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NEW POTENTIALS OF KOL'SKII'S METHOD FOR STUDYING THE DYNAMIC PROPERTIES OF SOFT SOILS

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Kol'skii's method employing the split Hopkinson bar (SHB) [1] is a most substantiated and widespread technique for dynamic testing of materials at strain rates of about 10^3 sec^{-1} [1]. It has gained wide acceptance for dynamic testing of metals and their alloys [2]; more rarely it has been applied to determination of mechanical properties of both polymeric and composite materials [3, 4]. Only a few works are available in which the SHB method has been applied to dynamic testing of rocks [5] and concrete [6].

In recent years we have proposed to apply the SHB method to obtain the dynamic deformation diagrams of soft soils [7, 8]. However, alongside with such diagrams, another mechanical characteristic of the soil, the resistance to shear, is of apparent interest. Determination of its dependence on the strain rate and pressure is of great importance for formulating the equation of state of soil media. In this paper is given a description of a modified SHB method to determine volume compressibility and resistance to shear at strain rates of about 10^3 sec^{-1} of soil materials.

Experimental Set-up. Figure 1 is shows the equipment, which is currently used at our institute for dynamic tests of both constructional materials and soils by the Kol'skii method. The main parts of the equipment are: a gas gun *1*, a split Hopkinson bar *3–5*, and a set of registering devices equipped with a personal computer *15* for automatic processing of experimental data.

The main difference between the proposed technique for testing soft soils and the conventional SHB scheme for compression tests consists in locating a soil specimen *4* in a steel end grip *10* preventing its radial deformation. This testing scheme is called a system with passively confined radial strain [6]. The confining 15 mm long end grip with 10-mm-thick walls is made of steel with an yield limit of 1000 MPa. It is slipped with small friction over the ends of the measuring rods (the clearance between the lateral surface of the rods and the inner surface of the grip is 50 μm). The circumferential strain of the end grip is measured using four sequentially connected strain gages located along the midsection of the grip.

The load pulses in the measuring rods arise from 50 to 500-mm-long strikers *2* accelerated by the compressed air in the barrel of a 20-mm-calibered gas gun [9]. Application of such a loading device allows easy variation of load parameters. In experiments on soils the strain rate varies from $5 \cdot 10^2$ to $3 \cdot 10^3$ sec^{-1}, the stresses in the sample reaching $\sim$ 300 MPa.

To measure the striker's exit velocity, two sources of light are installed at the end of the barrel. As a photodetector, fast-response photodiodes are used. Their signals are conveyed via trigger circuits *6* into a frequency meter *7* operating in the time-measuring regime. Given the base of the measuring gage and the time during which the striker flies past it, it is easy to compute the impact velocity.

The SHB itself consists of two rods *3* and *5* each 20 mm in diameter and 1 m in length with a sample-tablet *4* in between. The rods are made of high-strength steel or D16T aluminum alloy. The elastic strain pulses in the rods are measured by foil tension resistors *9* with a small base bonded to the middle of the measuring rods. To prevent the registration of flexural oscillations and to increase the signal's amplitude, these tension resistors were connected in series, four being bonded in each cross-section. Since only the varying component of strains in the rods is registered, a potentiometric scheme was chosen to feed the tension resistors. Both

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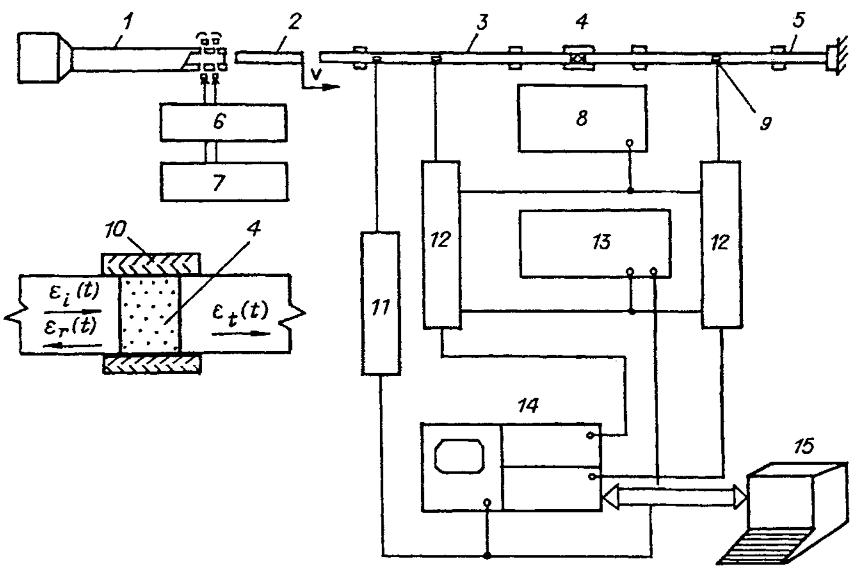

Fig. 1

groups of tension resistors draw direct current from a single stabilizator *8* by means of original feed and calibration circuits *12*.

To determine the scale coefficients relating the point coordinates in the oscillogram to the values of strain and time, electric calibration is used. For this purpose the first channel of a rectangular pulse generator *13* provides pulses passing to miniature relays whose contacts connect calibrated resistors of known values to the strain gages' circuits. The pulses generated by the second channel serve for synchronizing the registering oscillograph. The calibration accuracy is checked by comparing the loading pulse amplitude with the intensity of the excited wave calculated from the determined striker's velocity according to the one-dimensional theory of elastic waves.

The recording of strain pulses in the rods is carried out using a digital memorizing oscillopraph C9-8 *14*. To synchronize the oscillograph's sweep, a piezocrystal located near the end of the rod to be struck is used.An amplifier *11* is employed to amplify the synchronization signal. Information recorded in the oscillograph's memory is sent to an IBM PC/AT personal computer *15* via interfaces for further processing. In a similar manner (with the use of another oscillograph and power device circuit) the circumferential strain pulse is registered, the corresponding signal being transmitted to the computer as well.

Basic Dependences of the Method. Let us consider now the deformation of a soil sample in the steel grip end in the SHB system (Fig. 2). Stresses in soft soils in experiments with SHB usually do not exceed 300 MPa, since there is a significant difference in impedances of measuring rods and samples. In our tests the stresses reach 170 MPa. It should be noted that this value is well under the yield strength of the end grip's material.

The circumferential strain of the grip as measured by strain gages did not exceed 0.05% and the radial strains were of the same order of magnitude since the grip was in the elastic state. At the same time, the longitudinal strains of the sample reach 10% and even higher [7, 8]. Under these conditions the radial strains of the sample can be neglected.

Thus, the strained state of a sample can be considered as one-dimensional, and its stress state as three-dimensional. Then the principal components of the stress and strain tensors can be written as (see Fig. 2)

$$\sigma_1 = \sigma_x, \quad \sigma_2 = \sigma_3 = \sigma_r, \quad \varepsilon_1 = \varepsilon_x, \quad \varepsilon_2 = \varepsilon_3 = 0,$$

where σ_x and ε_x are longitudinal stress and strain, respectively, determined using the SHB method which enables one to plot the dynamic diagram of uniaxial compression of a sample according to Kol'skii's equations;

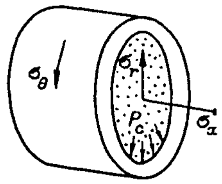

Fig. 2

σ_r is the radial stress. The maximum shear stress τ (the resistance to shear) occurs at the planes inclined at 45° to the x-axis, and its value at the planes is

$$\tau = (\sigma_x - \sigma_r)/2. \tag{1}$$

The pressure P in the sample and volume strain can be expressed in terms of the principal stresses as follows:

$$P = +(\sigma_x + 2\sigma_r)/3. \tag{2}$$

The volume strain is

$$\theta = \varepsilon_x. \tag{3}$$

Thus, if σ_r is known, with the help of Eqs. (2) and (3) one can plot the curve of volume compressibility of the soil and determine the resistance to shear by the formula (1).

The radial component of the stress tensor can be derived from the solution of the problem of elastic deformation of a thick-walled cylinder under internal pressure [10]. The radial stress relative to the end grip is the internal pressure under which the grip end undergoes an elastic strain. The relation between the internal pressure P_c and the circumferential strain ε_θ of the grip is the following:

$$P_c = [E(b^2 - a^2)\varepsilon_\theta]/2a^2. \tag{4}$$

Here E is the Young modulus of the end grip material, and a and b are the inner and outer radii of the grip, respectively.

Thus, Eq. (4) permits calculation of the radial stress component from the circumferential strain and allows one to estimate the material resistance to shear and the pressure in the sample by using Eqs. (1)–(3).

Results of Numerical Analysis of Soil Deformation. It is well known that the conventional scheme of Kol'skii method for compressive testing of constructional metals has been repeatedly criticized from the viewpoint of influence of different factors on the obtained strain diagrams. Particular emphasis has been placed on the validity of key assumption on the uniformity of the stressed-strained state (SSS) of the sample. The effect of both friction and inertial forces was shown to be negligible if proper conditions of testing were used and the SSS of the sample was uniform provided that the duration of the loading pulse exceeded the pulse propagation time along the sample [11, 12].

However, there is a lack of analogous studies on soil media. In order to check the uniformity of SSS along the sample, we performed a computational study of the soil's deformation in the SHB scheme with the passive confinement of radial strain [13]. We did not consider the influence of friction on the lateral side of the sample upon its axial compression since this problem needs special study. The modeling of the soil's tablet strain in the SHB system with the end grip was performed for the axially symmetric case using the program package described in [14]. The equation of state of the soil was taken from the model of a plastically compressible medium [15] with parameters determined in the plane-wave impact experiments [17]. The computational domain (a sample) was covered by a tetragonal net having five meshes in length and four meshes in radius.

Results of calculations are presented in Fig. 3. The stresses in the meshes along the sample are shown for different instants indicated by numbers near the curves (N is the number of a mesh). The obtained data are indicative of good uniformity of stress distribution along the sample: the stresses at the sample's ends

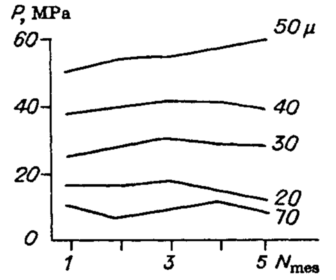

Fig. 3

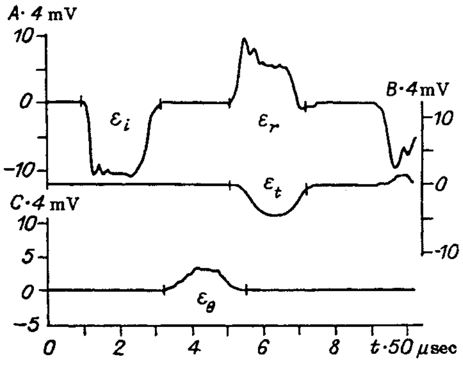

Fig. 4

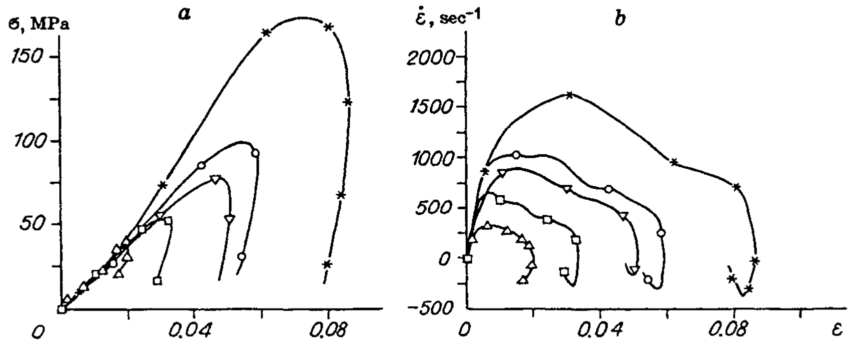

Fig. 5

differ from those in the meshes by no more than 10%.

Thus, the numerical results prove the quasi-static character of the sample's deformation in passively confined tests of the soils.

Automatic Control of Data Processing. The program package for data processing allows, in addition to obtaining the oscillographic information, synchronization of selected pulses, smoothing them with splines, plotting the true deformation diagram of the sample, and statistical analysis of data, including the regression modeling, etc.

After the test the whole oscillograph's memory with the recorded data on the strain pulses in the rods is transmitted into the computer via interfaces. It is convenient to transfer the whole memory because this makes it possible to provide a picture on the display that is identical to that on the oscillograph screen. This picture is to be used for subsequent thorough study of both shape and relative position of the pulses. Also, some additional information needed for data processing and experiment identification can be entered into the computer from the keyboard. The whole file is stored on floppy disks. During processing, both automatic and hand-operated corrections of pulses are possible, which enable one to remove the ghost signals arising sometimes during the analog-digital conversion in the oscillograph, and to approximate the chosen regions of the curves for smoothing high-frequency oscillations. Markers are used to label the beginning and the end of pulses for their subsequent treatments.

Time synchronization of strain pulses in measuring rods is known to be critical for dynamic diagramming of strains. Synchronization errors can distort the initial part of the strain diagram. Locking the pulses to each other is provided by maintaining the condition of equality (with possible minimum error) of forces on the sample's ends during the whole test [11]. After locking, the true deformation diagram of

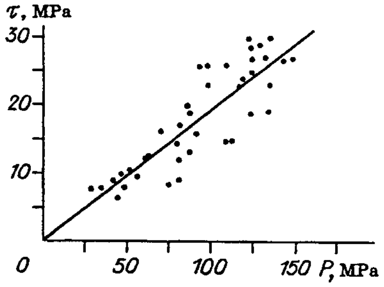

Fig. 6

uniaxial compression of the material under test and the corresponding evolution of the strain rate are plotted according to Kol'skii's equations.

The process of receiving and processing experimental data is almost wholly automated, but expert estimation and correction of separate procedures are still possible. The whole test, data processing, and obtaining the results in tabulated and graphic forms takes several minutes .

Alongside with plotting the dynamic deformation diagrams of a soil material under uniaxial compression, the program package allows one to obtain the volume compression curve and pressure dependence of the resistance to shear from the measured circumferential strain according to Eqs. (1)–(3). All experimental information (dynamic deformation diagrams, volume compression curve, resistance to shear, etc.) is stored in a special data bank.

Results of Tests on a Modeling Clay. The proposed modification of the SHB method was tested on modeling clay (OST 6-15-1525-86), the physicomechanical properties of which are close to those of clay soils. The tests were carried out at a temperature of 20°C (±2°C) and density of material 1.36–1.44 g/cm^3. Tablets 20.1 mm in diameter and 7.5–7.8 mm high were used as samples.

Figure 4 shows an oscillogram of pulses recorded in the computer memory. The two upper rays are strain pulses in the measuring rods; the lower one shows the pulse of circumferential strain of the end grip. As seen, the shape of the pulse that has passed is close to that in the end grip.

A typical strain diagram ($\sigma_s \sim \varepsilon_s$) for modeling clay under uniaxial compression with radial strain confinement and corresponding histories of evolution of the strain rate ($\dot{\varepsilon}_s \sim \varepsilon_s$) are presented in Fig. 5*a*,*b*, where the markers establish the correspondence between the curves. It follows herefrom that strain diagrams of the modeling clay have nonlinear character, the loading and unloading branches differing considerably from each other. The mean value of the loading branch modulus amounts to ~ 3000 MPa. The unloading branch has a more complex character and consists of two regions. The first one lying between the point with maximum stresses and that with maximum strains has a negative slope. The second has a modulus of about 15000–20000 MPa. The latter value seems to be dependent on the strain rate and the pressure achieved in testing.

Figure 6 shows the resistance to shear obtained by using the elaborated technique as a function of pressure. It should be noted that the values of both pressure and shear resistance have been determined according to Eqs. (1)–(3) from the value of maximum shear achieved in the test. The experimental results treated using the root-mean-square method are well approximated by a straight line and can be represented as $\tau = C + \tan\varphi \cdot P$ with $C = 0.34$ MPa and $\varphi = 10.9°$ (C is the coefficient of cohesion and φ is the angle of internal friction). An equation of this type is known as Coulomb–Moore's condition for soft soils [16]. It is of interest to compare the obtained parameters with the constants for clay soils determined in static conditions. The values of shear strength of soft soils are known to vary in a wide range that is dependent on the initial state of the materials. The latter, in its turn, depends on the porosity, humidity, and granulometry of the soil. According to the literature, the coefficient of cohesion and the angle of internal friction for clay soils can vary from 0.01 to 0.2 MPa and from 6 to 28°, respectively [17].

Thus, for strain rates of about 10^3 $\sec^{-1}$ the shear strength parameters determined in this work for the modeling clay agree well with the data for clay soils obtained in static and quasi-static tests. This confirms the assumption made in [17] that the angle of internal friction of soils depends weakly on the strain rate.

Conclusions. A new modification of Kol'skii method for testing soils is proposed which extends considerably its potential. Application of the confining end grip and measurements of its circumferential strain make it possible to determine the volume compressibility curve and pressure dependence of the resistance to shear. The potentials of the technique have been demonstrated by testing modeling clay. The technique is applicable for analysis of dynamic deformation of both soil media and free flowing bulk materials while the results of tests can be successfully used in formulating the equation of state and deriving the involved parameters.

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