ERRORS IN STRESS MEASUREMENTS IN SOILS UNDER SHORT-TERM LOADS

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The results of experimental investigations of systemic errors in stress measurements in sandy soils by strain gauges under short-term loads produced by detonation of a plane charge are presented. The effect of rigidity of sensitive elements of the gauges and the effects of stress concentrations around the gauge body on the stress field measured are analyzed. A comparison of the experimental results with the theoretical calculations of [1, 2] is offered. It is shown that the systemic errors will not exceed ± 3-7% if certain easily achieved requirements with respect to the gauges are fulfilled. The question of evaluating systemic error in stress measurement in soils under low intensity static loads has been examined in [3-6].

1. Experimental Method

Sensors used in stress measurements in soils during propagation of explosive waves [7-9] have a cylindrical form with ratio of height h to diameter D varying within the limits $h/D = 0.30$-0.166. The sensitive element of such gauges is a thin film of thickness δ, attached to the surface with a strain resistor glued to its surface.

The diameter of the film d is less than the body diameter, being, as a rule, within the range $d/D \leq 0.5$-0.75.

A strain resistor is mounted on the interior lateral surface of the gauge body, forming a half bridge with the working strain resistor. A second half bridge is located in the strain gauge amplifier. The principle of operation of such a gauge is based on the development of unbalance in the bridge upon action on the sensitive element by a dynamic load. Calibration of the gauge is performed statically in an oil chamber.

In contact measurements the gauge is mounted in a shield in a manner such that only the elastic film is located at the point of contact. Systematic errors are then connected with deformation of the film and depend on the relationship between the rigidities of the film and soil.

In measurements in unlimited masses the sensor is located within the soil, and in this case not only film deflection, but stress concentration around the gauge body, affects the measured stress field, as would inclusion of any other rigid body within the medium.

To evaluate the effect of film rigidity on measured stress, gauges were used with various d = 18-45 mm, $\delta = 1.0$-4.0 mm. The gauges were made from duralumin with a modulus of elasticity $E_0 = 7.4 \cdot 10^5$ kg/cm^2, Poisson coefficient $\nu_0 = 0.33$, and elastic limit $\sigma_S = 60$ kg/mm^2.

The gauges with various d and δ were mounted on a large ferroconcrete slab, with dimensions $2 \times 2 \times 0.5$ m^3 in its central portion, in a manner such that the surfaces of their sensitive elements were located at the same level as the slab surface. Sand was poured and rammed on the slab from above. Soil layer height was 0.5 m. Stress waves were generated by detonation of a plane charge of explosive. The sand density was $\gamma_0 = 1.45$-1.50 g/cm^3, with moisture content by weight of w = 5-7%.

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To study the effect of strain concentration around the gauge body, gauges with various ratios of h/D = 0.166, 0.33, 0.50, 1.0, and 2.5 were used. These particular gauges had the highest sensitive element rigidity in the experiment (d = 22 mm, δ = 3.0 mm).

Experiments were also conducted with the goal of studying the character of the stress distribution over the surface of a rigid cylindrical block located within the soil mass, as it interacts with an incident wave. This block, also made of duralumin, had a diameter of D = 150 mm and height h = 50 mm (h/D = 0.33). On the block surface (about the axis of symmetry and at distances of 30 mm and 60 mm from the axis) were mounted three sensors with diameter d = 18 mm and thickness δ = 2.5 mm.

The corrected densities of the gauges in the experiment γ_1 = P/V, where P is the gauge weight and V its volume, varied from 2.2 to 2.6 g/cm^3, with ratios of γ_1/γ from 1.37 to 1.65 (γ = 1 + 0.01 w, the soil density). For the cylindrical block γ_1 = 2.85 g/cm^3, γ_1/γ = 1.78.

The gauges with different forms and different h/D ratios were installed in the soil at the same relative distance from the explosive source. Here R = r/G, where r is distance in m, G is charge weight in kg.

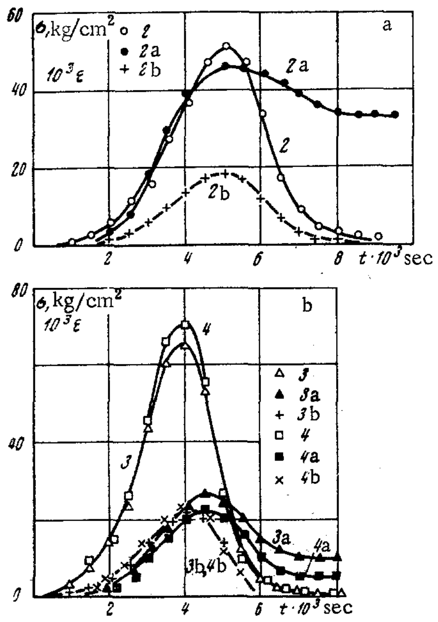

Fig. 1

A portion of the experiments was conducted in undisturbed soil with γ_0 = 1.50-1.55 g/cm^3, w = 5-7%.

The gauge indications were recorded by a type UTS-VT-12/35 amplifier and N-105 loop oscillographs. In all experiments loops of the same type were used, so that the time error was identical for each of a series of experiments, and had no influence on the value of the systematic errors under investigation [9].

2. Mechanical Characteristics of the Soil

In order to perform theoretical calculations to evaluate measurement errors it was necessary to have corresponding data on the mechanical characteristics of the soil in which the experiments were conducted. Therefore laboratory investigations were made on this soil to determine compressibility and plasticity under different modes of deformation in a quasistatic apparatus, using the method described in [10]. Samples with γ_0 = 1.50 g/cm^3 and w = 5%, diameter D_0 = 150 mm, and height h_0 = 30 mm were subjected to loading by a shock load three times. Total strain on the sample was measured by a tensometric glass, normal strains $\sigma_1(t)$ and $\sigma_2(t)$ by membrane sensors, and sample deformation $\varepsilon(t) = h_0^{-1} u(t)$ [u(t) is the displacement of the device piston] was measured by a tensometric displacement sensor. Experiments were repeated five times under one and the same conditions. Each of the parameters in an experiment was measured by two or three sensors. The mean variation coefficient β for stress and deformation with a statistical probability of α = 0.95 was β = ±15-17% in these experiments.

Figure 1a, b presents measurements of the quantities $\sigma_1(t)$, $\sigma_2(t)$, $\varepsilon(t)$ for three successive loadings of the samples [first load: 2) $\sigma_1(t)$, 2a) $\varepsilon(t)$, 2b) $\sigma_2(t)$; second load: 3) $\sigma_1(t)$, 3a) $\varepsilon(t)$, 3b) $\sigma_2(t)$; third load: 4) $\sigma_1(t)$, 4a) $\varepsilon(t)$, 4b) $\sigma_2(t)$]. The corresponding $\sigma(\varepsilon)$ curves, constructed by eliminating time t from the traces $\sigma_1(t)$ and $\varepsilon(t)$, are presented in Fig. 2 (curves 2, 3, and 4). Curve 1 is the result of a field study of $\sigma_1(\varepsilon_*)$ at the front of a shock wave $\dot{\varepsilon} = \partial\varepsilon/\partial t = \infty$, while curve 5 is from static studies ($\dot{\varepsilon} = 1 \cdot 10^{-5}$ sec^{-1}). It is evident from Figs. 1 and 2 that deformation rate significantly affects deformation of a given soil [10]. It is important to note that in dependence on the deformation rate the value of the modulus of deformation

$$E(\varepsilon) = \frac{d\sigma_1(\varepsilon)}{d\varepsilon}$$

varies significantly.

Meanwhile, for $\dot{\varepsilon} > 0$, the maximum values of E(ε) correspond (for σ_1 = const) to curve 1, where $\dot{\varepsilon} = \infty$, while the minimums correspond to curve 5 ($\dot{\varepsilon} \to 0$). The values of $E_*(\varepsilon)$ for $\dot{\varepsilon} > 0$ are greater than E(ε) under the same stresses.

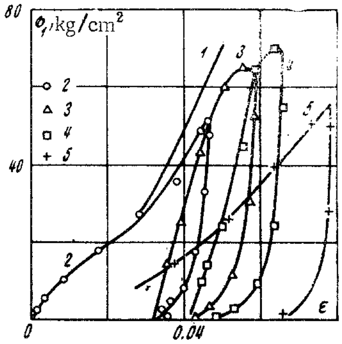

Fig. 2

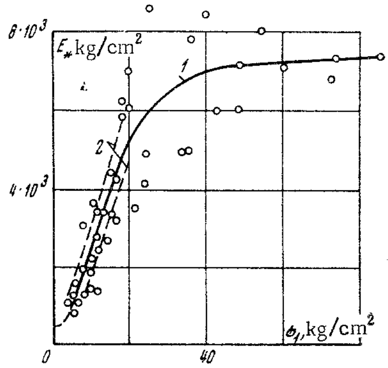

Fig. 3

It will now be of interest to obtain quantitative data on the behavior of E_* as a function of σ_1 for $\dot{\varepsilon} < 0$. For this purpose, oscillograms of $\sigma_1(t)$ and $\varepsilon(t)$ at $\dot{\varepsilon} < 0$ were divided into n equal time intervals $\Delta t = 0.25 \cdot 10^{-3}$ sec, and the mean moduli E_{*i} were then determined by the formula

$$E_{*i}{}^p = \frac{k_2}{k_1} \sum_{j=1}^{k_1} (\sigma_{1i+1/2,\, j}^{\,p} - \sigma_{1i-1/2,\, j}^{\,p}) \left[\sum_{j=1}^{k_2} (\varepsilon_{i+1/2,\, j}^{\,p} - \varepsilon_{i-1/2,\, j}^{\,p})\right]^{-1}$$
$$(i = 1, 2, \ldots, n;\; p = 1, 2, \ldots, l) \tag{2.1}$$

which were then placed in correspondence with the stresses

$$\bar{\sigma}_{1i}{}^p = \frac{1}{2k_1} \sum_{j=1}^{k_1} (\sigma_{1i+1/2,\, j}^{\,p} + \sigma_{1i-1/2,\, j}^{\,p}) \tag{2.2}$$

Here k_1 and k_2 are the number of strain and deformation measurements in each of the experiments, and l is the number of experiments in a series.

The function $E_*(\sigma_1)$, corresponding to curve 2 of Fig. 2, is presented in Fig. 3 (curve 1). The portion of the curve at $4 \le \sigma_1 \ge 20$ kg/cm² is approximated with sufficient accuracy by the linear rule

$$E_* = \alpha_1 + \beta_1 \sigma_1 \ (\mathrm{kg/cm^2}) \tag{2.3}$$

where

$$\alpha_1 = \bar{E}_* - r_1 \Delta S_1{}^2 [\Delta S_2{}^2]^{-1} \bar{\sigma}_1, \quad \beta_1 = r_1 \Delta S_1{}^2 [\Delta S_2{}^2]^{-1}$$
$$r_1 = \frac{1}{\Delta S_1 \Delta S_2} \sum_{p=1}^{l} \sum_{i=1}^{n} (E_{*i}{}^p \bar{\sigma}_{1i}{}^p - nl \bar{E}_* \bar{\sigma}_1)$$

and the correlation coefficient

$$\bar{E}_* = \frac{1}{nl} \sum_{p=1}^{l} \sum_{i=1}^{n} E_{*i}{}^p, \quad \bar{\sigma}_1 = \frac{1}{nl} \sum_{p=1}^{l} \sum_{i=1}^{n} \sigma_{1i}{}^p \,.$$
$$\Delta S_1{}^2 = \frac{1}{nl} \sum_{p=1}^{l} \sum_{i=1}^{n} (E_{*i}{}^p - \bar{E}_*)^2, \quad \Delta S_2{}^2 = \frac{1}{nl} \sum_{p=1}^{l} \sum_{i=1}^{n} (\sigma_{1i}{}^p - \bar{\sigma}_1)^2$$

are the dispersions of the quantities E_* and σ_1, respectively. Here $r_1 = 0.79$, $\alpha_1 = -400$ kg/cm², $\beta_1 = 300$. The dots 2 in Fig. 3 correspond to a probable interval with reliability $\alpha = 0.95$.

For successive loadings, the value of $E_*(\sigma_1)$ is larger than $E_*(\sigma_1)$ for the first load by 10-15% (for the same values of $\sigma_1 \le 20$ kg/cm²), which, however, is within the limits of experimental accuracy (Fig. 3).

The plasticity function for a given soil, as earlier in [7, 8, 10], can be taken as linear, and the plasticity condition written in the form

$$J_2 = (k\sigma + b)^2 / 6, \quad J_2 = 2(\sigma_1 - \sigma_2)^2,$$
$$\sigma = (\sigma_1 + 2\sigma_2) / 3 \tag{2.4}$$

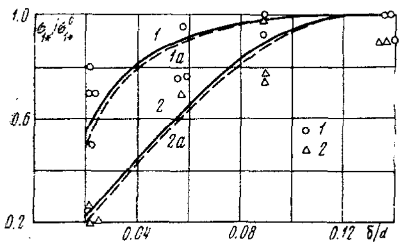

Fig. 4

where k = 1.50, b = 0 are experimental coefficients. From Eq. (2.4), in accordance with [10], we have the lateral pressure coefficient ξ_*

$$\xi_* = \frac{3\sqrt{2}-k}{3\sqrt{2}+2k} = 0.38$$

3. The Effect of Sensitive Element Deflection on Stress Measurement

Figure 4 presents the results of tests of sensors of varying rigidity installed on the slab. The ordinate represents the ratio $\sigma_{1*}/\sigma_{1*}^{\circ}$, while the abscissa is the dimensionless quantity δ/d, characterizing the rigidity of the sensitive element. Here σ_{1*} is the maximum strain recorded by a sensor, σ_{1*}° is the mean arithmetic value maximum strain from data of the most rigid sensor in an experiment ($\delta/d = 0.136$), equal to 5.1 kg/cm^2 for points 1, and to 41.1 kg/cm^2 for points 2. The points 1 and 2 correspond to location of sensor and slab for differing distances R from the explosion source: 1) R = 4.0, 2) R = 1.0. Curves 1 and 2 (Fig. 3) were constructed from the theoretical formula of [1]

$$\frac{\sigma_{1*}}{\sigma_1^0} = \left(1 - \frac{m(1-m)}{23.2}\frac{E}{J_1}\right)^{-1}, \quad m = \frac{1-2\nu}{2(1-\nu)} = \left(\frac{b_0}{a_0}\right)^2 \tag{3.1}$$

where σ_{1*} are the maximum strains recorded by a gauge, σ_1° are the "true" strains in the soil, E is the modulus of deformation of the soil, ν is the soil Poisson coefficient, b_0, a_0 are the propagation velocities of transverse and longitudinal waves in the soil, $J_1 = J(d/2)^{-3}$ is the dimensionless film (sensitive element) rigidity, $J = E_0\delta^3/12\,(1-\nu_0^2)$ is the film cylindrical rigidity, E_0 is the modulus of elasticity of the film material, and ν_0 is the Poisson coefficient of the film material.

For the sandy soils studied, m = 1/3, and $E = E_*(\sigma_{1*})$ according to curve 1 (Fig. 3). It is considered here that the interaction of sensor with shock wave occurs in a state of soil unloading $\dot{\varepsilon} < 0$.

To eliminate from Eq. (3.1) the unknown quantity σ_1°, all calculated values of σ_{1*} were divided by the quantity

$$\sigma_{1*}^{\circ} = \sigma_1^{\circ}\left(1 + \frac{m(1-m)}{23.2}\frac{E_*^{\circ}}{J_1^{\circ}}\right)^{-1} \tag{3.2}$$

where J_1° is the sensor rigidity with $\delta/d = 0.136$, and $E_*^{\circ} = E_*(\sigma_{1*}^{\circ})$. In calculating the values $\sigma_{1*}/\sigma_{1*}^{\circ}$ of curve 1 for $\delta/d = 0.02$–0.04, it was assumed that $E_* = 600$ kg/cm^2 (Fig. 4).

As is evident from Fig. 4, curves 1 and 2 describe the experiment sufficiently well. The mean variation β in these experiments for a reliability $\alpha = 0.95$ for curves 1 and 2 was ±25 and ±17%, respectively.

For comparison, the dashed lines of Fig. 4 show curves 1 and 2, as constructed from the data of [4], for the same experimental conditions as our curves 1 and 2.

Thus, the measurement error in maximum stresses for short-term loads can be determined with sufficient accuracy by the formula

$$\Delta_- = -\left(1 - \frac{23.2}{m(1-m)}\frac{J_1}{E_*}\right)^{-1}, \quad \Delta_- = \frac{\sigma_{1*} - \sigma_1^{\circ}}{\sigma_1^{\circ}} \tag{3.3}$$

Considering that Eq. (3.3) has been verified under the worst conditions, with $\dot{\varepsilon} < 0$, the evaluation of Eq. (3.3) will also be employed beyond the shock wave front.

The error values Δ_-, determined by Eq. (3.3) for the gauges examined above, are presented below:

$\sigma/d =$	0.022	0.057	0.089	0.136
$\Delta_- =$	0.450	0.085	0.020	0.010
$\Delta_- =$	0.790	0.380	0.150	0.050

The first and second columns correspond to curves 1 and 2 (Fig. 4). From these data and Eq. (3.3) it follows that gauges with $\delta/d = 0.022$ and 0.057 at stresses $\sigma_{1*} = 20$–40 kg/cm^2 have large errors and are not suitable for measurements. Therefore, in conducting experimental studies in the stress range indicated, more rigid gauges with $\delta/d = 0.089$–0.136 are usually employed [7–10].

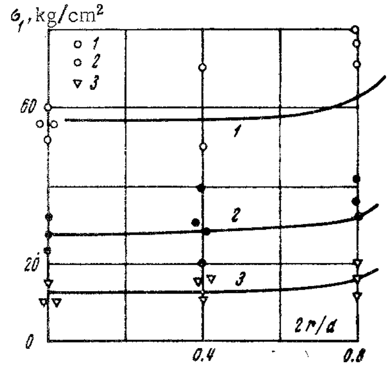

Fig. 5

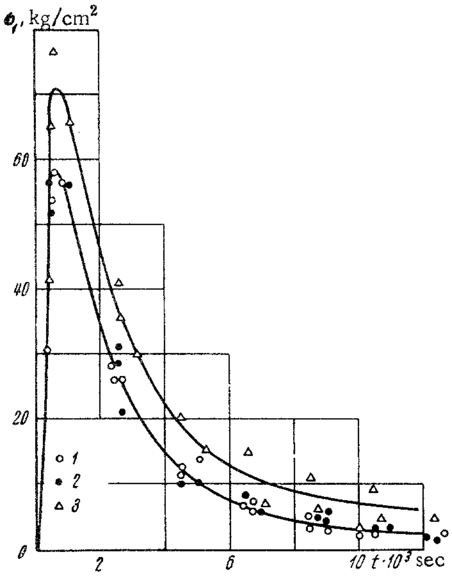

Fig. 6

4. Errors Related to Stress Concentration around the Body of a Gauge Located within the Soil Mass

Figure 5 presents the results of experiments to characterize the stress distribution over the surface of a rigid block with $h/D = 0.33$, located in a soil mass, as it interacts with an explosive wave. Points 1 and curve 1 correspond to time $t_1 = 0.5 \cdot 10^{-3}$ sec, points 2 and curve 2 to $t_2 = 2.5 \cdot 10^{-3}$ sec, and points 3 and curve 3 to $t_3 = 5.0 \cdot 10^{-3}$ sec. Curves 1, 2, and 3 are constructed from the results of theoretical calculations [2] applicable to these conditions. From these results it follows, in particular, that for $h/D \leq 1$ in the central portion of the sensor with $d \leq (0.3-0.5)$ D the stress distribution is close to equal, the stress concentration value is minimum and determined by

$$\Delta_{+} = m\frac{h}{D}, \quad \Delta_{+} = \frac{\sigma_{1*} - \sigma_1^{\circ}}{\sigma_1^{\circ}}, \quad \frac{h}{D} \leqslant 1 \tag{4.1}$$

where $m = (b_0/a_0)^2$, σ_1° is the stress value in the incident wave, and σ_{1*} is the stress value recorded by a rigid sensor.

Theoretical deductions on the constancy of stress on a rigid block with $d \leq (0.3-0.5)$ D are supported by the experimental data of Fig. 5. Analogous conclusions as to the decrease in the effects of concentration with reduction in the ratio d/D have been announced earlier in [3].

Equation (4.1) relates to moments of time when a quasistatic sensor motion regime has been established, i.e., when diffraction processes around the sensor can be neglected. This time t_0 occurs quite quickly for a sensor, and at $\gamma_1/\gamma \leq 1.5-2.0$ is $(2.0-2.5)\,D/a_0$, where a_0 is the propagation velocity of elastic waves in the soil [2]. For standard sensors in the experiments performed $\gamma_1/\gamma = 1.3-1.5$, and the value of t_0 at D = 60 mm is $0.5 \cdot 10^{-3}$ sec. For the block of Fig. 5, $t_0 \approx 1.2 \cdot 10^{-3}$ sec.

Figure 6 presents experimental data on the change with time of stress on the surface of the block of Fig. 5. Points 1 are the indications of a standard sensor located the same distance from the explosion source, with $h/D = 0.166$ ($d = 22$ mm, $\delta = 3.0$ mm, $\Delta_{-} = -0.050$), points 2 are the indications of a sensor in the central portion of the block, and points 3 the indications of a sensor at the block edge ($d = 18$ mm, $\delta = 2.5$ mm, $\Delta_{-} = -0.040$).

From the data of Fig. 6 it is evident that the indications of sensor 1 coincide with those of sensor 2 in the center of the block. This testifies to the establishment of a quasistatic regime for the sensor and block at time $t_0 = 0.5 \cdot 10^{-3}$ sec. The indications of sensor 3 over the course of the whole process are 25-30% higher than those of sensors 1, 2. This confirms the conclusion of [2] that stress concentration for sensors has a quasistatic character.

Figure 7 presents the results of strain measurements in a mass of sandy soil by gauges with the same rigidity ($\delta/d = 0.136$) for $d/D = 1/3$ at various h/D ratios. The ordinate shows maximum stress $\sigma_1{*}$ recorded by the sensors with various h/D values.

Points 1-3 correspond to sensors installed at various relative distances R from the explosion source: 1) R = 0.5, 2) R = 1.0, 3) R = 1.5.

The variation coefficients β for the sets of points 1, 2, 3 are, respectively, ±19.0, ±9.0, ±22.0% with a statistical probability of $\alpha = 0.95$.

It follows from the experimental results that the function $\sigma_1{*}$ (h/D) can be approximated with sufficient accuracy by the linear rule

$$\sigma_1{}^* = \sigma_1^{\circ} + m_1 h / D \tag{4.2}$$

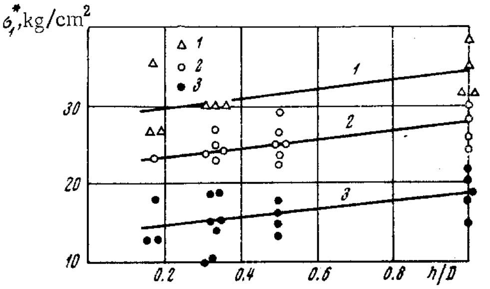

Fig. 7

where $\sigma_1°$, m_1 are experimental coefficients. For curve 1) $\sigma_1° = 28.5$ kg/cm², $m_1 = 6.3$ kg/cm², 2) $\sigma_1° = 22.0$ kg/cm², $m_1 = 5.9$ kg/cm³, 3) $\sigma_1° = 14.0$ kg/cm², $m_1 = 4.5$ kg/cm².

For the error $\Delta_+ = (\sigma_1{*} - \sigma_1°)/\sigma_1°$ we obtain from Eq. (4.2) a formula analogous to Eq. (4.1), but with different m values for curves 1-3: 1) m = 0.22, 2) m = 0.27, 3) m = 0.32.

The tendency to decrease in the value of m with increase in stress $\sigma_1°$ can be explained by the increase in that case of the role of plastic deformations of the soil, and qualitatively agrees with the conclusions of [11]. The evaluation of Δ_+ according to Eq. (4.1) at the value $m = (b_0/a_0)^2 = 1/3$, which is characteristic of the soil studied in its elastic state of operation, will then be an upper evaluation of the error related to stress concentration around the gauge body. For h/D > 1.0, the measurement error Δ_+ rises sharply. In the experiments it was shown, in particular, that for h/D = 2.5 the indications of the sensors σ_{1*} were almost twice as great as the indications at h/D = 1.0.

We present below the values of error Δ_+, determined for the cylindrical sensors with various h/D by Eq. (4.1) for m = 1/3

h/D	0.166	0.33	0.50	1.0
Δ_+	0.055	0.110	0.165	0.330

The evaluations obtained agree sufficiently well with the results of static studies [3, 12]. In [3], in particular, at d/D = 0.75 for dense sandy soil m = 0.6-0.65; for clays with moisture w = 13-16%, m = 0.39-0.45; for clays with w = 18%, m = 0.15. At the same time, it follows from the experiments of [3] that for a decrease in the ratio d/D to 1/3 the values of m decrease 1.5-2 times. In [12], for rigid bar-type sensors, at h/D = 1.35 the value of "overload" for static experiments in dense sandy soils with $\gamma_0 = 1.68$ g/cm³ was equal to $\sigma_1{*}/\sigma_1° = 1.54$-1.66. Therefore m = 0.40-0.49. For the action of a dynamic load, the data obtained in [12] for rod and membrane sensors are contradictory, and evidently indicate a significant scattering in the measurement results.

The investigations conducted indicate that if certain quite simple conditions are observed with respect to cylindrical gauge geometry ($h/D \le 1/5$–$1/6$, $d/D \le 0.3$–0.5) and sensitive element rigidity ($J_1/E_* > 1/8$), systematic errors in stress measurement in soils with short-term loads will not exceed $\Delta = \pm(3$–$7\%)$ and prove to be significantly (2-3 times) lower than random errors.

In connection with this, one must agree with the proposal of [5, 12] that it is necessary to calibrate gauges in soil. It can be expected in this case that random errors related to the irregularity of loading soil into the calibration chamber will prove to be significantly larger than systematic errors of the gauges themselves, and thus will reduce the accuracy of the entire experiment.

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