Determination of parameters of nonlinear soil strain

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Abstract. Under loads up to 0.1-0.3 MPa, soils exhibit elastic properties. With increasing load, viscous, plastic, and nonlinear properties of soils appear. Nonlinear properties of soils arise due to the micro-shattering of their structure under compression. As a result, the physical and mechanical characteristics of soils (density, strain modulus, Poisson ratio, etc.) change. In this article, from the results of experiments on loam compression obtained by other authors, changes in the soil strain modulus are determined. The results of experiments on compression of clay samples are presented. From the results of their processing, the values of the strain modulus of soil (loam) are determined. A numerical solution to the nonlinear equation of state (law of strain) of soils is obtained for strain values known from the experiment, and the strain modulus of clay is determined. A comparison of the values of the strain modulus obtained from the experimental results and numerical calculations showed a good agreement.

INTRODUCTION

Numerous publications are devoted to the study of clay deformation. In [1], Grigoryan conducted research on the stress-strain state of soils based on experiments. Rykov and Skobeev [2] measured stresses in soils under short-term loads. The authors of this article conducted a large number of experiments with various types of soils, including clays. However, numerical analysis was not performed due to technical restrictions. In this regard, no study of soil deformation modulus was conducted. In [3], Balandin et al. conducted tests on clay with low moisture content to find the parameters of the Grigoryan model of soil. The research was conducted using the PG-20 setup. These experiments made it possible to determine the compressive strength of clay at different strain rates and to obtain diagrams of experimental relationships between stresses and strains. Data analysis showed that the strain rate does not have a significant effect on the deformation pattern. In [3], numerical results were obtained that were coherent with the experiment when considering the dry friction coefficient. In [4], Eremeyev et al. conducted experiments on clay with low moisture content under uniaxial loading. Eremeyev et al. realized the Split Hopkinson Pressure Bar method. The strength of clay was determined using the Grigoryan model, and the parameters of this model were determined using the Kolsky method. Based on numerical modeling, the results were compared with experiments and their consistency was shown for a dry friction coefficient equal to 0.5. In [5], Konstantinov et al. presented the results of experiments and numerical simulations of dynamic deformation of dry clay at strain rates of ~103 s-1. Clay properties were determined using the Split Hopkinson Pressure Bar method. Based on the results of the experiments, the dependencies of axial stresses on axial strains were plotted and, based on the data obtained, a parametric identification of the clay deformation model was conducted in the form of the Grigoryan constitutive relation. Good agreement was obtained between the numerical and experimental results.

Balandin et al. [6] presented a comprehensive experimental and theoretical approach to studying the problem of high-speed deformation of soft soils. This approach combines the Hopkinson-Kolsky method and the method of shock experiments on plane waves. This approach makes it possible to study high-speed deformation. In [7], Luo et al. conducted tests on the dynamic compression of soil on the Hopkinson bar. The soil was a mix of dry clay and dry stone sand. The effects of different clay/sand ratios and water content on the compressive behavior were investigated. Compressibility was determined as a function of axial stress. The results obtained for this mix were compared with pure clay and sand samples. Bian et al [8] showed the importance of considering the deformation modulus to quantify the subsidence of soft clays. Tang et al. [9] studied the relationship between pressure and deformation of foundations built of gray clay. The influence of these factors on the deformation modulus was revealed. Tang et al. applied their results to two engineering problems and the data obtained matched the actual measured values, indicating its validity for practical application.

In [10], Pedroso et al. conducted an experimental study of a clay earth foundation with a plate loaded on it to evaluate the deformation modulus after the compaction of layers. Under load, an increase in soil moduli was recorded. Schuster et al. [11] studied the behavior of opaline clay fractions during 42 triaxial tests. The moisture content of samples, compaction, and drainage were considered. The samples exhibited brittle behavior characterized by cataclastic flow. The strength and Young's modulus of samples were close to the Reuss isostress limit. Fouad et al. [12] conducted a study of the characteristics of road pavement materials. They studied the optimal clay content at which high elastic characteristics and high resistance to plastic deformation under transport loads were maintained. The deformation modulus was assessed during triaxial testing. Wang et al. [13] showed that in the presence of 20% clay soils, the bearing capacity was reduced by 43%, and the deformation modulus was reduced by 31%. Li et al. quantitatively assessed the influence of the clay fraction and fabric on the static elastic properties of soft clayey rocks [14]. It was shown that with an increase in the clay fraction in soft clays, the deformation moduli decrease since some of the non-clay minerals are replaced by clay-water composites. Kinslev et al. [15] showed that for a reliable prediction of the occurrence of soil deformations over time, a detailed characterization of primary and secondary deformations is necessary. To better characterize time-dependent behavior, a new index, the primary time strain index, was defined

In [16], Lekstutytė et al. showed the influence of several factors on the soil deformation moduli, such as the intensity of the applied load in drained or undrained conditions, characteristics of the stress-strain state, etc. Ma et al. [17] indicated that with prolonged exposure to cyclic traffic loads, the accumulated deformation of red clay soil increases, the strength decreases, and problems, such as non-uniform settlement, arise. The influence of cyclic stress coefficients and compactness on the development of the dynamic modulus of elasticity of saturated red clay was analyzed. The purpose of the study is achieved by conducting a series of dynamic triaxial tests. The model derived by Ma et al. implements the prediction of the dynamic modulus of elasticity of red clay at an arbitrary time of cyclic vibrations. This provides a theoretical basis for correctly assessing the dynamic stability of soil under cyclic loading. Li et al. [18] proposed a tangent modulus method of undisturbed soil that is applicable to clays. Results obtained by Li et al. show that the proposed method for determining the tangential modulus of soil is theoretically feasible, and the accuracy of calculating the tangential modulus is significantly higher than that of the traditional compressive modulus.

In [19], Wang et al. considered spatial variability using the Monte Carlo method for analyzing the influence of spatial variability on time-dependent clay deformation. The authors of that article found that the uncertainty of creep deformation would accumulate over time until it becomes constant. Hov et al. [20] considered the characteristics and properties of clays using the example of Stockholm clays. As a result of the analysis, it was revealed that a common feature of clays is the low value of undrained shear strength and, as a consequence, low values of yield strength and odometer moduli. A great dependence of deformation moduli on moisture content is shown, which emphasizes the importance of selecting soil samples for experiments. In [21], Wang et al. showed that clays exhibit different long-term behavior at different cyclic stress ratios. The authors of [21] developed an improved plasticity model. A new unified interpolation function for the plasticity modulus and a new damage coefficient were given. Wang et al. compared results obtained with those available in the scientific literature and showed the adequacy of their approach, which considered the behavior of soils. Wang et al. [22] examined the evolution of the elastic modulus depending on stress using the example of the Nanjing metro. Laboratory experiments were conducted on soft clay samples taken from the Yangtze River floodplain to determine the parameters of a rainforced soil model with small strain stiffness and inverse analysis using the finite element method. The reference tangent module, the reference secant module, the reference load and unload module, and the reference initial module were determined. Studies by Wang et al. showed the importance of these parameters during the construction and operation of structures in soil.

In [23], Tang et al. showed the importance of studying the changes in the mechanical properties of clay from the Zhanjiang Formation. Soil characteristics were studied during thixotropy using triaxial consolidation and drainage tests. The results of the study [23] served as a guideline for calculating the strength and deformation thixotropy of clays. In [24], Maltseva et al. considered the stress-strain state of foundations of buildings and structures made of weak viscoelastic soils, the characteristics of which were determined experimentally. Maltseva et al. proposed a calculation method that more accurately predicts the deformation of foundations made of water-saturated viscoelastic soils than the solution for elastic and elastoplastic soils, in which pore pressure is not taken into consideration. The method of Maltseva et al. is new because it allows us to consider the residual pore pressure and viscoelasticity of soils simultaneously. In [25], Sabri et al. studies the properties of soils reinforced with fiberglass.

The results were compared with theory. A comparison of the reinforced and reference soil samples showed a 25% increase in deformation modulus after the reinforcement process at a pressure of 25 kPa. In [26], Ma et al. showed a model for calculating the settlement of a soft clay foundation using Hooke's law and the Duncan-Chang model. The authors of [26] presented a method for determining the deformation modulus of soil before and after damage under load. Jia et al. [27] showed that increasing the elastic modulus of the foundation soil would reduce the vertical deformation of the wall but increase the horizontal deformation. Hu et al. [28] investigated unsaturated compacted silty clays using triaxial tests. Experiments showed that the elastic modulus increased monotonically with strain rate at low confining pressures, but at high confining pressures, it first decreased and then increased. In [29], Guo et al. studied the deformation behavior of soft clay under long-term cyclic loading. Based on the experimental results, two equations were derived to predict the long-term elastic modulus.

Tiennot et al. [30] showed that clays influence stone properties at very low moisture content, whereas less swelling clays have an effect only when high moisture content is reached. In [31], Sun studied the deformation of saturated marine clay soils and showed the importance of conducting experiments. The mechanical characteristics of soils and their definition in various soil structures are important, for example, when calculating loads on the sides of a quarry [32]. The mechanical characteristics of soils are determined by various methods, for example, a quasi-static nature of the deformation process is observed by solving the wave problem [33]. In [34], Sultanov et al. established that the deformation moduli of clayey and loess soils under static and dynamic deformation vary depending on the strain rate, the state of the structure and the level of compressive load. Based on an analysis of the stress-strain state of soils in various sections, obtained by numerical calculations, in [35], Sultanov et al. obtained a condition under which the influence of wave processes on the mechanical characteristics of soils was excluded. This condition (formula) establishes a relationship between the wavelength, the velocity of wave propagation in soil, the thickness of the soil sample in the setup, and the duration of dynamic load. In [36], based on an analysis of the results of a numerical solution to the wave problem, Loginov et al. determined conditions for quasi-static deformation of soil under dynamic loading in the experiment. By comparing the experimental results with numerical calculations and the method of successive approximation, refined values of the mechanical characteristics of soils were determined based on the elastoviscoplastic model of soil deformation [36].

In [37], Khamidov et al. established that the maximum values of stress, strain, and particle velocity in viscous media vary according to a nonlinear law. In the initial region of the medium and near it, the stress first reaches a maximum, and then the strains and particle velocities reach maximum values [37]. In the construction and operation of buildings and the design of road pavements [38], the consideration of the possibility of seismic impact and the account for the properties of soils are also important.

METHODS

Due to the metric scale effect, laboratory tests may not reflect the deformation of soil masses in field tests. However, they can help save huge amounts of money. By studying changes in soil deformation moduli, we obtain results that reflect the situation as a whole well.

Soil properties can be described by mathematical equations between the stress and strain tensors and time. These equations are obtained from experiments. The experiment conducted considered the processes that occurred in soil under deformation. Experimental laws take into account the fact that soils are complex in composition. The experimental results show the non-homogeneity of samples. The point is that all properties inherent in soils are considered in the experimental law of compression, i.e. dependence $\sigma(\varepsilon)$ reflects this.

In studying the process of nonlinear deformation of soils based on a generalized model of a standard linear body, it is necessary to determine the deformation moduli and coefficient of internal friction (bulk viscosity) of soil.

There are two ways. First, we should formulate a mathematical statement to find a module through its components. Here, we face many difficulties. When solving them, some simplifications are made.

The second way is to find modules through experimental diagrams. Here, all the properties for various components are reflected in the curve, shown in the graph. This way is more accurate than the first. In this regard, we choose the second way.

From graph $\sigma(\varepsilon)$ we can express E_f (actual strain modulus) or E (secant strain modulus). To do this, we use dependence $\sigma(\varepsilon)$.

To find E_f, $\sigma(\varepsilon)$ is divided into small sections with the same step $\Delta\varepsilon$. Then $\Delta\sigma$ are determined, which correspond to $\Delta\varepsilon$ and $E_f=\Delta\sigma/\Delta\varepsilon$. The value of E is found as $E=\sigma/\varepsilon$, where σ and ε are the stress and strain values.

To describe the process of soil compression, we propose a mathematical model in the form of a physically nonlinear law of deformation of the standard linear body:

$$\frac{d\sigma}{E_D(\varepsilon)\mathrm{dt}} + \mu(\varepsilon)\frac{\sigma}{E_S(\varepsilon)} = \frac{d\varepsilon}{\mathrm{dt}} + \mu(\varepsilon)\varepsilon \tag{1}$$

Let us approximate it in difference form

$$\frac{\sigma_{i+1}-\sigma_i}{E_D(\varepsilon_i)\Delta t} + \mu\frac{0.5(\sigma_{i+1}+\sigma_i)}{E_S(\varepsilon_i)} = \frac{\varepsilon_{i+1}-\varepsilon_i}{\Delta t} + 0.5\mu(\varepsilon_{i+1}+\varepsilon_i) \tag{2}$$

$E_S(\varepsilon_i)$, ε_i are set from experimental data and viscosity modulus μ is selected and accepted. $E_D(\varepsilon_i) = 2E_S(\varepsilon_i)$.

The task is to correctly find the values of these soil characteristics using experiments. The following are the results of the numerical solution.

RESULTS

Consider the second load curve shown in Fig. 47 in [1].

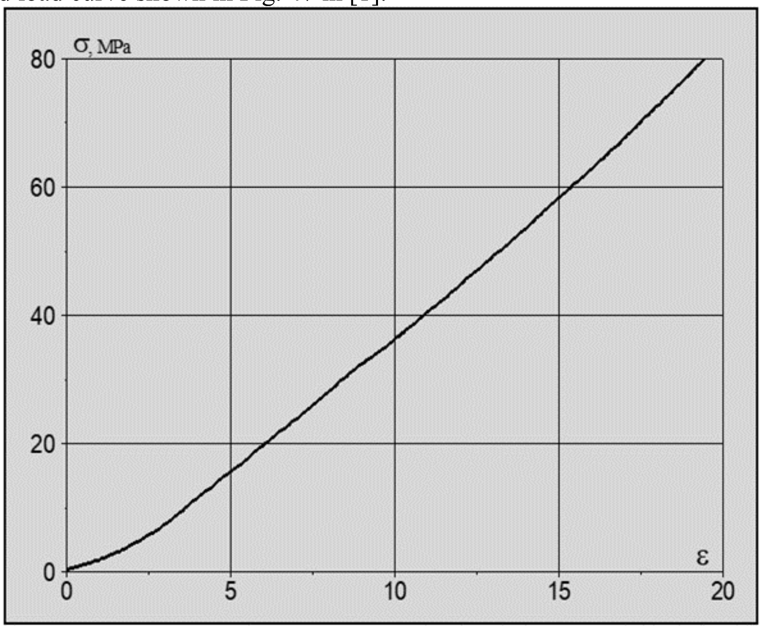

FIGURE 1. Second curve in Fig. 47 from [1], the stress-strain dependence

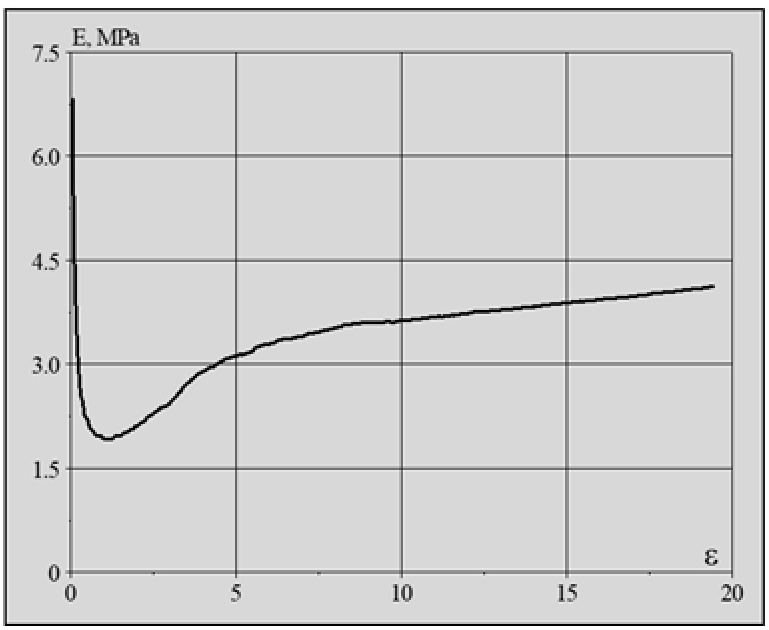

FIGURE 2. Change in the deformation modulus of clay under loading

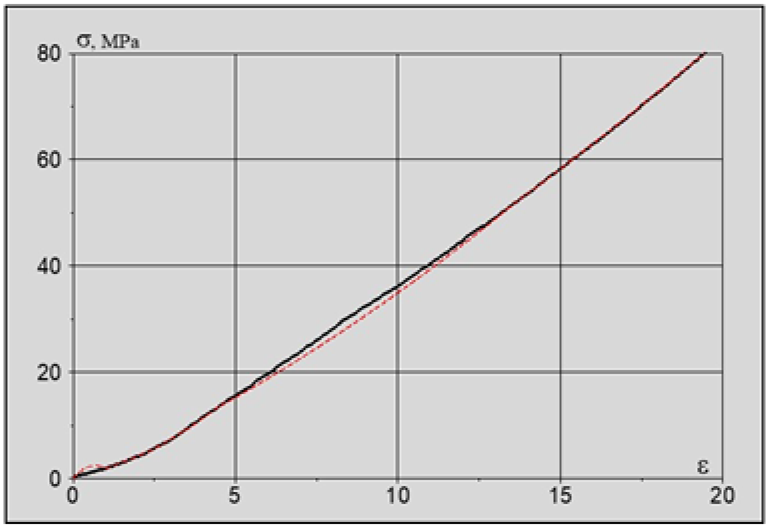

FIGURE 3. Stress-strain dependence. The program uses 7 points for calculation

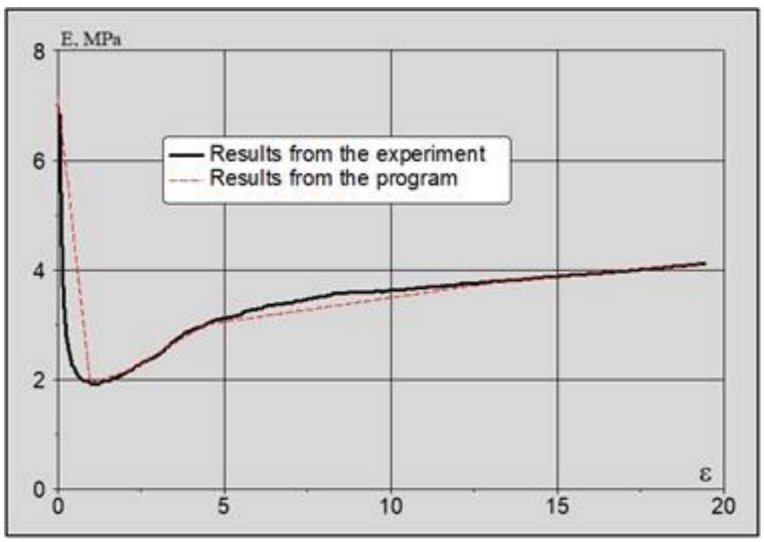

FIGURE 4. Change in the deformation modulus of clay under loading. The program uses 7 points for calculation

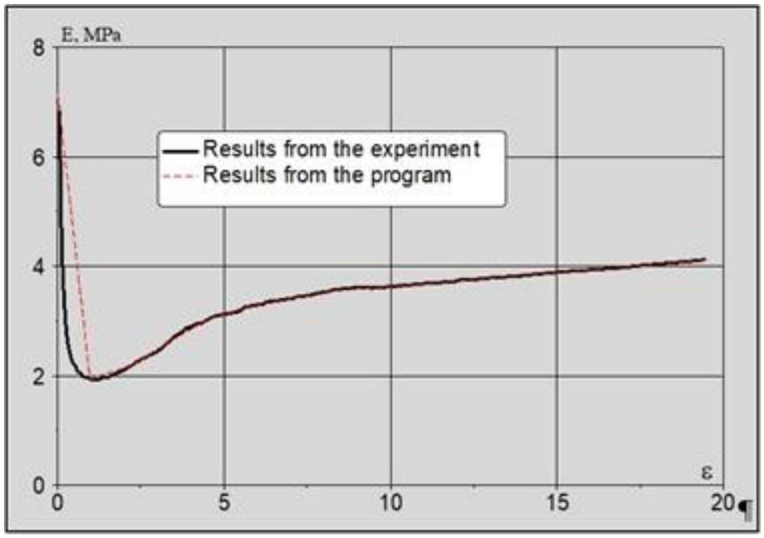

FIGURE 5. Change in the deformation modulus of clay under loading. The program uses 17 points for calculation

ANALYSIS

As seen from the above graphs, with an increase in the number of points from 7 to 17, almost complete agreement between the experimental curves and the curves obtained from the program is observed. From experiments, it can be noted that soil compression using dynamic loading setup UDN-150 or a similar device is a difficult process. Note that by stress σ we mean pressure P. This must be remembered, as σ=-P. In the graphs, the minus in front of σ is omitted for simplicity. Using graphs of soil loading (experimental) and the graphs we obtained, it is possible to determine the values of the mechanical characteristics of soils.

DISCUSSION AND CONCLUSIONS

The results analysis indicates that the curves effectively describe the process of soil compression. Graphs for clays are presented based on a mathematical model in the form of a physically nonlinear deformation law of a standard nonlinear body. The numerical analysis method of the mathematical model (2) demonstrates its reliability compared to the experimentally obtained results.

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