Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0082

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

FEATURES OF APPLICATION OF NON-LINEAR SOIL MODEL IN GEOTECHNICAL DESIGN

CARACTÉRISTIQUES D'APPLICATION DU MODÈLE DE SOL NON LINÉAIRE À LA CONCEPTION GÉOTECHNIQUE

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ABSTRACT: Efficiency and reliability of geotechnical design are determined by application of modern numerical procedures and mathematical models of soil reflecting its main mechanical properties, as well as by using appropriate instruments and test methods to determine parameters of these models. The necessity and timeliness of such a development of geotechnics in the now widespread use of high-performance computers is declared not only in Russian design standards, but also in the Law of Russian Federation on the safety of buildings and structures. Main feature of various soils is their complex origin with unique natural physical and natural stress states formed in them for a long time. But and in the cases of artificially formed soil massifs of embankments and islands, as well as chemically fixed soils, their physical and stress states are also unique. In these circumstances soils of each construction site should be considered as endemic type, and therefore a certain amount of in-situ mechanical researches with the least possible disturbance of natural soil state should be conducted before design. In this case it is necessary to consider second fundamental feature of soils – their evident complex nonlinear character of deformation, which distinguishes them from so-called constructive artificially formed materials (metal, concrete, brick, rubber, plastic).Thus soil parameters should be determined for nonlinear model from in-situ test data with use devices of direct force action on the soil, with simple scheme of loading soil due some complexities of inverse nonlinear procedure and with the least possible disruption of soil natural stress state to reflect this state indirectly at the test results. Static pressuremeter and plate loading tests in the bore hole correspond to this requirement at the greatest degree. But very limited set of measured stress and strain components at in-situ tests together with complex nonlinear deformation functions reduces the problem of determining soil parameters to the solution of, so-called, inverse, ill-conditioned problem. To obtain an unambiguous, physically correct solution of this problem special algorithmhm is required. One of a central position of this algorithm is the use of similarity of actual and numerically simulated soil deformation graphs as well as using some specific features of the problem. Applying soil models, that consider peculiarities of nonlinear deformation, using parameters from in-situ test results, allowed authors to solve several practical problems that cannot be solved within the framework of linear theories.

RÉSUMÉ: L'efficacité et fiabilité de la conception géotechnique sont déterminées par l'application de procédures numériques modernes et de modèles mathématiques du sol reflétant ses principales propriétés

mécaniques, ainsi que par l'utilisation d'instruments et de méthodes d'essai appropriés pour la détermination des paramètres de ces modèles. Un tel développement de la géotechnique dans l'utilisation désormais répandue d'ordinateurs hautes performances est nécessaire et opportun dans les normes de conception russes et dans la loi de la Fédération de Russie sur la sécurité des bâtiments et des structures. La principale caractéristique de divers sols est leur origine complexe avec des états de stress naturels et physiques uniques formés en eux pendant une longue période. Cependant, dans le cas de massifs de sols formés artificiellement de remblais et d'îles, ainsi que de sols chimiquement fixés, leurs états physique et de stress sont également uniques. Dans ces circonstances, les sols de chaque site de construction doivent être considérés comme du type endémique et, par conséquent, un certain nombre de recherches mécaniques in situ avec le moins de perturbations possibles de l'état naturel du sol doivent être menées avant la conception. Dans ce cas, il est nécessaire de prendre en compte la deuxième caractéristique fondamentale des sols - leur caractère évident nonlinéaire complexe de déformation, qui les distingue des matériaux artificiels (métal, béton, brique, caoutchouc, plastique).Il convient donc de déterminer les paramètres de sol pour le modèle non linéaire à partir de données d'essais in situ avec des dispositifs utilisant l'action directe de la force sur le sol, avec un schéma simple de chargement du sol en raison de la complexité de la procédure non linéaire inverse et en perturbant le moins possible l'état de stress naturel du sol. pour refléter cet état indirectement aux résultats du test. Les essais de pressiomètre statique et plaque dans le trou de forage répondent à cette exigence au plus haut degré. Cependant, un ensemble très limité de composantes de contrainte et de déformation mesurées lors d'essais in situ ainsi que de fonctions de déformation non linéaires complexes réduit le problème de la détermination des paramètres du sol à la solution du problème dit inversé mal conditionné. Pour obtenir une solution sans équivoque et physiquement correcte à ce problème, un algorithme spécial est requis. L'une des positions centrales de cet algorithme est l'utilisation de la similarité des graphes de déformation du sol réels et simulés numériquement, ainsi que l'utilisation de certaines caractéristiques spécifiques du problème. L'application de modèles de sol prenant en compte les particularités de la déformation non linéaire, à l'aide de paramètres issus de résultats de tests in situ, a permis aux auteurs de résoudre plusieurs problèmes pratiques qui ne peuvent être résolus dans le cadre de théories linéaires.

Keywords: soil, nonlinearity, parameters, in-situ, tests

Adequacy and effectiveness of geotechnical design depend crucially on the use of mathematical models that reflect real soil deformation features. Widespread use in design of high-performance computers made it possible to use soil models that reflect, firstly, the connection of soil deformation with progressive destruction of soil (development of local destruction in it), and secondly, change of the stiffness of the soil due to the rearrangement of its particles and hence change of stiffness characteristics (bulk modulus K, shear modulus G, Hooke-Young modulus for one-dimensional deformation E and Poisson's ratio ν) due to change of stress state. This mechanical phenomenon is defined as physical non-linearity. For soil it can be illustrated with diagram in Figure 1, as well as a fragment of the investigation of clay soil shown in Figure 2. Diagram of linear deformation, typical for structural materials (metals, concrete, rubber, and others) is shown in Figure 3. This diagram reflects Hooke's theory of deformation, which postulates, in contrast to the physically nonlinear theory, independence of above-mentioned stiffness characteristics from the stress state and therefore considers them as constants; K, G, E, ν. But for such complex medium like soil, as follows from the diagram in Figure 1, this is not correct. Moreover, motivation at the beginning of 20-th century for application in calculating soil deformations of Hooke's linear theory (Figure 3), based on linear shape of graphs of settlements of soil in some cases was not entirely correct: such

graphs may be consequence and of nonlinear relationships between strains and stresses, as in Figure 1. These relationships can be described, for example, in the framework of relatively simple phenomenological (as Hooke's theory), but nonlinear deformation theory. The simplicity of the theory (model) is important for its practical application. Below are formulas for bulk modulus K and shear modulus G of such a theory proposed in 1939 by A. Botkin (Botkin,1939):

$$K = \sigma/\varepsilon = A_0\sigma^{1-\alpha}$$

$$G = \frac{\sigma_i}{\varepsilon_i} = \sigma_U/(B + \varepsilon_i) \qquad (1)$$

Here $\sigma_U = A\sigma + C$ – Mises failure criterion;
σ and ε – first invariants of stress σ_{ij} and strain ε_{ij} tensors, respectively (volume deformation); σ_i and ε_i – second invariants of deviatoric parts of stress and strain tensors, respectively (shear deformation);

A_0, B_0, A, B, C are soil parameters.

Other two stiffness characteristics in accordance with general concepts of continuum mechanics can be expressed, if it is necessary, through characteristics K and G:

$$E = {3KG}/{(K+G)}$$

$$\nu = {(K-2G)}/{2(K+G)} \qquad (2)$$

Physically nonlinear theory (model) of deformation is a natural generalization of physically linear theory Hooke's (model) in the space of stresses and strains, which reveals objectively existing dependence of soil stiffness characteristics on stress-strain state. In particular, Botkin's model, in contrast to Hooke's model, associates deformation of the soil with its strength; for example, the formula for shear modulus G has such a form that value of G tends to zero when values of shear stresses approach their ultimate value. As a result, the theory reflecting real nonlinear features of soil deformation, resolves contradictions and problems occurring when Hooke's linear model is used for soils: incorrect distribution of stresses in the soil; significant calculated overestimate of strain distribution for soils like for rubber; not provided for by linear Hooke's theory; dependence of the value of stiffness parameter E on the method of it determination (plate loading test, pressuremeter test, test in consolidometer). To use in design nonlinear soil models, it is necessary to determine their parameters, for example, for Botkin's model these are parameters A_0, $B0$, α, A, B, C from formula (1).

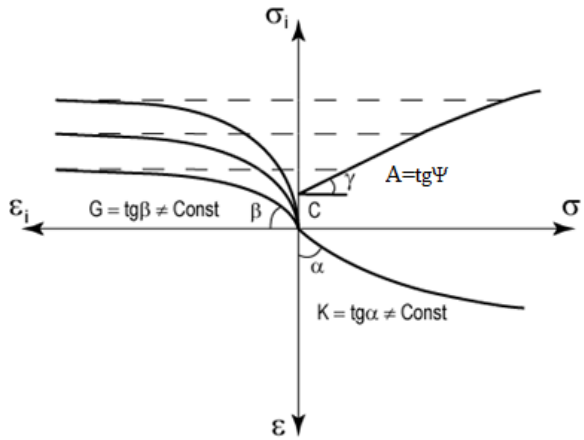

Figure 1. Diagram of nonlinear soil deformation (K ≠ const, G ≠ const); same notations as in formulas (1) are used

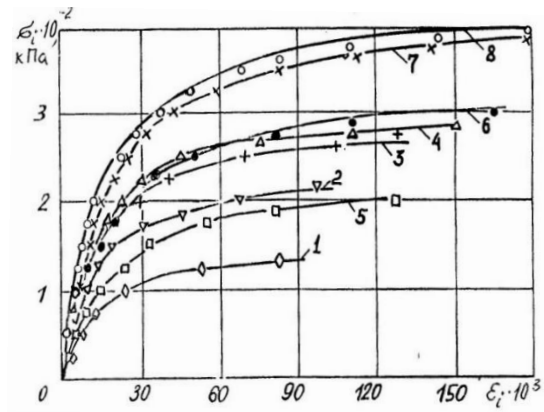

Figure 2. Shear strain curves (deviatoric part) of real soil test results, obtained in triaxial device: same

notations are used as in figure 1; higher curves correspond to a more rigid state of the soil due to its greater compression; pairwise adjacent curves (1-2, 3-4,5-6, 7-8) differ in the value of the parameter of the type of the loading μσ (Lode parameter); the lower graphs correspond to the value значению μσ= +1 (as in pressuremeter test); the upper graphs correspond to the value μσ= -1 (as in plate loading test)

Due to the difference in soil deformation at different values of Lode parameter μσ, the soil shows different stiffness in different types of tests (for μσ= +1 stiffness is less than for μσ= -1). Therefore, in the pressuremeter test Young's modulus E is smaller than in the plate loading test. At the same time, in the framework of the physically nonlinear theory deformation in both tests are described using same parameters A_0, *B0*, α, *A*, *B*, *C*. This means that these parameters can be determined both from results of pressuremeter tests and from results of plate loading tests. In principle, parameters of nonlinear model can be determined from results of laboratory test in riaxial apparatus (Figure 5); fragment of results is depicted in Figure 2.

However, as studies have shown, the deviation in this case of calculated and actual values of the deformations and forces in soil due to a disturbance of natural physical and stress state of the soil when sampling is about 150% (Alekhin,1983). This is more less than when using Hooke's model for soils, where for correcting a very large difference in the values of Young's modulus *E* (modulus of deformation for soils) obtained from laboratory and in-situ tests also large correction factors are used. But the more value of correction factors, the more they contain statistical error. Moreover, the correction factors are applied to scalar values, but according to formulas (1) and (2), the module *E* is a function of the stress state. Using of the correction factors to the mechanical parameters of soils is incorrectly also due to the complex origin of various soils with unique natural physical and natural stress states formed in them for a long time. In these circumstances soils of each construction site should be considered as endemic types, which requires some parallel in-situ and laboratory tests at each site for each soil to determine correction factors. It is not possible economically and practically. Finally, as mentioned above, the use of Hooke's model for soils does not ensure authenticity of calculations, and hence the reliability of designing. For reliable geotechnical design it is necessary to use models that considering physical nonlinearity of soils.

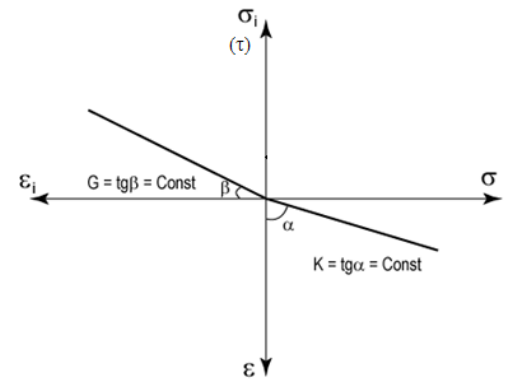

Figure3. linear deformation of structural materials (metal, concrete, rubber, etc.): K = const, G = const; same notations as in formulas (1) are used

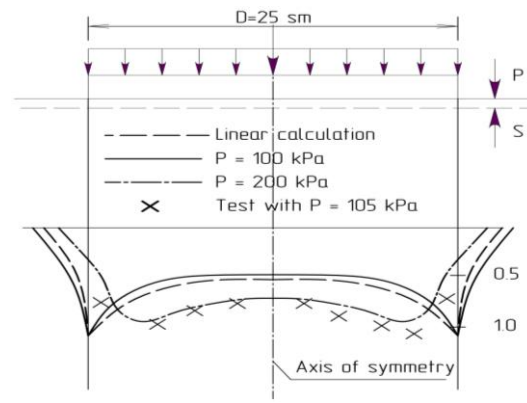

Figure 4. Graphs of contact stresses beneath rigid foundation (linear and nonlinear calculations)

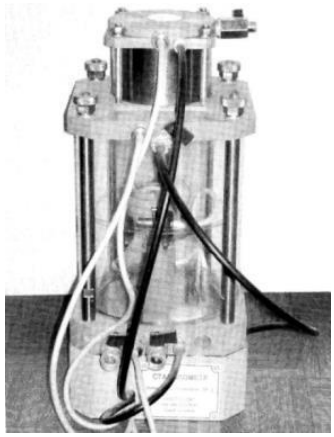

Figure 5. Triaxial apparatus for study of nonlinear soil deformation

Figure 6. Automatic pressuremeter device for in-situ tests in bore holes

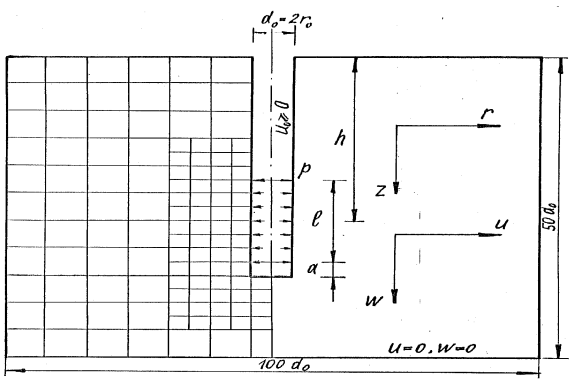

Figure 7. Scheme of a two-dimensional axisymmetric problem

To obtain parameters A_0, B_0, α, A, B, C of a physically nonlinear soil model with an acceptable accuracy for the soil (approximately 25 ... 30%) it is necessary to determine them from in-situ tests. The most appropriate method for this is a technologically effective pressuremeter test (Figure 6), which has a simple scheme (Figure. 7). But even for a simple calculation scheme, the procedure for determining parameters due to complex nonlinear relationships is reduced to an ill-conditioned problem (Tikhonov, 1979). To solve this problem, a special numerical procedure was used, based on proven methods for solving such problems, which involve the use of their specific features (Alekhin, 2016). The algorithm for determining parameters A_0, B_0, α, A, B, C from results of in-situ tests uses the following specific features of the problem: 1) the similarity of the actual and numerically modeled graphs of soil deformation; 2) practically significant discrete set of values of the angle of internal friction; 3) similarity of compression test plots and volume strain plots. Below is an example of using a physically nonlinear model to determine the distribution of stiffness in an array of Paleozoic soft plastic highly porous clay to determine the length of piles that provides design requirements for the deformations of a building. The values of K, G, E and ν were calculated by formulas (1) and (2) based on the coefficients obtained from the in-situ pressuremeter tests: A = 0,424; B = 0,03; C = 50 kPa; A_0 = 60; α =0,5.

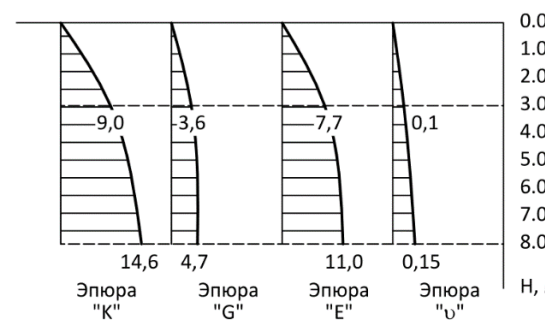

Figure 8. Increasing the rigidity characteristics of a homogeneous massif of Paleogene clay at the base of a 5-story building in the city of Serov (Northern Urals)

CONCLUSSIONS

1. Application of nonlinear soil models has great capabilities in geotechnical design.
2. Nonlinear soil models, which are logical generalization of linear soil models allow to take into account in geotechnical calculations two main features of soils: the complexity of their deformation and nature genesis.

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