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STRAIN CHARACTERISTICS OF SOILS AND THE METHODS OF THEIR DETERMINATION

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Abstract

A method is proposed for determining the strain characteristics of soils under dynamic loads, based on the results of experiments on dynamic compression of soils in laboratory conditions on a device of dynamic loading and for solving a wave problem, the statement of which is identical to the statement of the experiment. With the proposed method, the dynamic and static compression moduli, the unloading modulus, the viscosity coefficient of loess soil in the range of seismic loads were determined in accordance with the elastic-viscoelastic soil model developed by G.M. Lyakhov.

Key words: soil, dynamics, statics, soil compression, elasticity, plasticity, viscosity, laboratory experiment.

The state of the problem and its purpose. The complexity of determining the strain characteristics of soils is due to the wide variety of their types, forms, structures, composition, strain models [1-6]. The strain characteristics of soils are sensitive to the types of load, i.e. the values of strain characteristics significantly depend on the loading rate [1-3]. The determination of mechanical characteristics of soils has been the subject of many publications. In [1-3], the methods for determining the overall mechanical characteristics of soils from laboratory and field experiments of dynamic soil compression were considered.

Determination of mechanical characteristics of soils is directly related to the specific law of soil strain. Experimental determination of mechanical characteristics of soils, based on the specific laws of their strain, under static and dynamic loading are considered in [1-3,7-11]. In [1-3,7], mechanical characteristics of soils are determined on the basis of linear laws of soil strain, and in [8-11, 13-15], on the basis of nonlinear equations of state of soils.

Following [1-3], experimental-theoretical method for determining the strain characteristics of soft soils based on a specific model of soil strain and the results of experiments on a device of dynamic loading DDL-150 in laboratory conditions are considered in the paper. The aim of the work is to develop a unified theoretical and experimental method for determining the strain characteristics of soils, based on theoretical and experimental determination of soil compression diagram under static and dynamic loading.

The main point of the method and its components. In [1,2], based on laboratory experiments on the DDL-100 and DDL-150 devices, the mechanical characteristics of sandy soils, loams, and dense clays of undisturbed and disturbed structures were determined. To determine the mechanical characteristics of loess soils, widespread in earthquake-prone regions, a functioning DDL-150 developed in the Institute of Applied Mechanics of the Russian Academy of Sciences was purchased by the Institute of Mechanics and Seismic Stability of Structures of the Academy of Sciences of the Republic of Uzbekistan. The design of DDL-150 (hereinafter DDL) and the principle of its operation are described in detail in [1,2]. A cylindrical soil sample of undisturbed or disturbed structure with a diameter of 150 mm and a height of 30 mm is placed in the DDL soil receiving chamber. The soil sample is subjected to static or dynamic load through the upper piston, the lower plane of the soil receiving chamber is stationary. The DDL works on the principle of a compression device, where soil samples are tested by static compression.

The proposed method for determining the mechanical characteristics of soils is based on two components: the results of experiments and the numerical solution of theoretical problem of an adequate experimental statement. The first component is obtained by conducting experiments in the laboratory. Here, the reliability of the obtained experimental compression diagrams is important. The reliability of the experimental data is determined by statistical processing of experimental results taken as random variables. The experimental basis (the first component) of the proposed method should guarantee the statistical processing of experimental data, that is, these experimental data should be the results of serial, multiple experiments. The latter circumstance determines the need to realize the first component of the method in the laboratory.

The second component is based on the equation of state of soil; here the main requirement is the adequacy of the selected soil model to the process of soil strain in the experiments. Therefore, the right choice of soil model plays an important role in the methods for determining the mechanical characteristics of soils.

The main point of the proposed method lies in the fact that using a closed system of equations of motion with the selected model of soil strain, the dependence $\sigma_1(\varepsilon_1)$ (the soil compression diagram) is determined theoretically from the problem solution corresponding to the experiment statement; where σ_1-is the longitudinal (axial) compressive stress, ε_1-is the longitudinal strain, taken as positive values.

Then, using the approximate values of the parameters of the equation of soil state (model) determined from the results of experiments in the traditional way, a theoretical diagram $\sigma_1(\varepsilon_1)$ is constructed based on the solution of the wave problem. Comparing the theoretical and experimental diagrams $\sigma_1(\varepsilon_1)$, the values of the model parameters, i.e., the mechanical characteristics of soils, are corrected. After several approximations, sufficient and necessary accuracy of coincidence of experimental and calculated diagrams $\sigma_1(\varepsilon_1)$ is achieved.

Thus, the proposed method for determining mechanical characteristics of soils is based on the results of experiments and on solving the theoretical problem that describes the experiment. The accuracy of this method is proved by the fact that it includes well-known traditional methods for determining mechanical characteristics of soils, and based on them, the specified values of mechanical characteristics of soils. The main difference between the proposed method and the existing ones is that mechanical characteristics of soils are determined from solving the system of equations of soil motion that is adequate to the process of soil strain in the experiment. So far, mechanical characteristics of soils have been determined directly from experimental results by means of simple geometric operations.

Determination of the strain characteristics of soils based on the solution of the equations of motion and strain of soils increases the reliability of the values of these parameters, since in this case the entire process of soil strain is considered both theoretically and experimentally.

The statement of experiment and theoretical problem. The dynamic load acting on a soil sample placed in the DDL is initiated by dropping a load of a certain mass from a certain height along the guide rods.

A description of the measuring sensors and experimental technique and methods of statistical processing of the experimental results are given in detail in [1,2].

Soil compression on the DDL is done according to the following scheme: a dynamic load is applied on a layer of soil lying on a rigid stationary plane. The process of soil strain in the device is one-dimensional, since the load acts uniformly along the entire upper plane of the soil layer.

The theoretical problem is based on a model of elastic-viscoplastic medium proposed in [3] and has the following form:

$$\left.\begin{aligned}
&\frac{d\varepsilon}{dt}+\mu\varepsilon=\frac{d\sigma}{E_D dt}+\mu\frac{\sigma}{E_S} \text{ при } \frac{d\sigma}{dt}>0,\ \frac{d\varepsilon}{dt}>0;\\
&\frac{d\varepsilon}{dt}+\mu\varepsilon=\frac{d\sigma}{E_R dt}+\mu\sigma\left(\frac{1}{E_S}-\frac{1}{E_D}+\frac{1}{E_R}\right)+\mu\sigma_m\left(\frac{1}{E_D}-\frac{1}{E_R}\right) \text{ at } \frac{d\sigma}{dt}<0,\ \frac{d\varepsilon}{dt}>0;\\
&\frac{d\varepsilon}{dt}=\frac{d\sigma}{E_R dt} \text{ при } \frac{d\sigma}{dt}<0,\ \frac{d\varepsilon}{dt}<0;
\end{aligned}\right\} \quad (1)$$

where E_D is the dynamic soil compression modulus, E_S is the static soil compression modulus, is the unloading modulus, E_R is the viscosity parameter, μ-related to the viscosity coefficient by the ratio

$$\mu=\frac{E_D E_S}{\eta(E_D-E_S)} \quad (2)$$

where η is the coefficient of soil viscosity under volume variation, σ_m-is the maximum stress in a soil particle.

In (1), stress σ and strain ε correspond to stresses σ_1 and strains ε_1 in experiments. To simplify the notations in (1), the indices are omitted. Strain ε, as applied to experiments on the DDL, uniquely determines the change in soil layer volume. Therefore, it can be considered as volume strain, and σ as the pressure. Here, σ=- P, where P - is the pressure. It follows that the equation of state of soil (1) is the law of variation of the spherical part of the stress tensor, that is, the law of volume strain of soil. Volume strain ε and mass velocity under soil compression are considered as positive values.

From (1) and (2) it is clear that in this case the main strain or mechanical characteristics of soil are E_D, E_S, E_R, and μ or η. Hence, the main task is to reliably determine the values of these soil characteristics based on the results of experiments given above.

So far, the values of the above or other (based on other equations of state of soils) mechanical characteristics of soils have been determined directly from the results of experiments, using soil compression diagrams [1-4].

To determine the mechanical characteristics of soils from the solution of problems of dynamic soil compression on the DDL, it is necessary to solve the equation of soil motion, which has the form:

$$\rho_0\frac{\partial v}{\partial t}-\frac{\partial\sigma}{\partial x}=0,\quad \frac{\partial v}{\partial x}-\frac{\partial\varepsilon}{\partial t}=0 \quad (3)$$

where ρ_0- is the initial density of soil, v is the velocity of soil particles under compression.

The equation of one-dimensional motion of soil (3) in the DDL is sequentially closed by the equations of state of soil (1). In a closed system of equations (3), (1) the unknowns are σ, ε and v being the wave parameters in soil. The initial conditions of the problem are zero.

The boundary conditions of the problem corresponding to the experimental statement are as follows: at x = 0, the load σ=σ(t) is applied on the upper plane of the soil layer in the DDL by the upper piston motion; at x = x* the lower piston is stationary, i.e. v=0.

Mathematical formulation of the boundary conditions has the following form

$$\begin{aligned}
&\sigma=\sigma(t) \text{ at } x=0, 0<t<t_*;\\
&\sigma=0 \text{ at } x=0, t>t_*;\\
&v=0 \text{ at } x=x_*
\end{aligned} \quad (4)$$

At the front of the incident wave, the condition is met:

$$\langle\sigma\rangle=0, \langle\varepsilon\rangle=0, \langle v\rangle=0 \text{ at } x=ct \quad (5)$$

where c-is the velocity of longitudinal waves propagation in soil, $\langle\sigma\rangle,\langle\varepsilon\rangle,\langle v\rangle$- are the jumps in wave parameters.

In equations of state (1), the front line x=c*t* and the lines of all other fronts are straight lines. This follows from the linearity of the equations that make up the law of soil strain (1).

Thus, the process of dynamic strain of soil sample placed in the DDL is described by the system of equations (1), (3). Having solved this system of equations at boundary conditions (4), (5) and zero initial conditions, the parameters of the wave processes that occur in experiments on the DDL can be determined. The solutions to the problem under consideration were obtained by the method of characteristics, followed by the use of the numerical finite difference method according to an implicit scheme [4].

Experiment results obtained on the device of dynamic loading. The experiments on the DDL were carried out on loess soils samples of disturbed structure. After careful calibration of the measuring sensors, they were installed on the DDL. Further, soil samples were placed in the soil receiving chamber of the device and carefully, uniformly compacted. Before conducting the experiments, the specific gravity ρ_0, moisture content W, and soil granular composition were measured and determined for each experiment. In experiments, these soil characteristics were almost identical and had the following values ρ_0=1500 kg/m^3, W = 14%. The granular composition of soil was fine-grained one with a grain diameter of 0.05 mm. Soil samples were subjected to dynamic loading by dropping a weight of 1.05 kN from a height of 10 cm. After loading (testing) the soil sample was replaced with a new one, and the experiment was repeated. Thirty repetitions of the same experiment were conducted.

As a result of a series of experiments under identical loads, 120 records of axial stresses were obtained. Axial stresses $\sigma_1(t)$ were recorded by four stress sensors. The total number of axial strain $\varepsilon_1(t)$ records produced by three strain sensors under the same loads was 90. The number of lateral stress $\sigma_2(t)$ records, according to the readings of the two sensors under the same loading, was 60. There were also 30 records of the stress change over time, obtained from the power glass indices.

The obtained records of sensor readings were downloaded into the computer. The actual values of stress σ_1,σ_2 and strain were determined by multiplying by the corresponding values of the calibration coefficients using a computer.

Static experiments were also carried out in laboratory conditions on the DDL; the device was prepared for work in the same way as for dynamic experiments. Here, the load acting on soil sample was created using a hydraulic press. The load value was controlled using a manometer in a hydraulic press. The maximum load acting on soil sample was limited to 0.5-0.6 MPa, based on the results of dynamic experiments.

The obtained experimental dependences $\sigma_1(t)$, $\sigma_2(t)$, $\varepsilon_1(t)$, $\sigma_1(\varepsilon_1)$ under dynamic and static loads allow us to process them using the methods of mathematical statistics. Note that the repeatability of experimental data significantly increases the reliability of the obtained experimental results. The statistical processing of the results of experiments contributes to this, further increasing their reliability [1,2].

The value of mathematical expectation for the sampling (arithmetic mean value of experimental data) and for the considered points of time of dynamic experiments (curve 1) and static experiments (curve 2) are shown in Fig. 1

For simplicity, the confidence bands for mathematical expectation in the form of vertical and horizontal lines or quadrangles are not shown in Fig. 1.

The scatter of experimental data is 10-15%. This is quite acceptable for experiments on dynamic loading of soil samples [1,2].

Determination of the mechanical characteristics of loess soil based on the law of an elasto-viscoplastic medium. From the soil compression diagram (Fig. 1),

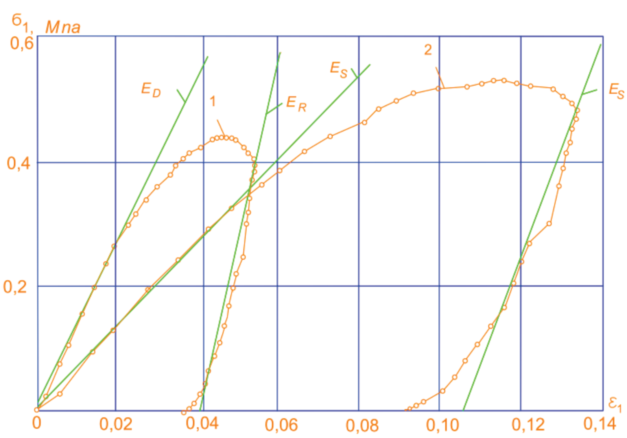

Fig. 1. Experimental dependences of longitudinal stress on strain

on the basis of equations of soil state (1), the model parameters, i.e. mechanical characteristics of soils are determined in the usual way [1-3].

According to the experimental diagrams of loess soil compression shown in Fig. 1, E_D=140 kg/sm²MPa. In reality, this value of the dynamic compression modulus is not true, since the true value of the dynamic compression modulus must correspond to the dynamic compression of soil at the strain rate $d\varepsilon_1/dt \to \infty$. In our case, $d\varepsilon_1/dt$ in the experiments was equal to 1 sec^{-1}. Therefore, the value of the dynamic compression modulus E_D in this case is approximate. More precisely, the value of E_D can be determined using the DUSPA device (a measuring device for ultrasonic signals propagation and attenuation velocity). The DUSPA device allows with fairly satisfactory accuracy to measure the propagation velocity of longitudinal ultrasonic waves in a soil sample. Table 1 shows the results of these measurements conducted in laboratory conditions for loess soils.

The velocities of longitudinal waves in the sample of loess soil were determined at a frequency of ultrasonic waves of 32-35 kHz. The weight density and soil moisture content were determined by standard methods [1-3]. Table 1 shows the value of E_D determined by formula:

$$E_D = \rho_0 c^2/g \qquad (6)$$

where g-is the acceleration of gravity. The value of according to formula (6) is approximately 7.3 times greater (at W = 14.6%, ρ_0=1500 kg/m³) than the value determined by the results of experiments (Fig. 1). This is due to the significant difference in strain rates in experiments on the DDL and the DUSPA. Therefore, the values of determined using the DUSPA are closer to the true value of E_D- to the modulus of dynamic compression of loess soils.

As seen from Table1 with increasing moisture content in soil, the values of c and, consequently, E_D increase. These data do not contradict the well-known research results [3].

However, according to Table 1, in some cases, an increase in soil density leads to a decrease in longitudinal wave velocity in soil. These data contradict

Table 1

Determination of the modulus of dynamic soil compression

Test number	Soil density ρ_0, kg/m³	Wave propagation velocity s, m/sec	Modulus of dynamic compression	Moisture content W , %
1	1500	260,0	103,3	14,6
2	1600	270,0	116,0	14,6
3	1700	287,0	143,0	14,6
4	1800	277,0	141,0	14,6
5	1900	266,0	137,0	14,6
6	2000	238,1	115,7	14,6
7	1500	250,0	187,1	28,0
8	1600	316,4	163,5	28,0
9	1700	352,1	215,0	28,0
10	1800	341,3	214,0	28,0
11	1900	363,6	256,0	28,0

the generally accepted patterns of wave propagation in continuous media. Therefore, this inexplicable factor is related to the scatter in measurement results.

Theoretical dependences $\sigma(t)$, $\varepsilon(t)$, $\sigma(\varepsilon)$ are constructed based on the solution of the problem, adequate to the experiment statement using approximate experimental values of mechanical characteristics of soils determined from the experimental results, i.e. E_D=14 MPa, E_S=6,5 MPa, E_R=28,6 MPa, μ=100 s^{-1}, $\gamma=E_D/E_S$=2,154, $\beta=E_D/E_R$=0,5.When solving theoretical problem of the load acting on the upper surface of soil layer, at *x = 0* (the upper piston of the DDL), the experimental dependence $\sigma(t)$ is assumed. According to experimental stress changes in time σ_{max} = 0.441 MPa, *t = 0.1* sec. Varying the values of and a fairly good agreement could be achieved.

Numerical calculations were performed at E_S=8,3 MPa, E_D=20,75 MPa, μ=200 s^{-1} , β=0,5, γ=2,5, c=116,5 m/s

Calculation results obtained at these initial data and experiment are shown in Fig. 2. Here, the experimental and calculated dependences (curve 1 is an experiment, curve 2 is a theory) have a satisfactory agreement. The discrepancy is about 10%. This is a fairly good agreement between experimental and theoretical results. It was achieved as a result of variation (refinements) of the initial mechanical characteristics of soils directly determined by the results of experimental data. As the results of the above studies show, the initial values of mechanical characteristics of soils were inaccurate. They can be refined as a result of their

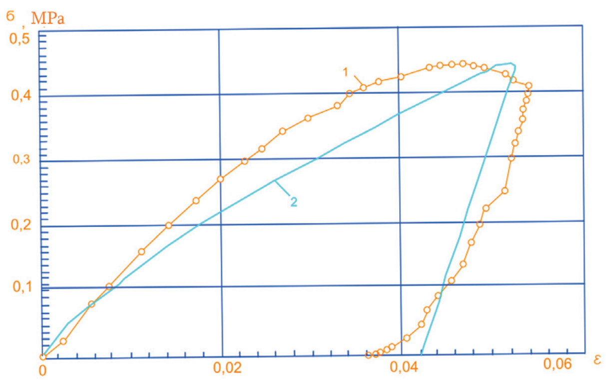

Fig. 2. Comparison of experimental (curve 1) and theoretical (curve 2) diagrams of soil compression

comparison with theoretical calculated data.

Table 2 shows the approximate values of mechanical characteristics of loess soil, determined by the results of experiments, and their refined values obtained by the method of successive approximations proposed in this paper.

Table 2 shows that the approximate and refined mechanical characteristics of loess soils differ from 16 to 900%. These data were obtained in laboratory experiments. The results of field experiments have even greater discrepancy with the theoretical ones, since in the latter case the statement of the experiments is approximate. Therefore, it is impossible to apply statistical methods in processing the results of these experiments.

Research results given in Table 2 show that the technique proposed in this work significantly improves the determination of the values of mechanical characteristics of soils.

Thus, comparing the results of experimental and theoretical studies on dynamic compression of soil samples, it is possible to determine with high accuracy the values of mechanical characteristics of soils.

Conclusions

On the device of dynamic loading (DDL), developed in the Institute of Applied Mechanics of the Russian Academy of Sciences, a series of laboratory experiments were conducted and the diagrams of loess soils compression under dynamic and static loads were determined.

On the basis of experimental diagrams of soil compression , it was found that, at relatively small loads, σ1max = MPa loess soils exhibit viscous and plastic properties under strain; these properties are described by the G.M. Lyakhov viscoplastic model. The parameters of the viscoplastic model are determined from experimental results as mechanical characteristics of loess soils according to the proposed method.

A numerical solution of the wave problem is obtained, the statement of which is identical to the experiment statement on the DDL. By comparing the experimental and theoretical diagrams of soil compression and using the method of successive approximations, more accurate values of strain characteristics of loess soil are obtained based on the G.M. Lyakhov elastic-viscous-plastic soil model.

It is shown that the approximate and refined values of soil strain in this case differ by 16-900%.

Table 2

Comparison of mechanical characteristics of loess soil

Mechanical characteristics of loess soil	Approximate values	Refined values	Difference in %
Modulus of static compression E_S, MPa	6,5	8,3	27,7
Modulus of dynamic compression E_D, MPa	14,0	20,75	48,2
Unloading modulus E_R, MPa	28,6	41,5	31,1
Viscosity parameter μ, sec^{-1}	20	200	900,0
Longitudinal wave velocity s, m/s	100	116,5	16,5
Density ρ, kg/m^3	1500	1500	-
$\gamma=E_D/E_S$	2,154	2,5	16
$\beta=E_D/E_R$	0,5	0,5	-

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