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MEASUREMENT OF THE DYNAMIC CHARACTERISTICS OF SOFT SOILS USING THE KOLSKY METHOD

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A modified Kolsky method for dynamic tests of soft soils in an elastic holder is analyzed. It is shown the axial and radial stresses in the sample are uniform. The rational geometry of the holder is determined. Friction is found to have an effect on the dynamic strain diagram obtained. It is suggested that this effect can be reduced by lubricating the inner surface of the holder.

Key words: *Kolsky method, soils, inertial reaction, wave processes.*

Introduction. The behavior of soils under the action of intense dynamic loads is of interest in analyzing wave processes in soils with a view to derive the equations of state and use them in numerical methods of solving penetration problems and problems of interaction of soil and various structures in cases of earthquakes, explosions, and impacts. The insufficiency of systematic data on the dynamic properties of soils is due to the lack of standard high-speed test methods, which, in turn, is due to significant methodical difficulties in performing such tests. The main method used in dynamic tests of materials is the split Hopkinson bar (SHB) method proposed by Kolsky [1]. For high-speed tests of soils and other low-density media, the SHB method was modified by using a confining elastic holder [2]. Further development of this modification [3] made it possible to obtain, in addition to uniaxial strain diagrams, values of radial stresses, pressure, shear resistance, and the side pressure coefficient at strain rates of approximately 10^3 sec^{-1}. Bazhenov et al. [4] performed a numerical analysis of the applicability of this modification for soil tests at high strain rates and established that the ratio of the sample and holder dimensions has a significant effect on the results obtained. The present study is devoted to further analysis of the uniformity stresses in soil samples, the effect of the holder material, sample length, and friction forces on the obtained physicomechanical characteristics of soils.

Experimental Procedure. Bazhenov noted [4] that the use of a holder whose length L exceeds the length l of the soil sample gives rise to an error proportional to the ratio L/l in finding radial stresses in the soil from measured hoop strains of the holder. An excess of the holder length over the sample length is dictated to the necessity of centering the holder about the bars.

Figure 1 shows the holder used in our study. The collars 1 mm wide and 3 mm long at the end surfaces of the holder center it about measuring bars 1 and 4 precisely enough and, as shown by calculations, practically do not influence the stress–strain state (SSS) of the holder. Depending on the load amplitudes used, holders 3 were made of D16T alloy and 30KhGSA steel at a ratio of the outer diameter b to the caliber a equal to 1.5. The higher deformability of the aluminum alloy compared to steel allows the hoop strains on the outer surface of the holder to be more accurately recorded using strain gauge 2 at low pressures in soil sample 5.

The basic principles of the experimental procedure used to determine the dynamic characteristics of soils and a description of the wave processes occurring in the SHB system are contained in [3]. The load on the holder from the soil, which is characterized by the stress component $\sigma_{rr}(t)$, is related to the hoop strain $\varepsilon_{\theta\theta}(t)$ recorded on the outer surface of the holder by the well-known analytical solution for the SSS of a thick-wall pipe segment

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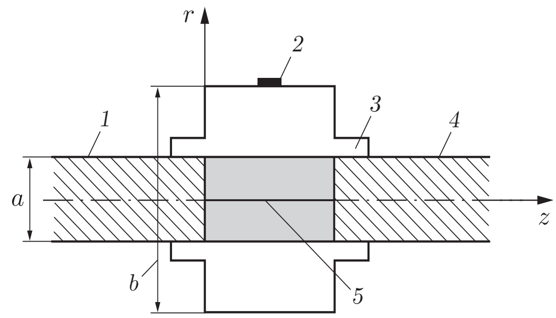

Fig. 1

under the action of a constant internal pressure. The hoop and radial stresses in a pipe with inner diameter a and outer diameter b under the action of internal pressure q are expressed by the following formulas [5]:

$$\sigma_{\theta\theta} = A - B/r^2, \qquad \sigma_{rr} = A + B/r^2.$$

Here

$$A = qa^2/(a^2 - b^2), \qquad B = -qa^2b^2/(a^2 - b^2).$$

Thus,

$$\sigma_{rr} = \sigma_{zz} = 0, \qquad \sigma_{\theta\theta} = 2qa^2/(b^2 - a^2) \tag{1}$$

on the outer surface of the holder and

$$\sigma_{rr} = -q, \qquad \sigma_{zz} = 0, \qquad \sigma_{\theta\theta} = q(b^2 + a^2)/(b^2 - a^2) \tag{2}$$

on the inner surface.

In the experiment, the internal pressure q is the stress σ_{rr} in the soil, and, hence, in addition to an axial compression diagram, one can obtain the side pressure coefficient $K_\sigma = \sigma_{rr}/\sigma_{zz}$, the shear resistance τ, the pressure P, and the stress and strain rates. Expressions (1) and (2) are valid for elastic strains of the holder. Let us estimate admissible soil stresses that do not cause plastic strains in the holder. Using the Tresca–Saint Venant plasticity criterion [5] and relation (2), we find that plastic strains arise on the inner surface of the holder for longitudinal stresses in the soil $\sigma_{zz} = (1 - (a/b)^2)\sigma_T/K_\sigma$ (σ_T is the yield strength of the holder material). Plastic strains on the outer surface of the holder, where hoop strain pulses are recorded, should arise at somewhat larger values of the longitudinal stresses, namely for $\sigma_{zz} = ((b/a)^2 - 1)\sigma_T/K_\sigma$. For $b/a = 1.5$ and $K_\sigma = 0.5$, we obtain $\sigma_{zz}/\sigma_T = 1.1$–$2.5$ if $\sigma_T = 200$–300 MPa for D16T alloy. Thus, the elasticity requirement for holder strains is satisfied for rather high soil stresses.

To assess the effect of the sample length on the strain diagram, we performed a series of tests of sand soil at air dampness. In all tests, the sample length l coincided with the holder length L and was 6.5, 9.5, and 20 mm. The samples were loaded by trapezoidal strain pulses with a duration of approximately 175 μsec and durations of the leading and rear edges of 15–20 μsec.

In Fig. 2, the dotted curve shows the longitudinal stress in the soil versus strain for $l = 9.5$ mm, and the solid and dot-and-dashed curves correspond to sample lengths of 6.5 and 20 mm, respectively. From the figure one can see that at small strains, the strain diagram shows oscillations due to wave loading of the sample; the oscillation amplitudes decrease as the sample thickness decreases. Since the minimum sample length is limited by the requirement of representativeness of the volume (the sample thickness should at least an order of magnitude exceed the soil particle size), we used samples 9.5 mm thick in the experiments. All strain curves in Fig. 2 have a segment with zero stresses, which is the smallest for the sample 6.5 mm long and the largest for the sample 20 mm long. In the tests of samples of different lengths, the propagation speed of small-amplitude compression waves in sand was determined from the time delays between the transmitted and reflected pulses, which was equal to approximately 430 m/sec.

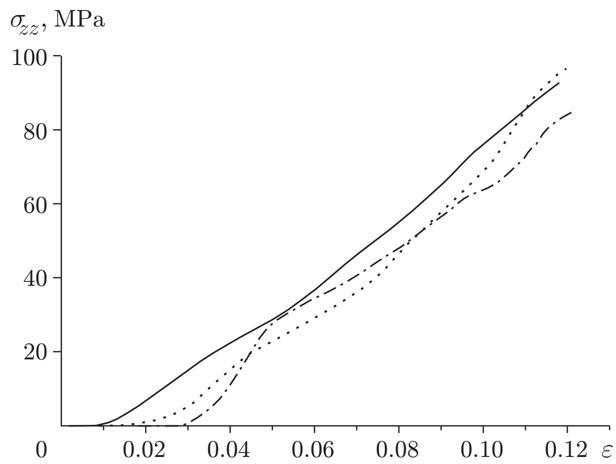

Fig. 2

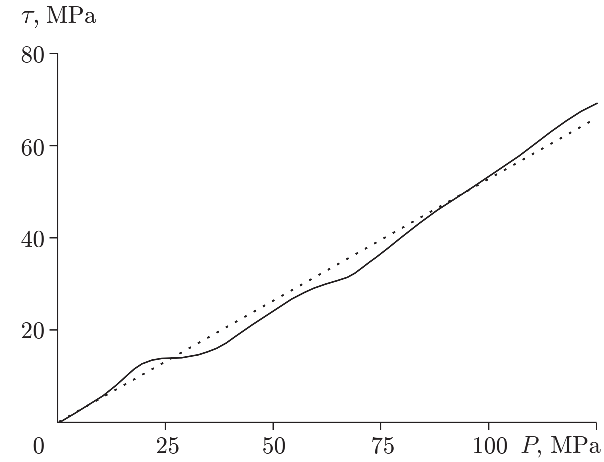

Fig. 3

The dependence of the shear resistance of sand on pressure was obtained from the averaged test data for samples $l = 9.5$ mm long. This dependence is shown in Fig. 3 (solid curve). The dotted curve in the figure shows the approximation linear dependence $\tau = P \tan \varphi$, where φ is the angle of internal friction in the soil. For the tested sand of air dampness and density 1.6 g/cm^3, the angle of internal friction is 27.8°.

Results of Numerical Calculations. As is known, one of the main prerequisites of the Kolsky method is the assumption of uniformity of the SSS of the sample. To verify this assumption, we performed numerical calculations using the Dinamika-2 applied software [6]. The dynamic deformation of soils in the numerical procedure is described by the relations of Grigoryan's model of soil [7]. To use this model in the calculations, it is necessary to specify the dependence of the pressure P on the strain ε (loading and unloading diagram) and the dependence of the yield strength on pressure. The parameters of the initial segment of the curve $P = f(\varepsilon)$ are determined from experiments using the SHB system [8]. The experimental data are approximated by the power-law dependence proposed by Rykov [9]:

$$P = M\theta^n, \qquad \theta = 1 - \rho_0/\rho. \tag{3}$$

The constants M and n are determined for each type of soil from the results of a series of experiments using, for example, the least-squares method. In the range of pressures above 200 MPa, we used the results of plane-wave

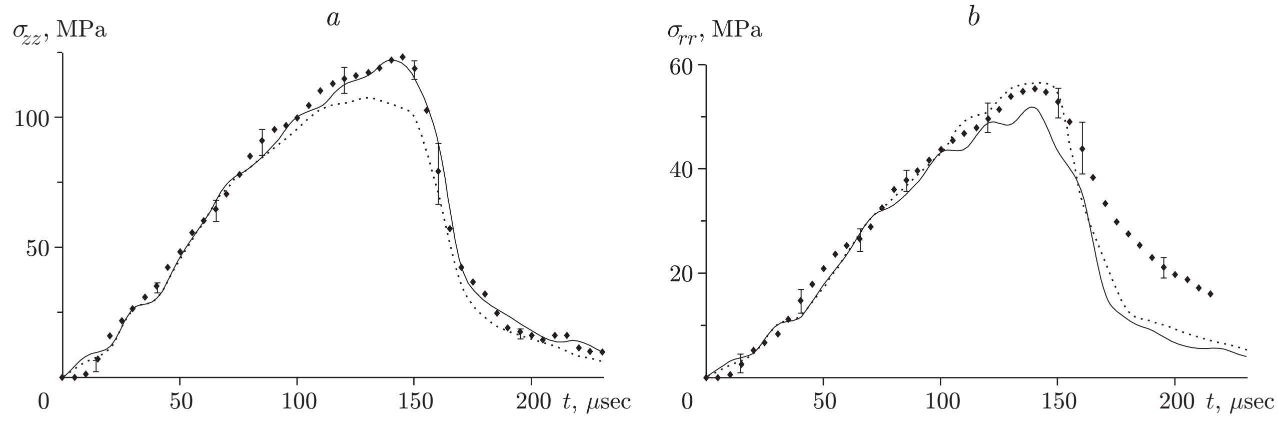

Fig. 4

shock experiments [10]. The experimental dependence of the shock-wave velocity D on the mass velocity U for the linear case $D = A + BU$ can be reduced using the conservation laws at the shock-wave front to the form

$$\sigma(\theta) = -\rho_0 A^2 \theta/(1 - B\theta)^2. \tag{4}$$

For $P(\theta)$, a similar dependence with different constants A and B is used. In the range of moderate pressures of 50–200 MPa, which has been poorly studied at present, we employed interpolation with a Bezier parametric cubic polynomial [11], which ensures continuity of the velocities of a sound (derivative $dp/d\rho$) at the joint nodes. The procedure for plotting the shock adiabat and rarefaction curves for soft soils is described in [9].

The dynamic dependence of the yield strength σ_T on the pressure is assumed to be linear [7, 9]:

$$\sigma_T = \sigma_0 + kp. \tag{5}$$

For cohesionless soils, in particular, dry sand, the quantity σ_0, which has the physical meaning of cohesion, is close to zero, and the constant $k = 2\tan\varphi$.

The calculations were performed for bars and a holder made of D16T alloy, which has an elastic modulus $E = 70$ GPa, Poisson's constant $\nu = 0.3$, and density $\rho = 2.7$ g/cm^3. For sand of density $\rho_0 = 1.6$ g/cm^3, the constants M and n in the power-law dependence (3) obtained by experimental-data processing were 2.0 GPa and 1.76, respectively, which correlates well with the results of [7]. The constants of the shock adiabat (4) were taken from [9]: $A = 400$ m/sec and $B = 2.2$. The values of the constants of the interpolating polynomial were as follows: $\alpha = \beta = 0.06$, $p_1 = 10$ MPa, and $p_4 = 200$ MPa. In the functional dependence for rarefaction, $\gamma_c = 2$ and $\gamma_p = 5$ (using the notation of [11]). The initial velocity of sound for rarefaction was $C_0 = 250$ m/sec, the shear modulus was $G = 150$ MPa, and the constants in the dependence (5) of the yield strengths on the pressure were $k = 1.06$ and $\sigma_0 = 0$.

Figure 4 gives the results of numerical calculations of wave processes in the SHB system. Figure 4a shows time curves of the axial stresses at the center (solid curve) and on the side face of the sample (dotted curve) in comparison with experimental data (markers). There is good agreement of the results at both the loading and rarefaction stages. Figure 4b gives calculated radial stresses at the center (solid curve) and on the side face of the sample (dotted curve). In this figure, the markers shows the data obtained by formula (1) using measured hoop strains of the holder. The indicated boundaries of the confidence interval are determined with a reliability of 0.94 [12]. Thus, the results given in Fig. 4 suggests that the stress state of the sample is uniform.

The difference between the results of the numerical experiment and the full-scale experiment does not exceed the error of the full-scale experiment, which indicates that the parameters of the soil model were correctly determined for the range of loads studied.

Analysis of Friction Effects. Since soils (especially sand) are abrasive materials, the results can be affected by the friction force that arises on the inner surface of the holder. To estimate the friction and the influence

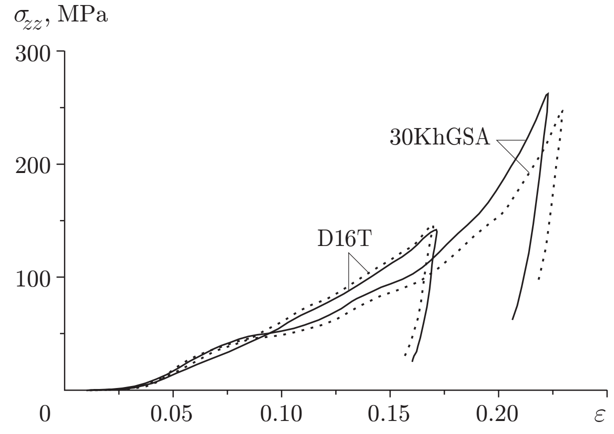

Fig. 5

of the hardness of the holder material, we performed experiments in which sand was loaded into Duralumin and steel holders whose inner surfaces were lubricated. The sand was loaded into the Duralumin holder up to axial stresses of 150 MPa and into the steel holder up to 400 MPa. Figure 5 shows strain diagrams obtained for holders with graphite lubrication of their inner surfaces (dotted curve) and for holders without lubrication (solid curves).

It is evident that at stresses of up to 50 MPa, the strain diagrams obtained with the use of Duralumin and steel holders virtually coincide. The effect of friction is insignificant in both cases. At stresses above 50 MPa, the $\sigma_{zz} = f(\varepsilon)$ diagrams obtained in the experiments with steel holders are noticeably below. The strain diagrams obtained using Duralumin holders with and without lubrication practically coincide at stresses over 50 MPa, too. This can be explained as follows. After the tests, one can see a noticeable abrasive strain one the inner surface of the Duralumin holder due to the contact interaction of the sand particles and the holder material. The additional resistance that arises in this case makes a significant contribution to the longitudinal stresses, eliminating the lubrication effect. For steel holders, this effect is less pronounced because of the higher hardness of steel, as is suggested by the absence of abrasive strain on the inner surface of the holder; as a result, the $\sigma_{zz} = f(\varepsilon)$ diagram is lower. At the same time, the lubrication effect on the strain diagram obtained using steel holders becomes significant.

Thus, to obtain a reliable strain diagram for soil over a wide range of pressures, one can use holders from D16T alloy and 30KhGSA steel simultaneously. At low pressures, the longitudinal and radial stresses are correctly determined using Duralumin holders, and at higher pressures, steel holders should be used. The longitudinal stresses of approximately 400 MPa obtained in experiments with steel holders and steel measuring bars are close to the data of the plane-wave experiments of [11]; therefore, it is possible to perform their comparison and to plot strain diagrams over a wide range of load amplitudes.

Conclusions. From the results of the studies performed, a rational design and geometry of the holder were proposed that allow one to obtain reliable data on the dynamic compressibility and shear strength of soft soils. Using holders made of different materials in experiments, it is possible to explore a rather wide range of loads, whose upper boundary is larger than the lower boundary in plane-wave experiments. It was found that friction forces have an effect on the inner surface of the holder at pressures in soil above 50 MPa; in this connection, it is proposed to apply a thin layer of a lubricant to the inner surface of the holder. Numerical analysis of the axial and radial stresses in the sample showed that they are uniform, indicating that the main prerequisite of the Kolsky method is satisfied.

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