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Experimental And Theoretical Studies Of Soils Flexible Rigidity

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Abstract – This article discusses the experimental and theoretical determination of the soil stiffness characteristics. These parameters in practice are the basis for calculating the joint work of bases and foundations.

Keywords – Beam, Soil, Foundation, Soil Stiffness, Reactive Pressure, Flat Flume, Computational Model, Active Area Of Soil.

I. Introduction

A large number of studies are devoted to the accounting problems for the structure interaction with a foundation [1–3]. In the calculation methods developed and used in practice, the exact definition of the physical parameters meaning that take into account the foundation structure interaction with the base is not sufficiently sanctified in the literature. There is no clear understanding of the advantages and disadvantages of using certain models for calculating the joint work of the "foundation-basis" system. In the calculation methods developed and used in practice, building structures and foundations are considered as a single complex, obeying the basic laws of structural mechanics, and the foundation itself is a contact zone with a soil foundation. In this case, the soils are conventionally taken as an elastic foundation with the main characteristic, the bed coefficient (Fig. 1).There are known models when the "building-base" system is taken as a whole; the three-dimensional subgrade under the building is considered as an elastic medium [10] (Fig. 3). In this article, an attempt is made to analyze the existing calculation methods using

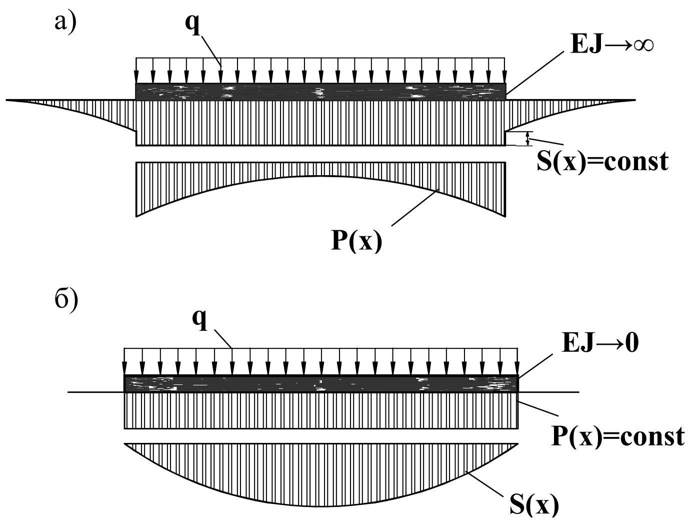

Figure1**.** Plots of settlement and reactive forces under an absolutely rigid beam (a) and an absolutely flexible beam (b).

contact models and to determine the physical essence of the stiffness parameters, taking into account the real soils properties included in these equations.

Below is the main properties overview of known contact models. Foundations interacting with the subgrade perceive both external, specified operational and reactive subgrade forces. Determining the reactive forces of the foundation interacting with the foundation structure is a complex mechanical task, since the subgrade exhibits a wide variety of properties. Changes in these soil properties during the building and structure operation can significantly affect the resulting forces in structures. To solve determining problem the interaction between the structure and the subgrade, various models have been proposed [1-2,6,7,9].

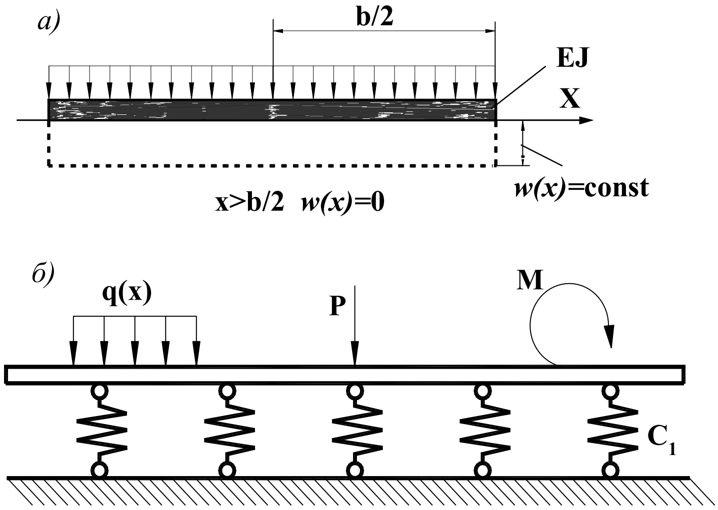

Figure: 2. Computational models a) Winkler-Zimermann with uniform b) and Zhemochkin B.N with arbitrary loading

It is known from classical mechanics that a loaded beam (slab) deformations with stiffness *EI* lying on a soil foundation depend on the adopted contact model. The beam (slab) deformation is significantly influenced by both the structure itself and the subgrade properties rigidity. For example, for two boundary conditions: 1 - with an absolutely rigid beam, the soil displacements within the loaded area are constant *S(x)=const*, and the reaction pressure has a saddle-shaped diagram (fig.1. a); 2 - the beam is absolutely flexible, while the base movement has a bend form with a maximum deflection in the center of the loaded area, and the reactive pressure diagram along it, constant *P(x)=const*(fig. 1. b).

When calculating foundations, based on contact elastic models, the reactive pressure $p(\mathrm{x})$ linearly depends on both the soil stiffness to local collapse C_1 (proposed by Winkler-Zimerman) and the soil resistance to bending C_2proposed (P.L. Pasternak [1]).The mathematical expression for this model is as follows

$$P(x) = C_1\mathrm{w}(x) + C_2\ddot{\mathrm{w}}(x)(1)$$

As follows from this expression, the reactive pressure $P(x)$ depends on the value of the stiffness coefficient of a thin layer of the base (bed). In essence, this layer can be conventionally considered as sequential springs in the normal and tangential directions. They do not characterize the resistance of deeper layers to compression and bending of soils located deeper in the active deformable zone of the base. (fig.2).

The concept of stiffness for soils with significant internal friction and little adhesion is more complex in nature. Since soils in nature are widespread in three-dimensional space, the classical concept of stiffness inherent in structural materials has a different semantic factor for soils. For example, the soil medium can be considered as layer-by-layer two-dimensional massive strata (stripes) that exhibit the properties of local collapse during compression and internal friction during bending. Unlike structural materials, for soils, the stress state distribution area is limited; therefore, incorrect selection of this area can significantly affect the calculating settlements and deflections results.

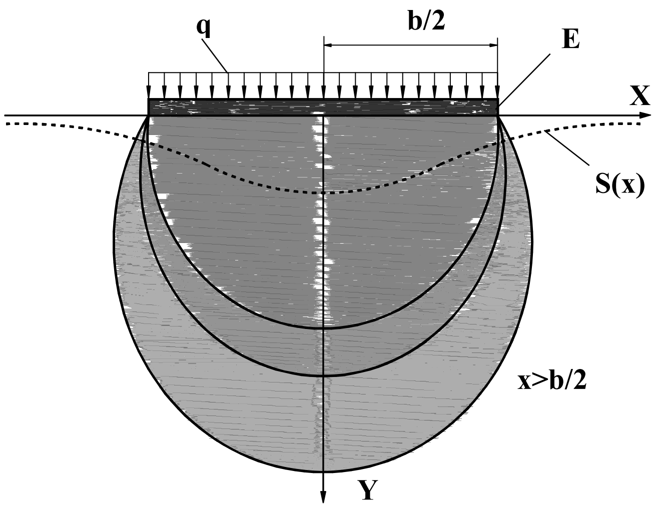

Figure: 3. Calculation model of elastic half-space

Strength parameters (angle of internal friction and adhesion) should be referred to as mechanical (elastic) properties for soils. As you know, these properties of soils are significantly influenced by: mineral and granulometric composition; density; humidity and many other factors. Despite such a complex structure and nature of soils, they are identified with structural materials, taking into account their specific properties. Hence, the same terminological definitions follow, such as SSS, continuity (elasticity, plasticity, and viscosity), rigidity, etc.

In relation to soils, the concept of stiffness is conventionally divided into two groups (models). The first one characterizes the stiffness of the soil to crushing or, otherwise, as the resistance of the soil to volumetric compression. The ideal model of this behavior of the volume of the soil, which has a prismatic (cylindrical) shape, can be attributed to their resistance to compression. In this case, a soil layer with a length of $H_s = \Delta Hn$, is considered, located in a cylindrical cage. Here, the rigidity concept is understood as the pressure ratio to (crushing) the soil layer settlement. With regard to the bending stiffness of the limited soil volume, it must be considered in the structure, which is affected by various external forces.

To clarify the physical nature of the resistance of the soil to bending, the authors proposed a combined model consisting of a lower structural beam with rigidity $E_c I_c$, hinged on two supports and a layer of a specific type of soil laid on it. This model makes it possible to experimentally establish the effect of the growing soil layer on the deflection of the beam. If the soil does not have flexural rigidity, then a linear increase in the deflection of the beam from the accumulated soil layer is expected. If the soil has such properties, then such a proportional relationship will be violated.

II. Experimental studies of soil bending stiffness

The task is carried out using a flat tray, which allows modeling the interaction of the bending structure and the subgrade under various external loads.

The flat chute (Fig. 4.) is made in the form of a frame structure made of channels №22. The tray test chamber has the following dimensions: *AxBxH*=120x22x120 cm. The frame consists of two side posts (1) and two horizontal beams (2). The lower beam (3) of the chute, with final rigidity *EI*, is pivotally attached to two side posts (1) (4). The rear wall of the tray is made of sheet steel (5), and the front wall is made of two glass sheets 2x4 mm thick between the beams (2) and (3), to measure the compensating loads, a dynamometer is installed (or an adjustable screw support for measuring the deflection of the beam). With the complete unloading of the screw support, installed under the center of the beam, it receives the maximum deflection from the reactive forces of the soil layer poured into the tray. Thus, such a tray differs from the known ones in that it allows, among other parameters, to determine the flexural rigidity of the subgrade.

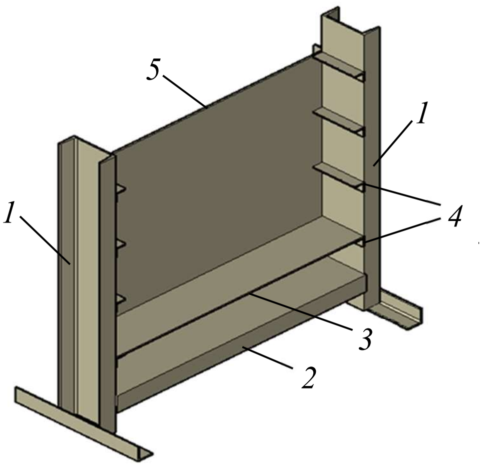

Fig. 4. Design of an experimental tray for determining the bending stiffness of the soil.

At the beginning of the experiment, a metal beam (3) pivotally supported on two supports is tested for a concentrated and uniformly distributed specified load. The stiffness of a metal strip *EI* is determined by its deflection depending on the loads and, therefore, is considered known.

The experiment is carried out in two ways: in the first case, a soil layer H_i is poured onto the metal beam and the maximum deflection f_i of the beam is measured. The experiment continues until the moment when the backfill thickness does not significantly affect the deflection of the beam, i.e. $\Delta f_i \cong 0$. Moreover, for this type of soil, the ratio$H_i = H_s$ и H_s / L . In the second case, a dynamometer is installed under the center of the beam (at the bottom), with the help of which compensating reactive loads N_i(depending on the accumulated soil thickness H_i) are fixed. The experiment continues until the moment when the thickness of the backfill has no significant effect on the readings of the dynamometer $\Delta N_i \cong 0$. And in this case, for this type of soil, ratios $Hi = H_s$ и H_s/L are fixed. The load on the beam from the soil is determined in two ways: by deflection and by compensating loads (measured by the readings of a dynamometer installed in the center of the beam). The deflection of the beam (3) from gravitational and measured reactive loads is used to determine the stiffness of the soil to bending. As follows from Fig. 5, on the one hand, according to the calculation, a proportional increase in the gravitational pressure of the soil is expected from the layer height, i.e.$P(x) = \gamma bH$. In fact, the measured compensating loads, as well as the soil layer deflection, show that with an increase in its height, these loads increment (deflections) gradually decreases. When the condition$H \geq H_s$, the layer height will practically not affect gravitational pressures$P(x)$ (deflection f). The comparative diagram shown in Fig. 5 was obtained from the results of the experiment with crushed stone. To determine the compensating loads installed in the center of the beam, we use the well-known expression [8]:

$$N = 1.25qb\frac{L}{2} = 1.25\gamma Hb\frac{L}{2},(2)$$

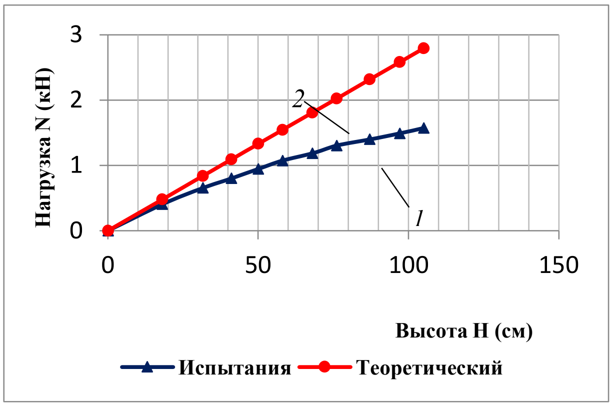

Fig.5. Compensating load curves . 1- dynamometer indicators from the height of the soil layer and 2- calculated by the expression (2)

where N- the compensating loads value, determined by the readings of the dynamometer.

The deflection of a metal strip pivotally supported on two supports, loaded with a uniformly distributed load, is determined by the expression [8]:

$$f = \frac{5qL^4}{384EI_0} \qquad (3)$$

where$f$- beam deflection length L from a uniformly distributed load of intensity q from soil with rigidity $t = EI_0$.

To determine the combined beam deflection value depending on the compensating loads value (determined from the dynamometer readings), it is necessary to use the calibrated curve $f = f(N)$,, built for the metal beam.

III. Design model that takes into account the bending stiffness of soils

The proposed model, in contrast to (1), mathematically characterizes the crushing and deflection of the soil layer under the foundation with the following stiffness parameters (Fig. 1):

$$w(x) = C_1 \mathrm{w}_1(x) + C_2 \mathrm{w}_2(x).(4)$$

The first part of the equation characterizes the soil layer stiffness by crushing with thicknessH_s, compressed under compression conditions, i.e. $\varepsilon_{x=y=0}$ or by the depth of the stamp imprint into the ground. The second part of the equation characterizes the deflection $\mathrm{w}_2(x)$ of soil layers together with a beam (strip) pivotally supported on two conditional supports.

$$q(\mathrm{x}s) + q(\mathrm{xc}) = \frac{384EIf}{5L^4}, \quad (5)$$

where $q(\mathrm{x}_{sL}), q(\mathrm{x_c})$ – distributed gravitational load from soil and beam structure;$EI = E_0I_0 + E_\mathrm{c}I_\mathrm{c}$- reduced beam stiffness;$t = E_0I_0$- flexural stiffness of the soil and $E_\mathrm{c}I_\mathrm{c}$- stiffness of the metal strip.

For example, if we assume that the deflection of the soil layer obeys the parabolic function law of the form:

$$f(\mathrm{x}) = c - ax^2, \qquad (6)$$

where $c = f_{max}$ $(x = 0)$ and $a = \frac{4f}{l^2}(x = L/2)$, then its second derivative is equal to the radius of curvature [8]

$$f(\ddot{\mathrm{x}}) = -2a = -\frac{8f}{L^2} = \frac{1}{R} = \rho. \quad (7)$$

Equation (4), taking into account (5) and (7), can be written in the following form:

$$p(\mathrm{x}) = \frac{384EIf}{5L^4} = \frac{48EI}{5L^2}\frac{8f}{L^2} = \mathrm{C}_2\frac{8f}{L^2}. (8)$$

Comparing expression (8) with (1) and assuming$E_\mathrm{c}I_\mathrm{c} = 0$,we obtain the numerical value of the parameter C_2 proposed by P.L. Pasternak [1]:

$$C_2 = p(x)\frac{L^2}{8f}, \qquad (9)$$

$$or \qquad C_2 = \frac{48}{5L^2}E_0 I_0 = \frac{4}{5}\frac{bH^3}{L^2}E_0 = \frac{t}{L^2} \quad (10)$$

$$Note\ that\ for\ L = \pi,\ expression\ \frac{48}{5L^2} = \frac{48}{5\pi^2} \cong 1.$$

Definition: from expression (10) it follows that the flexural rigidity of the parameter P.L. Pasternak$C_2 = E_0 I_0$ *characterizes the radius of curvature* $\rho = \frac{1}{R}$ penetrating *soil layer with dimensions in plan b,H and length*$L = \pi$ *from a single uniform load* $p(x) = \gamma Hb = 1$ *or for a weightless beam at*$q(x) = 1$.

The experiments analysis with sands and gravel showed that the ratio $\frac{H_s}{(l/2)}$ value can be approximately determined by the expression:

$$\frac{H_s}{(l/2)} \cong tg\varphi. \qquad (11)$$

Using expression (5), we determine the total rigidity of the metal strip and the layer of soil laid on it:

$$E_0 I_0 + E_c I_c = (E_c I_c + \sum_{i=1}^{n} t_i) = \frac{5qL^4}{384f}. \qquad (12)$$

In this case, expression (12) will take the following form:

$$E_0 I_0 = \frac{2{,}5L^5 b\gamma}{384}k\left(\frac{tg\varphi}{f}\right) - E_c I_c = \frac{L^4 b}{\varepsilon}k\frac{\gamma tg\varphi}{153} - E_c I_c = t. \quad (13)$$

where $\varepsilon = \frac{f}{L}$ – is relative deflection; k – is correction factor.

Expressions (12) and (13) make it possible to determine the reduced bending stiffness of the soil based on the results of trough tests.

If we assume that only distributed forces q (x) act on a soil layer with a thickness H as an external load, then expression (3) will show a linear increase in its deflection (Fig. 6). A slightly different picture will be observed if the conditional beam (soil layer) is considered as weighty. In this case, with an increase in the number of layers n with thickness ΔH and, accordingly, gravitational forces$P(x) = \gamma b \Delta H n$, the increment of deflections will decrease (Fig. 6). This indicates that the intense load $p(x)$ for the soil cannot be identified as an external load$q(x)$. Therefore, when solving geotechnical problems, it should be written separately as a sum$q(x) + P(x)$, since the latter is a medium with internal friction.

Thus, the deflection f of the contact surface from the soil layer weight with a thickness ΔH and a length L with intensity P(x) increases in proportion to the square root of the number of layersn.

In this case, expression (5) is written in the following form:

$$f = P(x)\frac{L^4}{kt} \quad (14)$$

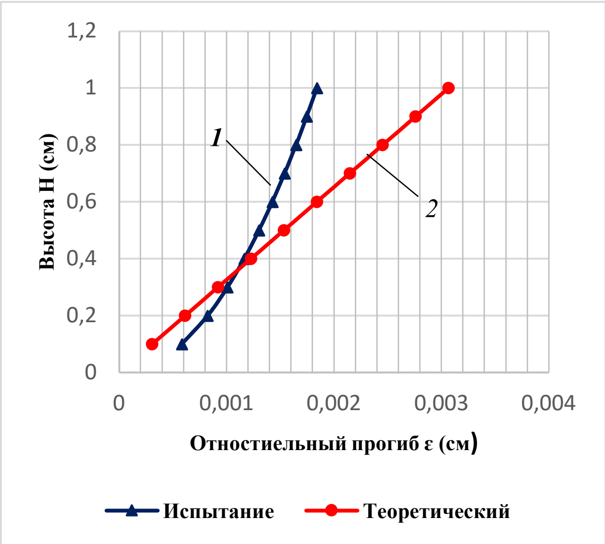

Fig. 6. Deflection curves *f: 1- the deflection meter indications* from *the soil layer height and 2-calculated by the expression (3)*

Expression (5) for the gravitational soil forces is written in the form:

$$P(x) = \gamma b \Delta H \sqrt{n} = kt\frac{f}{L^4} = kt\frac{\varepsilon}{L^3} (15)$$

where:

$$t = \frac{L^3}{k\varepsilon} P(x) = \frac{L^3}{k\varepsilon} \gamma b \Delta H \sqrt{n}. \quad (16)$$

In the experimental determination of the parameter t, it is necessary to take into account the metal strip stiffness EI:

$$t = \frac{L^3}{k\varepsilon} P(x) - \frac{384EI}{5},$$

Expression t (16), in contrast to C_2 (9), characterizes the stiffness of the soil layer relative to the deflection ε of length L^3at a single distributed load$P(x)$.

Using expression (15), we compare the stiffness parameter t of the soil in relation to one strip for the $t_m$model and for real problemst_r. Suppose that for both bands $n = 1$ the conditions of equality of $P(x)$ and ε are satisfied. In this case

$$t_m = \frac{L_m^3}{k\varepsilon} P_m(x) \; and \, t_r = \frac{L_r^3}{k\varepsilon} P_r(x) \; or \frac{t_r}{t_m} = \frac{L_r^3}{L_m^3}.$$

from here $t_r = t_m \left(\frac{L_r}{L_m}\right)^3$. (17)

Wherein,$P_m(x) = \gamma b_m \Delta H_m \sqrt{n}$ and $P_r(x) = \gamma b_r \, \Delta H_r \, \sqrt{n}$ in n=1

$$\Delta H_r = \Delta H_m \frac{b_m}{b_r}. \qquad (18)$$

The parameter of the soil layer stiffness to bending t characterizes one layer deflection of the soil layer with a thickness ΔH with geometric dimensions in plan (Lb) loaded with a single distributed *gravitational load P (x) equal to the experimental value.*

This parameter value, for example, for sand, will be determined from the results obtained from experiments.

Example. It is required to determine the real stiffness of the soil layer t_r for the foundation with $b_m; L_m = 1.5; 10 \; mpo$ known experimental values of the same soil $b;L = 0{,}22\;;\; 1{,}24 \; m$ stiffness parameter$t_m = 5 кHm^2$. The design scheme is shown in Fig (7).

According to expression (17), we determine the soil layer stiffness to bending:

$$t_r = t_m \left(\frac{L_r}{L_m}\right)^3 = 5\left(\frac{10}{1{,}24}\right)^3 = 5 \cdot 524 = 2622кН \, m^2;$$

$$t_r = t_m \left(\frac{L_r}{L_m}\right)^3 = 5\left(\frac{30}{1{,}24}\right)^3 = 5 \cdot 524 = 70805kN \, m^2;$$

$$H_r = H_m \frac{b_m}{b_r} = 1{,}0 \frac{0{,}22}{1{,}5} = 0{,}15 \, m;$$

$$P_m(x) = \gamma b_m H_m = 14{,}4 \cdot 0{,}22 \cdot 1 = 3{,}16 \text{ kNm}.$$

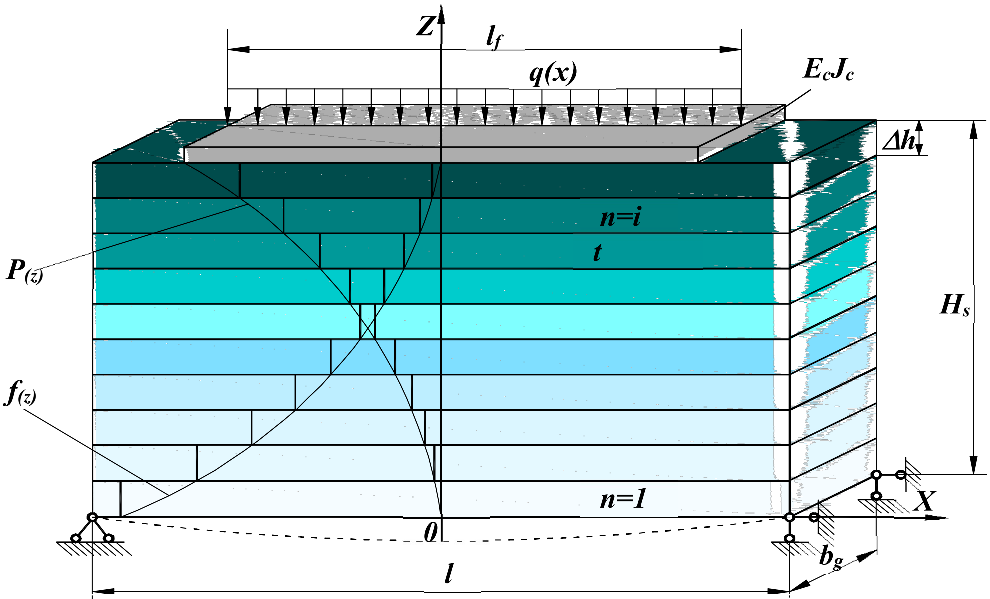

Fig7. Mechanical model for determining the bending stiffness of the soil and used in the design of beams on a soil foundation

The rigidity of an elementary strip 1.5 m wide, 0.15 m high, forL_r $= 10{,}30$ m is, respectively,$t_r = 2622;\ 70805$ кН м^2

Considering the basic rule of mechanics, when on two supports n the number of beams (strips) with the same stiffness $t_r$and gravitational load are folded $\mathrm{P}_m(\mathrm{x})$, equal to the layer thicknessΔH_r , its final deflection will remain unchanged equal$\varepsilon = f/L$. The total number of layers n depends on the actual layer thickness. For example, taking into account (10):

$$H_s \cong \left(\frac{l}{2}\right) tg\varphi = 5 * 0{,}8 = 4 \text{ м};$$

$$n = \frac{4}{0{,}15} = 26.$$

The compensating reactive loads value is determined taking into account the expression (2):

$$N = \sqrt{(\gamma Hb)}1.25\frac{L}{2} = \sqrt{(14{,}4 * 4 * 1{,}5)}1.25\frac{10}{2} = 58\text{кН},$$

$$or \frac{N}{Lb} = \sqrt{(\gamma Hb)}\frac{1.25}{2b} = \frac{1.25}{2}\sqrt{\frac{(\gamma H)}{b}} = \frac{58}{10*1{,}5} = 3{,}8\ kPa.$$

In the case of determining the stiffness t for a weightless foundation, the compensating loads value is taken to be zero.

Characteristic of soil stiffness C_1 , located deeper than the bending area of the base $H > H_s$, determined by traditional methods.

IV. Conclusions

1. In all known contact models [1,2,6,9], the reactive pressure $P(x)$ is directly proportional to the settlement (deflection) of the foundation with the proportionality (stiffne²ss) coefficients C (4).It was experimentally established that for the proposed model the parameter of the soil layer bending stiffness t characterizes one soil layer deflection with a thickness ΔH with geometric dimensions in plan (Lb), loaded with a single distributed gravitational load$\mathrm{P}(\mathrm{x})$.

2. It was found that the flexural rigidity of the parameter P.L. Pasternak $\mathrm{C}_2 = E_0 I_0$ characterizes the curvature radius p of the sagging soil layer with dimensions in plan b, H and length $L = \pi$ from a single uniform load $p(x) = \gamma Hb = 1$ or for a weightless beam$q(x) = 1$.

3. The active area of deflection of soil layers, as well as the depth of propagation of the compensating loadH_s , for practical calculations can be determined by expression (10).

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