BIO Web of Conferences **149**, 01072 (2024) https://doi.org/10.1051/bioconf/202414901072
Genetic Resources 2024

Experimental studies on shear stiffness of soil under external loading conditions

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Abstract. Calculation of foundations using elastic models simplifies the calculation of loads and impacts on foundations. However, in some cases they can significantly distort the real deformations, foundation efforts and in some cases cause their damage. In practice, designing and calculating foundations using these models, there are cases of excessively high concentrations of bending moments and shear forces, which requires a high percentage of reinforcement in these nodes. Sometimes, for example, with distributed loads, with the real presence of such efforts, calculations performed on models with a bedding coefficient show, on the contrary, their absence. The type of the adopted model and the rigidity of the foundation structures have a significant impact on the calculated deflection of the beam. The value of the adopted values of the model parameters also has a great impact on the calculation results. Calculation models in the area of contact with the soil base, the reactive pressure of the foundation P (x) linearly depends on the coefficient of local soil compression C1 and the shear resistance of the soil C2.

1 Introduction

Calculation of beams and slabs on an elastic foundation is the most studied and thoroughly developed section of the theory of elasticity and structural mechanics. In these works, the mechanical properties of the foundation are fundamentally divided into two groups. The first group includes models characterizing local elastic deformations with foundation rigidity coefficients "C", and the second group includes models that allow modeling the foundation as an elastic half-space with the main deformation characteristics "E" and "μ". Calculation of foundations using elastic models simplifies the calculation of loads and effects on foundations. However, in some cases they can significantly distort the real deformations, foundation efforts and in some cases cause their damage. In practice, design and calculation of foundations using these models, there are cases of excessively high concentrations of bending moments and shear forces, which requires a high percentage of reinforcement in these nodes [1-5, 7, 9-12].

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absence. The type of the adopted model and the rigidity of the foundation structures have a significant impact on the calculated beam deflection. The values of the adopted model parameter values also have a great impact on the calculation results. For example, the Winkler-Zimmerman model includes the coefficient of soil rigidity for crushing, and the model proposed by P.L. Pasternak adds a second parameter of soil rigidity for bending to it. In the calculation methods developed and used in practice, the values of these parameters are determined based on the provisions of the classical theory of elasticity. When determining the values of the equation parameters, the rigidity of the structures is mainly taken into account and the shear rigidity of the soil is not taken into account. There are many unresolved issues in determining the function of beam deflections and the reactive soil pressure on structures. The regulatory documents do not regulate the methods of applying calculation models that take into account the joint operation of the "structure-soil foundation" system [8, 13-18].

Determining the opposing soil forces on the foundation structure, when the foundation structure works together with the soil, is a complex mechanical problem, since in the process of the opposite effect of the soil on the foundation structure, the soil begins to exhibit different characteristics. The fact that the soil exhibits these properties can cause overstressing of the foundation structure during the operation of buildings and structures [19-21].

2 Materials and Methods

In practice, in the process of calculating a lying beam or slab on an elastic foundation, calculation models are used that characterize various physical and mechanical properties of the soil. The accuracy of calculating the foundation and base of buildings will depend, first of all, on the correctness of the choice of the adopted calculation model, close to the actual physical and mechanical properties of the soil under the foundation.

To solve the problem of determining the interaction of the structure and the soil base, various models are proposed. The simplest model characterizing the interaction of structures, for example, beams and slabs on an elastic foundation was proposed by Winkler-Zimerman. In this model, the main parameter is the elasticity coefficient of the base or otherwise the bed. This model does not take into account the distributing capacity of the soil and therefore an imprint remains under the loaded surface, which is restored when the load is removed.

To some extent, the distributing capacity of the soil is taken into account in contact models with two rigidity parameters. In order to eliminate this error, a second component was added to models with a one-parameter equation. In this case, the bending of the beam lying on the soil foundation is calculated using two-parameter models.

From the following mathematical expression it is clear that when calculating foundations and when calculating beams (slabs), existing calculation models in the area of contact with the soil foundation, the reactive pressure of the foundation P(x) linearly depends on the coefficient of local soil compression proposed by Winkler-Zimerman C_1 and the shear resistance of the soil C_2 proposed by P. L. Pasternak.

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

To determine the second parameter C2, various authors have proposed mathematical expressions that imitate the real properties of soils to varying degrees. In particular, the models proposed by P.L. Pasternak, M.M., Filonenko-Borodich, Vlasov, N.N., Leontiev to varying degrees allow taking into account the distributing capacity of soils. The main disadvantage of these models is the mechanical accounting, by introducing shear reactive stresses along the beam contact. The shear rigidity parameter C_2 is considered in a functional relationship with C_1. The main disadvantage of contact models is that the reactive pressure function P(x) is determined depending on the deflection w(x) of the beam with a proportionality coefficient equal to C_1 and C_2. These models do not allow taking into account the distributing capacity and plastic deformations in soils. Another, no less important problem of the contact model is that when calculating the internal forces and deformations of the beam, the reactive stress function P(x) from various types of loading remains unknown. In this case, a fair question arises as to how to correctly select the reactive pressure function P(x).

3 Results and Discussion

Soil calculation models based on the theory of elasticity when solving theoretical problems cannot fully describe the distribution of stresses under the foundation. None of the calculation models is universal and is used only to solve a specific problem. The correct choice of soil mechanics models allows you to choose not only the stability and safety of buildings and structures, but also an economical solution for the building foundation. In computer programs used in practice, computational models based on the Winkler and Pasternak model (for example, Lira CAD) are widely used. Experiments have shown that when calculating the deformation states of the foundations of buildings and structures on calculation models, the deformation states obtained as a result of actual in-kind work differ from each other. These calculation models do not take into account the bends that form in the foundation structure as a result of soil deformation under the foundation. This is one of the main drawbacks of calculation models.

The occurrence of stresses in the foundation structure depends on the depth of the active soil massif under the foundation, i.e. on its deformation and the limit of stress propagation. In most literature [13, 14], it is considered that the active soil massif under the strip foundation has a width of 2b from the center of the foundation and is almost equal to the depth of 6b from the boundary of the foundation sole, see Fig. 1 (where b is the width of the foundation). This is an important indicator when carrying out excavation work and designing foundations. Based on the compressibility of soils under the foundation to a depth of H_s, anti-subsidence measures for the building are developed.

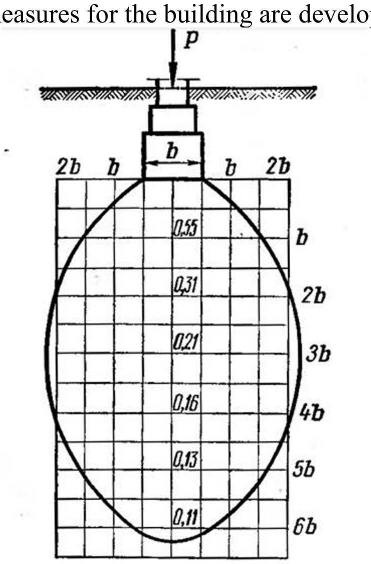

Figure 1. Stressed zone of the base soil under the foundation sole: b - width of the foundation sole; P - load from the building, transferred by the foundation to the base

In the active soil mass under the foundation, in addition to the compression of soil particles, mutual horizontal and inclined shear can also be observed. Thus, the soil resists compression and horizontal and inclined shear under the action of a force. Soil compression refers to the Winkler calculation model and mainly leads to S-settlement of the foundation. As a result of soil shear, excessive stresses arise in the foundation structure, i.e., they cause torsional states and bending of the foundation.

In this paper an attempt is made to solve the shear stiffness of the soil by experimentally determining the deflection diagram of a beam f(x) lying on a soil foundation from various external loads. In this case, the integral value of the bending stiffness is taken as the sum of the structural stiffness of the beam E_c I_c and the shear stiffness of the soil foundation - t. The stiffness of a beam, the displacement of which is limited at the ends, is determined by methods known in mechanics. As for the shear stiffness of the soil, it is determined experimentally in a special flat tray. Unlike traditional testing methods, a metal beam (strip) is installed at the bottom of the tray and rests on two hinged supports. The experiment is carried out with measurement of the maximum displacement (deflection) of the beam (strip) f(L/2) or, in its absence, with measurement of the reactive force in the center of the beam P(L/2) (Fig. 2) during the process of backfilling the soil layer. The methodology for determining the shear stiffness of the soil and its maximum deflection of the beam is considered by the authors in [3]. In accordance with these studies, it was established that the value of the reduced rigidity of the beam E_c I_c and the soil base - t is accepted as a single value.

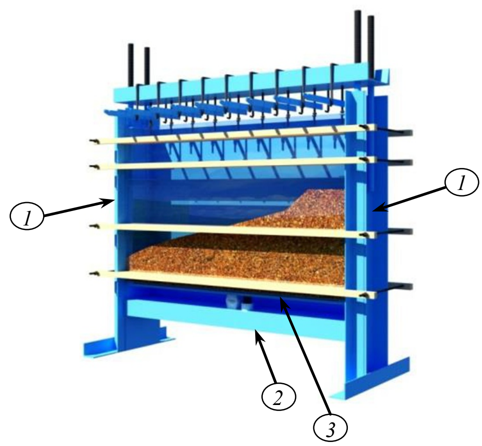

Figure 2. General view of a flat tray in an experimental state

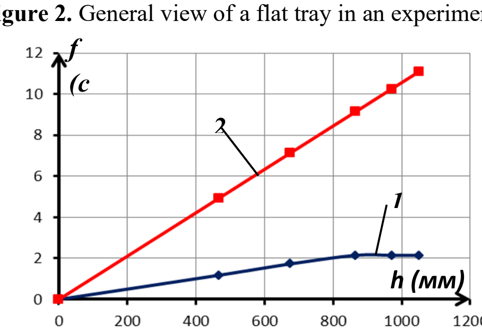

Figure 3. Graph of maximum bending f of soil and beam with increasing thickness of soil layers h. 1 - determined on the basis of experiment; 2 - determined by theory.

The task is accomplished using a flat tray, which allows modeling the interaction of the bending structure and the soil base layer under various external loads. The flat tray (Fig. 2) is made in the form of a frame structure made of No. 22 channels. 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 of the tray (3) rests freely on two side posts (1). In the middle of the flat metal beam shown in Fig. 2, a dynamometer (4) is installed to measure the compensating load and a jack (adjusting screw) for experimental purposes. When the metal beam is released from the full load, which is installed under the center of the beam, the area bends to the maximum, from the gravitational load of the soil layer, which is attached to the beam. Thus, such a tray differs from the known ones in that it allows, among other parameters, to determine the shear rigidity of the soil base.

The rigidity of the 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 Hi is poured onto the metal beam and the maximum deflection of the beam fi is measured. The experiment continues until the backfill thickness does not have a significant effect on the beam deflection, i.e. $\Delta f_i \cong 0$. In this case, for this type of soil, the ratios $H_i = H_s$ and H_s / L are fixed.

Based on the experimental data, the required rigidity of the "elastic beam - soil layer" system is determined. And in this case, for this type of soil, the ratios $H_i = H_s$ and H_s / L are fixed. The load on the beam from the soil is determined by the deflection. The shear rigidity of the soil is determined by the deflection of the beam from gravitational and measured reactive loads [1]. The comparative diagram shown in Fig. 3 was obtained based on the results of the experiment with coarse-grained sand. As can be seen from the graph in Fig. 3, on the one hand, the calculations expect a proportional increase in the gravitational pressure of the soil from the layer height, i.e. P(x)=γbH. In reality, the measured compensating loads, as well as the deflection of the beam with the soil layer, show that with an increase in its height, the increment of these loads (deflections) gradually decreases. When the condition H≥H_s is met, the layer height will have virtually no effect on the gravitational pressure P(x) [2].

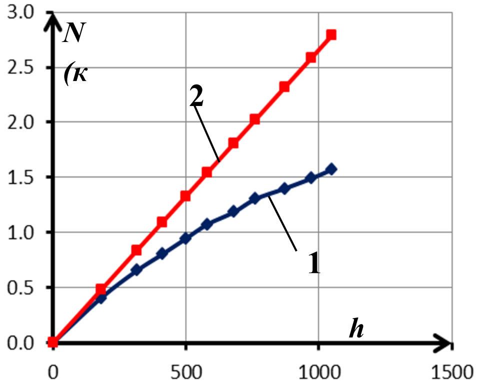

Figure 4. Graph of the dependence of the change in force N in the lower part of the soil with an increase in soil layers h. 1-determined on the basis of experiment. 2-theoretically determined by formula (2).

The comparative diagram shown in Fig. 4 was obtained based on the results of an experiment with crushed stone and coarse sand. To determine the compensating loads installed in the center of the beam, we use the well-known expression:

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

 https://doi.org/10.1051/bioconf/202414901072

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

With an increase in the height of the soil layer (h>65 cm), the gravitational force does not affect the selected point of the lower part of the soil layer, i.e. the shear rigidity of the soil increases Fig. 4.

The deflection of a metal strip hinged on two supports, loaded with a uniformly distributed load, is determined by the expression:

$$f = \frac{5qL^4}{384E_0I_0}$$

where f is the deflection of a beam of length L from a uniformly distributed load of intensity q from soil with rigidity t=E_0 I_0. From expression (2), we determine the value of the soil's deflection rigidity:

$$t = E_0I_0 = \frac{5qL^4}{384f_{max}} - E_cI_c$$

Based on the experimental studies conducted, we will determine the physical essence of the calculation parameters of the equations that allow us to determine contact stresses, displacements and forces in the body of foundations.

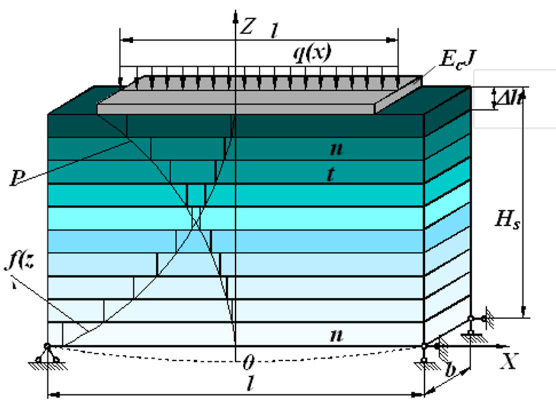

Figure 5. Calculation scheme of the proposed model for determining the shear rigidity of soil.

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

$$P(x) = C_1w_1(x) + C_2w_2(x)$$

The first part of equation (4) characterizes the rigidity of a soil layer to compression with thickness H_s, compressed under compression conditions, i.e. $\varepsilon_{x=y=0}$or by the depth of the imprint $S_f$of the stamp in the soil.

$$C_1 = P_m/S_f$$

where Pm is the average pressure under the stamp.

The settlement can also be determined by the results of compression tests of soils. In this case, it is determined by the known expression using the layer-by-layer summation method up to H_i=2D

$$S_f = \beta\sum_{H_s}\frac{P_fh_i}{E_i} = \sum_{H_s}\frac{P_0\alpha h_i}{E_i} = \beta\frac{P_0h_i}{E_i}\sum_{H_s}\alpha_i$$

Based on the above, we can conclude that the value of the bedding coefficient C1 reflects the condition of soil rigidity in the contact area of the foundation, displacement (depth of the foundation imprint in the soil) and is determined from the condition of compression of the soil layer of thickness H_s.

The second part of equation (4) characterizes the rigidity of the soil layers to deflection w_2 (x).

In accordance with expression (2), we will consider the soil deflection together with a beam hinged on two conditional supports. For the case of a uniformly distributed load, the deflection of such a beam is determined by the known expression:

$$q(x_{sL}) + q(x_c) = \frac{384EIf}{5L^4}$$

where $q(x_{sL})$,$q(x_c)$ – distributed gravitational load from the soil and the beam structure;

$EI= E_0 I_0+E_c I_c$ – reduced beam rigidity;

$t=E_0 I_0$ - shear rigidity of the soil;

$E_c I_c$ - rigidity of the experimental metal strip.

Analysis of the experiments conducted with sand and crushed stone showed that the value of the ratio $\frac{H_s}{(l/2)}$ can be approximately determined by the expression:

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

The parameter of shear rigidity of the soil layer t characterizes the rigidity of one layer of the soil layer with thickness Δh and geometric dimensions in the plan of 4bxL loaded with a single distributed gravitational load P(x). The calculation scheme of the proposed model is shown in Fig. 5. Using the above expression (8), it can be stated that the shear rigidity of the soil massif t with thickness H_s can be determined by expression (9):

$$t = \omega I_0 E_0 = \omega E_0 \frac{4bH_s^3}{12} = \omega E_0 \frac{bH_s^3}{3}$$

Where: b is the width of the foundation, 4b is the width of the stress zone of the soil massif of the foundation under the sole of the foundation;

H_s is the thickness of the active zone (massif) of the soil;

E is the modulus of soil deformation;

$\omega \cong (4 \div 5)$ is the correction factor depending on the type of soil.

Thus, for practical purposes, the shear rigidity t of a soil massif with thickness H_s and width 4b (b is the width of the foundation) can be determined with accuracy using expression (9).

4 Conclusion

The shear stiffness of the soil depends on the density, granulometric composition of the soil and the thickness of the layer H_s.

Experiments have shown (Fig. 3) that with an increase in the soil layer, with a soil layer thickness of H≈60 cm, the shear resistance of the soil increases, that is, with an increase in the height of the soil layer, the shear stiffness of the soil increases.

Experiments have shown (Fig. 4) that with an increase in the height of the soil layer (h>65 cm) at the selected point of the lower part of the soil layer, the gravitational force does not affect, that is, the shear stiffness of the soil increases.

The parameter of the shear stiffness of the soil layer t characterizes the stiffness of one layer of the soil layer with a thickness of Δh with geometric dimensions in the plan of 4bxL loaded with a single distributed gravitational load P(x). The calculation scheme of the proposed model is shown in Fig. 5.

The active area of shear rigidity of soil layers, as well as the depth of propagation of the compensating load H_s, for practical calculations can be determined by expression (9).

The coefficient ω in the proposed expression (9) is proposed to be determined experimentally through a flat tray, Fig. 2, depending on the type and physical parameters of the soil.

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