].

However, the surface of the cone is disturbed during operation, especially in the field. Meyerhoff introduced the concept of a rough cone when the friction along its lateral surface is equal to the tangent of the angle of internal friction of the test sedimentary rock. He proposed a concrete wedge and a copper cone treated with sand for testing.

A new design of a so-called perfectly rough cone was proposed at National University "Poltava Polytechnic".

The scheme of this stepped conical tip is shown in Fig. 2.

It includes a cone and a shank and is characterized by the fact that, in order to create friction conditions on the ground, the cone is made with cylindrical steps.

The tip consists of a cone - 1 and a shank - 2.

The cone is made with cylindrical steps having a ratio of $\delta/h_c = tg\alpha$, and the ratio of the step height to the cone height is taken to be 0.05 - 0.1.

When the tip is buried in the soil under the cylindrical steps, areas of compacted soil are formed, which move with the tip and form a soil jacket in the form of a cone with a base at an angle to the vertical, α.

The proposed tip clearly meets the conditions of a rough cone and creates conditions for friction between soil and soil.

Penetration and probing tests were conducted in sandy and clay soils to identify the expected phenomenon.

The methodology of these studies was based on a set of experimental data on penetration and probing of soils of various types and conditions, and then generalization of the results obtained in accordance with the conditions adopted for equation (1).

Fig. 3, a shows the experimental data on the penetration of coarse, homogeneous, quartz, air-dry sand by a smooth and stepped conical tip with the same geometric parameters:

α = const;

hc = const;

dc = const.

The test was performed using a laboratory penetrometer LP-1.

The porosity coefficient of the sand varied from 0.90 to 0.72 and, accordingly, the angle of internal friction from 32° to 36°.

Line 1 establishes the relationship between the inverse of the dry soil density, $1/\rho_d$, and the logarithm of the penetration index, *U*, obtained with a smooth metal cone.

a)

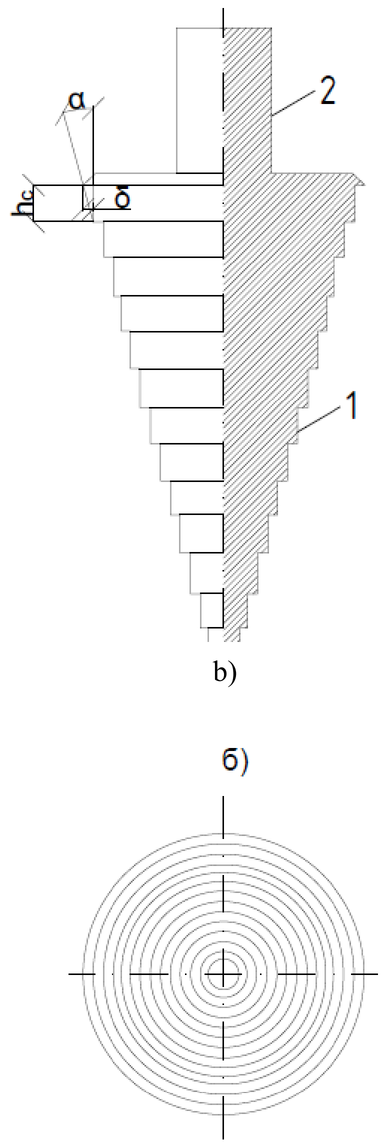

Figure 2 – Stepped conical tip for penetration and probing:
a - section; b - plan; 1 - conical part; 2 - shank,
hc - height of steps; δ - ledge; α - angle between the vertical and the cone face

Line 2 establishes a similar relationship, but with a stepped tip.

There is a large difference between the values of the penetration rates - they are 3 times higher for stepped tips.

Fig. 3, b shows similar data for a loam of a disturbed structure.

The angle of internal friction of the soil varied between 14 and 16°.

All things being equal, the specific penetration resistance obtained with a rough tip is 1.3 times greater than for a smooth one.

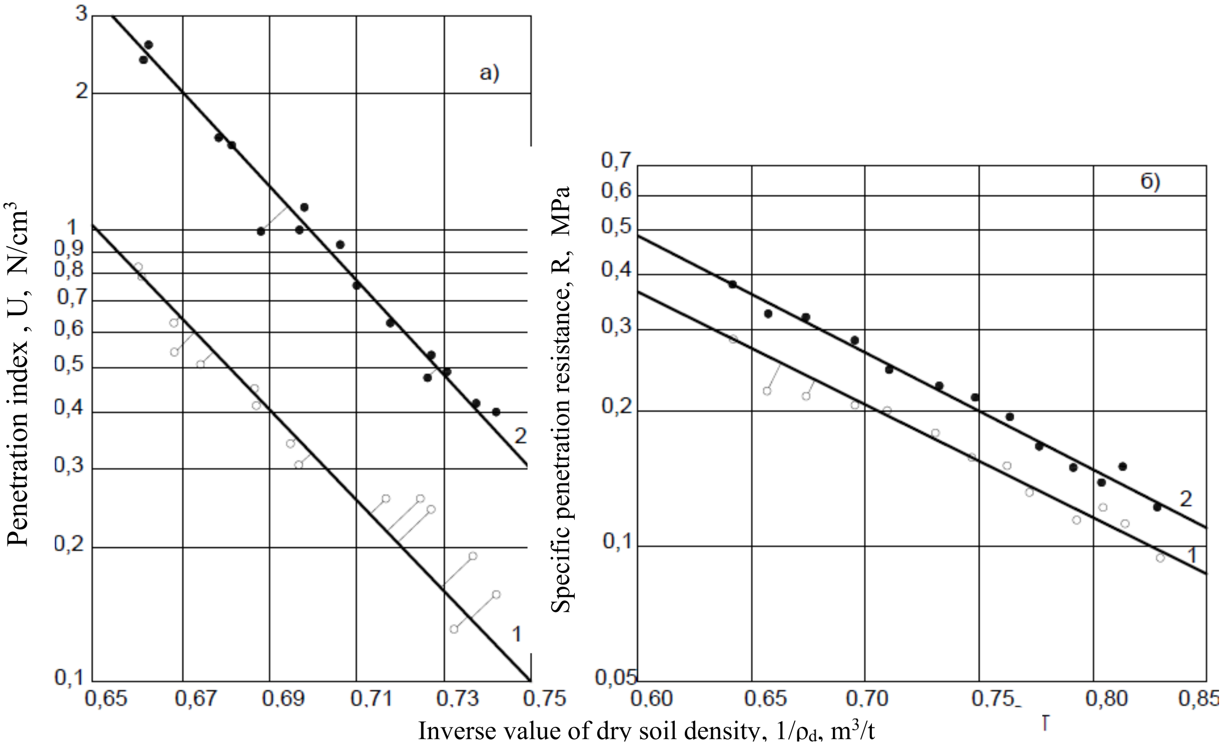

Figure 3 – Results of penetration tests of soils with smooth and stepped conical tips:
a - sands; tips: 1 – smooth, 2 - stepped;
b – loam; tips: 1 – smooth; 2 – stepped

The results confirm the notion that a soil shell is formed around the stepped tip, which moves along with the tip. This causes friction between the soil and the tip.

This value determines the value of the penetration index for sands and the specific penetration resistance for loams. If we assume the coefficient of friction of the metal on the soil f = 0.10 - 0.12, then the results can be confirmed by calculation.

Thus, the greater the angle of internal friction of the soil, the greater the error when using a conventional smooth metal tip in penetration tests. It is noticeable when testing sands and may be negligible when penetrating water-saturated clay soils.

Fig. 4 shows the results of probing coarse, homogeneous, air-dry, quartz sands in laboratory conditions using the LZU-1 installation with tips with different angles, α, between the base and the vertical of the cone.

Conical tips with the same cone base diameter d_c = *const* were used.

Fig. 4, a shows the data for smooth tips, and Fig. 4, b – for stepped tips.

For each value of the angle α, the probing was performed at seven values of the dry soil density, ρ_d, of both smooth and rough tips.

As a characteristic of sand probing, the value V_A was taken, which is calculated by the following formula

$$V_A = \frac{P - P_o}{H \times A}, \tag{4}$$

where A – cone base area.

The obtained data confirm the well-known statements [11] about the formation of an elastic core under flat and conical dies.

According to these ideas, the shape of the elastic core is close to conical, and its angle α ≈ 22.5°.

If the smooth tip has a 2α < 22.5°, the core is not formed, and friction occurs on the metal.

If 2α > 22.5°, then elements of this core appear, and the larger α, the more elements of the elastic core are formed.

A flat die has a complete elastic core.

The graphs in Fig. 4, a show that with the formation of elastic core elements, the intensity of the increase in the probing index decreases, i.e., the effect of friction on the soil is manifested.

Fig. 4, b shows the graphs obtained using stepped tips.

According to these data, the soil resistance to penetration of perfectly rough tips of the same diameter is practically independent of the cone opening angle.

There is a slight tendency to increase the probing resistance with an increase in the angle α, which confirms Meyerhoff's conclusions.

These examples show the high efficiency and reliability of using the relationship equation (1) in solving various phenomenological research problems.

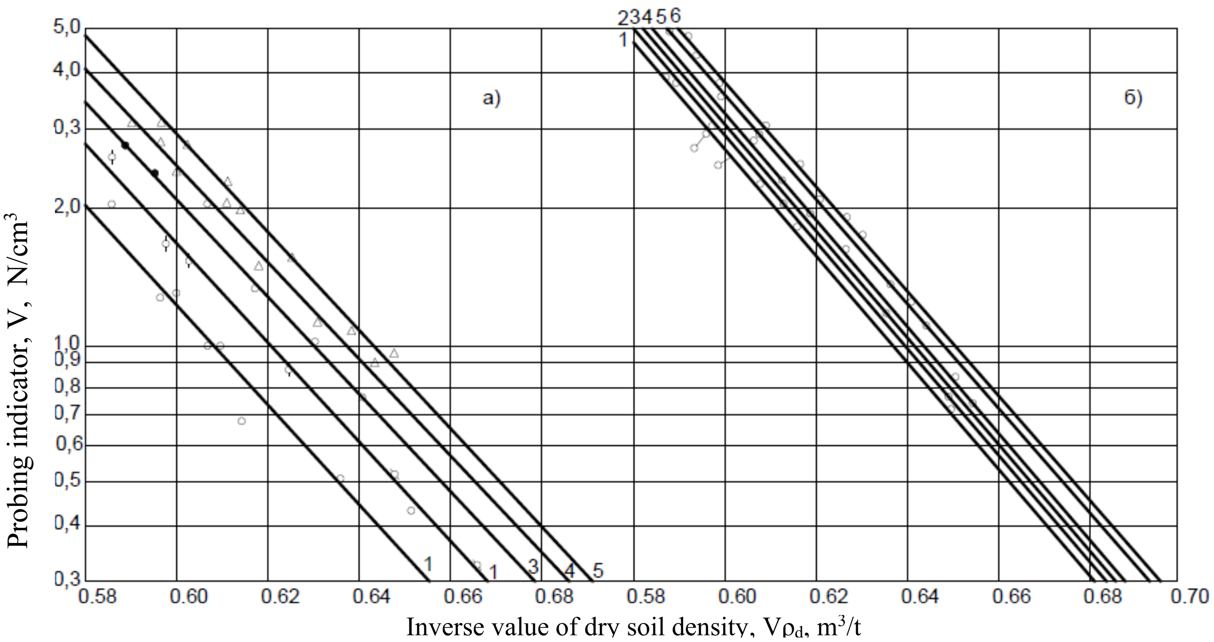

Figure 4 – The probing results of sands with smooth and stepped conical tips:
a - smooth with angle α: 1-10°; 2-15°; 3-22.5°; 4-30°; 5-45°;
b - stepped with angle α: 1-10°; 2-15°; 3-22,5°; 4-30°; 5-45°

Improving the tip for penetrating soils with anisotropic properties.

At National University "Poltava Polytechnic", a "Penetration tip for soils with anisotropic properties" was created (Patents for: invention No. 17737 and industrial design No. 1473) (Fig. 5).

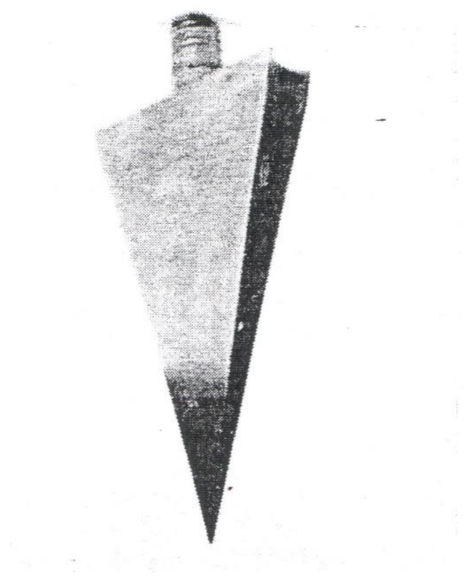

Figure 5 – Tip for penetrating soils with anisotropic properties

Due to the small angle between the working faces and the concavity of the side faces (which eliminates the interaction of the rock with the side surfaces), the tip introduces minor measurement errors in anisotropic sedimentary rocks.

The interaction of the soil occurs only along the surfaces of the working faces, i.e. at an angle that differs slightly from the direction of the central axis: for example, if the angle between the working faces is 8, the angle by which the working surface of the faces is deviated from the central axis is 4°.

The side faces do not interact with the rock (they are still lubricated with grease).

To improve the accuracy of n_α, we developed a "Method for determining the soil anisotropy coefficient by the penetration method" (Patent for Invention No. 49904).

It involves stripping at least two adjacent areas to the shape of planes located at different angles α to the horizon and penetrating each of them in a direction perpendicular to its tip according to Patent No. 17737.

Penetration in each direction is carried out with at least four tips with different angles between the working faces, for example, $\beta = 20$, 15, 10, and 5, with the determination of R for each direction of penetration and each angle β, calculation of the values of the coefficient $n_{R\alpha}$ for the corresponding angles β, approximation of the data of the dependence $n_{R\alpha} = f(\beta)$, in particular, by a power function, and extrapolation to the value of $n_{R\alpha}$ corresponding to $\beta = 0°$.

Thus, in cases where the values of soil anisotropy coefficients differ significantly from $n_\alpha = 1.0$, the accuracy of estimating the stress-strain state of rock masses can be increased by using physical relations of orthotropic or transverse-isotropic media in their model.

Conclusions

Thus, by expanding the subject matter of applied problems for studying the physical and mechanical parameters of sedimentary rocks using the tested high-speed penetration method, the following was established.

1. The equations of the relationship between the physical and mechanical properties of soils are established for individual varieties that have constant indicative characteristics (plasticity number, mineralogical composition, structural features, etc.) based on the results of generalizing numerical experimental data. Using the penetration method and having the density-moisture values, it is possible to determine the required characteristic in any element of the soil massif.

2. The possibility of using the equations of the relationship between the physical and mechanical characteristics of soils to generalize the results of experiments in solving research problems is proved.

3. The "Penetration tip for soils with anisotropic properties" and the "Method for determining the soil anisotropy coefficient by the penetration method" were developed and patented, which make it possible to increase the reliability of the assessment of the stress-strain state of rock masses when using physical relations of orthotropic or transversal-isotropic media in their model.

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