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Research paper

Deep Compactor with a Concrete Mixture Laid in a Form Interaction Process Investigation

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Abstract

Analytically, rational parameters of a vibration machine for internal compaction of concrete mixes are determined and rational modes of vibration exposure by a flat working body on a concrete mix are established.
The dynamic system "vibration machine - concrete medium" is investigated, in which the latter is represented as a system with distributed parameters, taking into account the elastic, viscous, inertial and energy properties of the concrete to be compacted. The partial differential equation was compiled describing the change in stresses in a compacted medium depending on the dynamic elastic modulus, dynamic viscosity coefficient, inelastic resistance coefficient and inertia of the medium to be densified as a function of density, relative deformation and texture of the concrete mix. The propagation of visco-elastic-plastic deformation waves in a compacted concrete mix, represented as a half-space, is investigated. As a result of solving the wave equation of oscillations, the regularity of the propagation of viscous-elastic-plastic deformation waves in the half-space of a concrete mixture being compacted is established. The amplitudes of vibrations and stresses arising in the compacted mixture are determined depending on its physico mechanical characteristics. The vibration amplitude of the vibration machine was determined, its rational parameters were established, and rational modes of vibration impact on the compacted concrete mix found in the form of a half-space were found. A vibration machine in the form of a flat vertical plate, in the upper part of which a horizontal vibration exciter is mounted, is proposed. The given dependences allow one to substantiate rational ones depending on the physico mechanical characteristics of the medium being compacted, the thickness and width of the layer being compacted, the angular frequency of the forced oscillations and the amplitude of the disturbing force.

Keywords: *vibration machine, parameters, concrete mix, internal compaction, amplitude, stress.*

1. Introduction

The internal (deep) vibration of concrete mixes with a vibrator is the least energy-intensive compared to other compaction methods, since a part of the vibrator immersed in the compacted medium directly transmits to it a vibration effect with minimal energy costs. For these purposes, are used deep vibrators [1 - 4] with a diameter of a mace (tip) from 36 to 76 mm. For technological equipment, mounted deep vibrators with tip diameter from 75 to 133 mm are used. These vibrators usually provide compaction of the concrete mix in a radius of 200 to 300 mm, depending on the diameter of the tip and the mobility of the concrete mix. For the integrated mechanization of the process of compaction of concrete mixtures using deep vibrators, collected in packages and having individual drives [5]. These devices have a rather complicated construction and are used for very large volumes of concreting. To increase the efficiency of vibrating, a planar deep compactor [6] was proposed, made in the form of a vertical flat plate on which two immersion vibrators are mounted with each one individually driven. Due to the large weight, this deep compactor could not be used in the construction industry as a manual mechanism, the effectiveness of its use was not investigated and, consequently, it was not widely used. It should be noted that all immersion vibrators are supplied with planetary vibrators by vibration exciters, which quickly fail [7].
Therefore, the creation of a high-tech deep-compacter, which has a simple structure, high reliability and ensures the compaction of concrete mixtures of various consistencies, is an urgent task.
The purpose of these studies is to establish rational modes of vibration exposure to the concrete mix and to develop on this basis a highly efficient planar deep vibratory compactor.

2. The material and results of the research

Based on preliminary theoretical studies [8, 9, 10, 11], a planar deep sealer was developed, equipped with a vibration exciter of horizontally directed vibrations (Fig. 1).
To determine the characteristics of the interaction of a vibrating depth seal with a concrete mix, laid in a mold, we investigate the dynamic system presented on fig. 1. Here the vibrating deep sealer is immersed in concrete mix 3, which is in shape and presented as a system with distributed parameters. In the computational scheme under consideration, it was assumed that under the action of the vibration exciter 2, the vertical plate 1 performs only horizontally directed oscillations perpendicular to the plane of the plate 1. The rheological model of the medium to be compacted in a form that takes into account the action of elastic, dissipative and inertial

forces arising in this medium under dynamic influence, it is possible to present in the form of the scheme represented on fig. 2

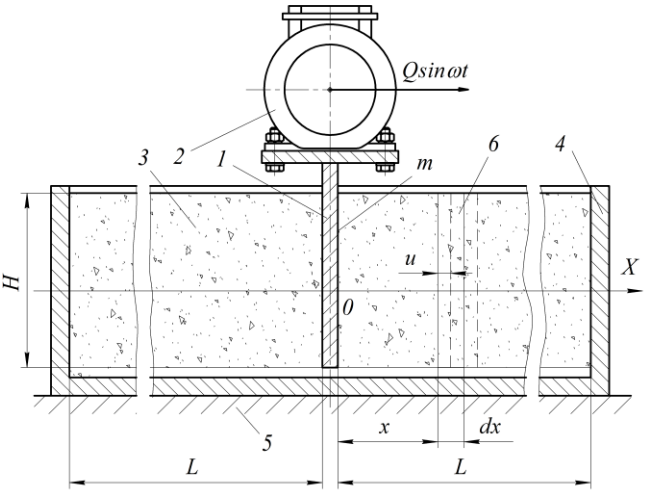

Fig. 1: The design diagram of the interaction of a deep compacter with a concrete mix in the form: 1 - a flat vertical plate; 2 - vibration exciter; 3 - concrete mix; 4 - form; 5 - base; 6 - selected item.

In accordance with the adopted rheological model, we investigate a uniaxial stress state that occurs in a compressed medium only in the horizontal direction under the action of a vibration perturbation. In this case, the movement of the layer of concrete mix in the direction of the coordinate in time is described by the following wave equation of oscillations:

$$E\frac{\partial^2 u(x,t)}{\partial x^2}+\eta\frac{\partial^2 u(x,t)}{\partial x\partial t}-\rho L_1\frac{\partial^3 u(x,t)}{\partial x\partial t^2}+$$
$$+\mu\frac{\partial u(x,t)}{\partial x}=\rho\frac{\partial^2 u(x,t)}{\partial t^2}. \quad (1)$$

We will solve the equation (1) under the following boundary conditions:

$$-m\frac{\partial^2 u(0,t)}{\partial t^2}+EF\frac{\partial u(0,t)}{\partial x}+\eta F\frac{\partial u(0,t)}{\partial t}-$$
$$-\rho L_1 F\frac{\partial^2 u(0,t)}{\partial t^2}+\mu F u(0,t)=-Q\sin\omega t; \quad (2)$$

$$u(L,t)=0, \quad (3)$$

where L – the length from the vertical plate of the deep seal to the end wall of the form.
The first boundary condition (2) describes the interaction of the vertical plate with the concrete mix to be compacted, and the second boundary condition (3) shows that the propagation of the disturbance wave is limited by the end wall of the form and the displacement of the sealing medium at its contact with the end wall of the form is absent, i.e. $u(L,t)=0$.

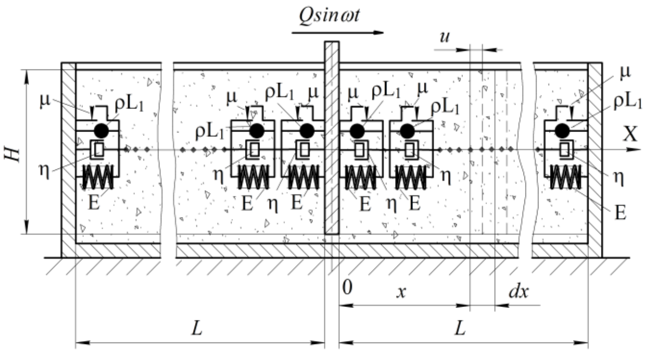

Fig. 2: Rheological model of a concrete medium compacted in a form.

The expression $Q\sin\omega t$ in the boundary condition (2) can be represented as the imaginary part of a complex function, i.e. $Q\sin\omega t=Qe^{i\omega t}$. Then the solution of equation (1) can be represented as the imaginary part of the complex function [8]:

$$u(x,t)=U(x)e^{i\omega t}, \quad (4)$$

where $U(x)$ is complex amplitude of oscillations, which must satisfy the boundary (boundary) conditions for the design scheme shown in Fig. 2
Substituting the function (4) into the wave equation of oscillations (1) and solving the resulting equation, we determine the motion of the medium to be sealed in the direction of the coordinate
X in the following complex form

$$u(x,t)=e^{-\delta x}[Be^{(ik+\alpha)x}+De^{-(ik+\alpha)x}]e^{i(\omega t-\xi x)}, \quad (5)$$

where B and D are the integration constants (complex values) determined from the boundary conditions (2) and (3); δ – the attenuation coefficient of the disturbance in the compacted layer of concrete mix,

$$\delta=\frac{\mu+\rho L_1\omega^2}{2E}; \quad (6)$$

ξ –dissipation coefficient,

$$\xi=\frac{\eta\omega}{2E}. \quad (7)$$

k – wave number,

$$k=\sqrt{\frac{1}{2}\left(\frac{\rho\omega^2}{E}+\xi^2-\delta^2\right)+\sqrt{\frac{1}{4}\left(\frac{\rho\omega^2}{E}+\xi^2-\delta^2\right)^2+\xi^2\delta^2}}; \quad (8)$$

α – absorption coefficient characterizing the decrease in the disturbance amplitude with distance from the source of vibration exposure,

$$\alpha=\sqrt{-\frac{1}{2}\left(\frac{\rho\omega^2}{E}+\xi^2-\delta^2\right)+\sqrt{\frac{1}{4}\left(\frac{\rho\omega^2}{E}+\xi^2-\delta^2\right)^2+\xi^2\delta^2}}. \quad (9)$$

By substituting the dependence (5) into the boundary condition (3), we find the relationship between the integration constants B and D in a complex form:

$$B=-D\frac{e^{-(\alpha+ik)L}}{e^{(\alpha+ik)L}}. \quad (10)$$

Based on the expression (10), we transform the dependence (5) and obtain the solution of equation (1) in the following form:

$$u(x,t)=De^{-\delta x}\left[\frac{e^{(\alpha+ik)(L-x)}-e^{-(\alpha+ik)(L-x)}}{e^{(\alpha+ik)L}}\right]e^{i(\omega t-\xi x)} . \qquad (11)$$

Substituting the dependence (11) into the boundary condition (2) and we find the integration constant D (complex value) in the following form:

$$D=\frac{Qe^{(\alpha+ik)L}}{e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}}\left[-m\omega^2-0{,}5F(\rho L_1\omega^2+\mu)-0{,}5i\eta\omega+\right.$$
$$\left.+EF(\alpha+ik)\frac{e^{(\alpha+ik)L}+e^{-(\alpha+ik)L}}{e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}}\right]^{-1} . \qquad (12)$$

Substituting the integration constant D (12) into dependence (11), we find the solution of the wave equation of oscillations (1), satisfying the boundary conditions (2) and (3), in a complex form:

$$u(x,t)=Qe^{-\delta x}\frac{e^{(\alpha+ik)(L-x)}-e^{-(\alpha+ik)(L-x)}}{e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}}\times$$
$$\times\left[-m\omega^2-0{,}5F(\rho L_1\omega^2+\mu)-\right.$$
$$\left.-0{,}5i\eta\omega+EF(\alpha+ik)\frac{e^{(\alpha+ik)L}+e^{-(\alpha+ik)L}}{e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}}\right]^{-1}e^{i(\omega t-\xi x)} . \qquad (13)$$

Let us transform the fractional expression in square brackets of dependence (3), bringing it to the following form:

$$\frac{e^{(\alpha+ik)L}+e^{-(\alpha+ik)L}}{e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}}=\frac{ch(\alpha L)\cos kL+i\cdot sh(\alpha L)\sin kL}{sh(\alpha L)\cos kL+i\cdot ch(\alpha L)\sin kL} . \qquad (14)$$

After substituting the expression (14) in dependence (13) we get:

$$u(x,t)=Qe^{-\delta x}\frac{e^{(\alpha+ik)(L-x)}-(e^{-(\alpha+ik)(L-x)}}{e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}}\times$$
$$\times\left[-m\omega^2-0{,}5F(\rho L_1\omega^2+\mu)-0{,}5i\eta\omega+\right.$$
$$\left.+EF(\alpha+ik)\frac{ch(\alpha L)\cos kL+i\cdot sh(\alpha L)\sin kL}{sh(\alpha L)\cos kL+i\cdot ch(\alpha L)\sin kL}\right]^{-1}e^{i(\omega t-\xi x)} . \qquad (15)$$

Multiplying the numerator and denominator of the expression
$\frac{ch(\alpha L)\cos kL+i\cdot sh(\alpha L)\sin kL}{sh(\alpha L)\cos kL+i\cdot ch(\alpha L)\sin kL}$,
standing in square brackets in dependence (15), on the complex number adjoint to the denominator, i.e. on
$sh(\alpha L)\cos kL-i\cdot ch(\alpha L)\sin kL$,
and converting as a whole the expression in square brackets of the denominator of dependence (15), we get

$$u(x,t)=Qe^{-\delta x}\frac{e^{(\alpha+ik)(L-x)}-e^{-(\alpha+ik)(L-x)}}{[e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}]}\times$$
$$\times\frac{1}{[c_b-(m+m_b)\omega^2-ib_b\omega]}e^{i(\omega t-\xi x)} , \qquad (16)$$

where c_b – the reduced stiffness of the concrete mix to be compacted,

$$c_b=0{,}5EF\frac{\alpha\cdot sh(2\alpha L)+k\sin 2kL}{sh^2(\alpha L)+\sin^2 kL} ; \qquad (17)$$

m_b – reduced mass of compacted concrete mix,

$$m_b=0{,}5F\left(\frac{\mu}{\omega^2}+\rho L_1\right) ; \qquad (18)$$

b_b – reduced coefficient of inelastic resistance of compacted concrete mix,

$$b_b=\frac{0{,}5F}{\omega}\left[E\frac{\alpha\cdot\sin 2kL-k\cdot sh(2\alpha L)}{sh^2(\alpha L)+\sin^2 kL}+\eta\omega\right] . \qquad (19)$$

In dependence (16) we transform expressions
$e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}$ и
$e^{(\alpha+ik)(L-x)}-e^{-(\alpha+ik)(L-x)}$,
bringing them to the following form::

$$e^{(\alpha+ik)L}-e^{-(\alpha+ik)L}=2sh[(\alpha+ik)L]=$$
$$=2[sh(\alpha L)\cos kL+i\cdot ch(\alpha L)\sin kL] ; \qquad (20)$$

$$e^{(\alpha+ik)(L-x)}-(e^{-(\alpha+ik)(L-x)}=2sh[(\alpha+ik)(L-x)]=$$
$$=2\{sh[\alpha(L-x)]\cos k(L-x)+i\cdot ch[\alpha(L-x)]\sin k(L-x)\} . \qquad (21)$$

In this case, the expression (16) is converted to the following form:

$$u(x,t)=Qe^{-\delta x}e^{i(\omega t-\xi x)}\times$$
$$\times\frac{sh[\alpha(L-x)]\cos k(L-x)+i\cdot ch[\alpha(L-x)]\sin k(L-x)}{[sh(\alpha L)\cos kL+i\cdot ch(\alpha L)\sin kL][c_b-(m+m_b)\omega^2-ib_b\omega]} . \qquad (22)$$

Multiply the numerator and denominator of expression (22) by complex numbers
$[c_b-(m+m_b)\omega^2]+ib_b\omega$ и
$sh(\alpha L)\cos kL-i\cdot ch(\alpha L)\sin kL$,
conjugate to complex numbers that are in the denominator and, extracting from the obtained dependence the imaginary part of the complex function formed, and also transforming it, we obtain the desired solution of the wave equation (1), satisfying the boundary conditions (2) and (3), in the following form:

$$u(x,t)=\frac{Qe^{-\delta x}}{\sqrt{sh^2(\alpha L)+\sin^2 kL}\sqrt{[c_b-(m+m_b)\omega^2]^2+b_b^2\omega^2}}\times$$
$$\times\{sh[\alpha(L-x)]\cos k(L-x)\sin(\omega t-\xi x-\varphi)+$$
$$+ch[\alpha(L-x)]\sin k(L-x)\cos(\omega t-\xi x-\varphi)\} , \qquad (23)$$

where φ – phase shift between the amplitude of the disturbing force and displacement,

$$\varphi=\varphi_2-\varphi_1 ; \qquad (24)$$

$$\varphi_1 = arctg\frac{b_b\omega}{c_b-(m+m_b)\omega^2}; \quad (25)$$

$$\varphi_2 = arctg\frac{ch(\alpha L)\sin kL}{sh(\alpha L)\cos kL}. \quad (26)$$

The obtained solution (23) of the wave equation of oscillations (1), satisfying the boundary conditions (2) and (3), describes the law of oscillations of a concrete layer of a mixture compacted in the form of a deep sealer depending on the coordinate x, i.e. at. $L \le x \ge 0$. When $x = 0$ the obtained dependence (23) describes the law of oscillations of the layer of the mixture adjacent to the vertical plate, and at the same time describes the law of oscillations of the planar deep compacter, i.e.

$$u(0,t) = \frac{Q}{\sqrt{[c_b-(m+m_b)\omega^2]^2+b_b^2\omega^2}}\sin(\omega t+\varphi_1) =$$
$$= A\sin(\omega t+\varphi_1), \quad (27)$$

where A – oscillation amplitude of the vertical plate,

$$A = \frac{Q}{\sqrt{[c_b-(m+m_b)\omega^2]^2+b_b^2\omega^2}}. \quad (28)$$

Substituting the dependence (23), which this describes the law of oscillations of the considered dynamic system, into the equation

$$\sigma(x,t) = E\frac{\partial u(x,t)}{\partial x}+\eta\frac{\partial u(x,t)}{\partial t}-\rho L_1\frac{\partial^2 u(x,t)}{\partial t^2}+\mu u(x,t), \quad (29)$$

determine the change in stresses that occur in the compacted layer under the action of vibration perturbation $Q\sin\omega t$:

$$\sigma(x,t) = \frac{AEe^{-\delta x}\sqrt{\alpha^2+k^2}}{\sqrt{sh^2(\alpha L)+\sin^2 kL}}\times$$
$$\times\{sh[\alpha(L-x)]\sin k(L-x)\sin(\omega t-\xi x-\varphi-\varphi_3)-$$
$$-ch[\alpha(L-x)]\cos k(L-x)\cos(\omega t-\xi x-\varphi-\varphi_3)\}-$$
$$-\frac{0{,}5Ae^{-\delta x}\sqrt{(\mu+\rho L_1\omega^2)^2+(\eta\omega)^2}}{\sqrt{sh^2(\alpha L)+\sin^2 kL}}\times$$
$$\{ch[\alpha(L-x)]\cos k(L-x)\sin(\omega t-\xi x-\varphi+\varphi_4)+$$
$$+sh[\alpha(L-x)]\sin k(L-x)\cos(\omega t-\xi x-\varphi+\varphi_4)\}, \quad (30)$$

где φ_3, φ_4 – углы сдвига фаз,

$$\varphi_3 = arctg\frac{\alpha}{k}; \quad \varphi_4 = arctg\frac{\eta\omega}{\mu+\rho L_1\omega^2}. \quad (31)$$

Stresses arising in a layer of concrete mixture in contact with a vertical plate, i.e. when x = 0, determined from the following expression:

$$\sigma(0,t) = \frac{AE\sqrt{\alpha^2+k^2}}{\sqrt{sh^2(\alpha L)+\sin^2 kL}}[sh(\alpha L)\sin kL\sin(\omega t-\varphi-\varphi_3)-$$
$$-ch(\alpha L)\cos kL\cos(\omega t-\varphi-\varphi_3)]$$
$$-\frac{0{,}5A\sqrt{(\mu+\rho L_1\omega^2)^2+(\eta\omega)^2}}{\sqrt{sh^2(\alpha L)+\sin^2 kL}}\times$$
$$\times[ch(\alpha L)\cos kL\sin(\omega t-\varphi+\varphi_4)+$$
$$+sh(\alpha L)\sin kL\cos(\omega t-\varphi+\varphi_4)], \quad (32)$$

The stresses arising in the layer of concrete mixture in contact with the end walls of the form, i.e. when $x = L$, determined from the following expression:

$$\sigma(L,t) = -\frac{AEe^{-\delta L}\sqrt{\alpha^2+k^2}}{\sqrt{sh^2(\alpha L)+\sin^2 kL}}[\cos(\omega t-\xi L-\varphi-\varphi_3)-$$
$$-\frac{0{,}5Ae^{-\delta L}\sqrt{(\mu+\rho L_1\omega^2)^2+(\eta\omega)^2}}{\sqrt{sh^2(\alpha L)+\sin^2 kL}}\sin(\omega t-\xi L-\varphi+\varphi_4). \quad (33)$$

Using expressions (17 - 19), we define specific values:
– reduced stiffness (c_{by}) compacted concrete mix,

$$c_{by} = \frac{c_b}{F} = 0{,}5E\frac{\alpha\cdot sh(2\alpha L)+k\sin 2kL}{sh^2(\alpha L)+\sin^2 kL}; \quad (34)$$

–reduced mass (m_{by}) compacted concrete mix,

$$m_{by} = \frac{m_b}{F} = 0{,}5F\left(\frac{\mu}{\omega^2}+\rho L_1\right); \quad (35)$$

– reduced coefficient of inelastic resistance (b_{by}) compacted concrete mix,

$$b_{by} = \frac{b_b}{F} = \frac{0{,}5}{\omega}\left[E\frac{\alpha\cdot\sin 2kL-k\cdot sh(2\alpha L)}{sh^2(\alpha L)+\sin^2 kL}+\eta\omega\right]. \quad (36)$$

The obtained expressions (34 - 36) can be used in the case of the use of a continually discrete computational model describing the interaction of a planar deep sealer with a concrete mixture in the space limited by the end walls of the form at various values of the areas of interaction surfaces of the working body with the concrete medium.
Based on the above theoretical dependencies, a planar deep vibratory compactor was developed that performs strictly horizontal vibrations in a closed space that compacts the concrete mix in the form in the direction of the coordinate x, with the following main parameters: the mass of the deep compactor – m = 7 kg; the amplitude of the disturbing force of the vibration exciter - = Q =0,981 kN; the angular frequency of forced vibrations – ω = 292 rad / s; the surface area of the vertical slab, interacting with the concrete mix (by two-way contact) – F = 800 cm2; the oscillation amplitude of the vertical plate in a strictly horizontal direction, perpendicular to the plane of interaction, is vertically poured in with the concrete mixture, at idle (without interaction with the concrete mixture) – A = 0.167 cm; the distance from the vibrating working body to the end wall of the form L = 60 cm.
After the deep compactor was introduced into the medium being processed, its oscillation amplitude, which at idle is 0.167 cm, decreases and, depending on the mixture consistency, is 0.067 - 0.104 cm at the beginning of the compaction (Fig. 3). The deepest seal has the greatest amplitude of oscillations when interacting with a concrete medium having a rigidity of 120 s. As the density of the concrete medium increases, the amplitude of oscillations of

the depth seal decreases and at the final stage of compaction for all mixtures it becomes approximately the same and is 0.0268 – 0.0294 mm.

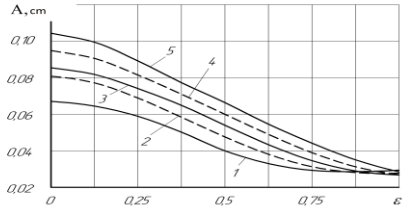

Fig. 3: Changes in the amplitude of vibrations of a deep-surface planar vibration compactor interacting with a compacted medium of different consistency depending on the relative density of the concrete mix at L = 60 cm: 1 - with a draft of 3.5 - 4 cm; 2 - when the stiffness of the mixture S = 30 s; 3 - at S = 60 s; 4 - at S = 90 s; 5 - at S = 120 s

As a result of the research it was found that plastic with a draft of a cone DC = 3.5 - 4 cm and moderately hard concrete mixtures of rigidity S= 30 - 60 s can be processed with a deep planar vibro-compactor with sufficiently high productivity with a processing length L = 60 - 70 cm. At the same time, when the cone of the concrete mix is DC = 3.5 - 4 cm, the required duration of the vibration compaction is 15–20 s, and when the rigidity is S = 30–60 s, the compaction time is 30–54 s (longer duration corresponds to greater rigidity), and with stiffness S = 90 s, the duration of compaction is 68–80 s.

Thus, the proposed planar deep vibratory compactor provides effective compaction of concrete mixes in a form with less energy consumption.

3. Discussion

Using the above expressions, it is possible to determine, with an approximate (simplified) formula, with a sufficient degree of accuracy, the stress amplitude arising in the packed layer of the concrete medium depending on the action of elastic and inertial forces, and the forces of inelastic resistance

– in contact with the sealing surface of the depth compactor:

$$\sigma(0) = A\left(m_{by}\omega^2 + \left|b_{by}\right|\omega + E/L_1\right); \quad (37)$$

– upon contact with the end wall of the form:

$$\sigma(L) = e^{-\delta L} A\left(m_{by}\omega^2 + \left|b_{by}\right|\omega + E/L_1\right). \quad (38)$$

For the considered design scheme, the effective length of the compacted layer L_1 is assigned when the following condition is met:

$$\text{– если } \frac{\pi}{2\omega}\sqrt{\frac{E}{\rho}} \ge 0{,}5L, \text{ то } L_1 = 0{,}5L; \quad (39)$$

$$\text{– если } \frac{\pi}{2\omega}\sqrt{\frac{E}{\rho}} \le 0{,}5L, \text{ то } L_1 = \frac{\pi}{2\omega}\sqrt{\frac{E}{\rho}}. \quad (40)$$

4. Conclusions

Based on the analysis of existing methods and designs of vibratory machines, a planar deep vibratory compactor for concrete mixes of various consistencies is proposed. The proposed compactor is made in the form of a flat vertical plate, in the upper part of which a vibration exciter of horizontal directional vibrations is mounted. A physical and mathematical model of a dynamic system was compiled, describing the interaction of a deep compactor with a concrete mix. The regularity of the movement of the deep compactor and the concrete mixture to be compacted is determined depending on the physicomechanical characteristics of the medium being compacted, the length of the layer being compacted, the angular frequency of forced vibrations, the amplitude of the disturbing force, and the geometric parameters of the vertical plate interacting with the concrete mix. The obtained analytical dependences allow us to calculate the rational parameters of a planar deep sealer and modes of vibration exposure.

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