A. S. Morgun, Dc. Sc. (Eng.), Prof.; A. O. Shvets; O. S. Shevchenko

ASPECTS OF THE BOUNDARY ELEMENT METHOD APPLICATION FOR PREDICTING RELIABILITY OF HIGH-RISE STRUCTURES

The paper deals with theoretical substantiation of the foundation engineering nonlinear problem, which requires application of reliability and plasticity theories, computer processing. Plasticity consideration makes it possible to increase bearing capacity of the foundation construction.

Keywords: *boundary element method, state equations, elasticity, plasticity, stress-strain state.*

Introduction

One of the important current foundation engineering problems is development and implementation of more advanced and cost-effective methods of designing building structures (foundations are the most common among them), which are directed towards identification and realization of their reserves. High-rise buildings are rather special structures, which require individual binding to definite construction site soils while binding conditions are practically always unique.

Despite their apparent simplicity, processes occurring in soils are rather complex as objects of research and control. At the given moment some aspects of the mechanism of subsoil deformation under load still remain unstudied.

Scientific research in the field of soil mechanics has always been directed towards improvement of the methods for designing bases and foundations. To ensure reliability in designing bases and foundations of buildings, it is necessary to take into account numerous physical and mechanical characteristics of soils for their behavior simulation.

Problem statement, defining relationships

The paper deals with the prediction of subsidence of the foundation structure – a plate for 12-storey building, shown in Fig. 1. For analytical consideration of the problem of forming a mathematical equivalent for soil material behavior under load the paper makes use of the theory of solid and porous bodies. Under the action of external forces both elastic ε^{elast} and plastic residual ε^{plast} deformations occur in soil ($\approx 95\%$).

Fig. 1. Facade of a 12-storey building

An essential difference of soils from homogeneous elastic bodies is the fact that under the action of external loads residual deformations are always accompanied by elastic deformations, even if loads are inconsiderable. The sum of residual and elastic deformations gives total deformation of soil base.

Simultaneous presence of soil zones, which work both in elastic and plastic zones, require application of the elasticity and plasticity theories for soil behavior simulation [1 – 4].

It is known that solution of the mixed problem of soils elasticity and plasticity theories gives close approximation of the subsidence calculation results to reality. Current trend of transition to computer-aided calculation methods has dramatically changed the priorities towards the necessity to develop more reliable mathematical models of non-linearly deformed soil bodie, composed from the layers with different properties.

Experimental investigations have shown that even in rather weak soils of fluidic consistence no soil displacement is observed beyond the boundaries of deformation zone [5].This points to the fact that deformation zone is an active working zone of the foundation base, where a dynamic process of soil compaction goes on for a certain period, which reflects the essence of joint work of the foundation and the base until it comes to the state of equilibrium.

In natural conditions multilayered soil structures have different textures. In the proposed model weighted average soil characteristics are taken as input parameters.

The model takes into account 10 characteristics of the influence of engineering-geologic soil properties on its deformation process: E=13,309 MPa; ν=0,35, e=0,67, $\rho^{min} = 1{,}47\ t/m^3$, $\rho^{max} = 2{,}14\ t/m^3$, $\rho = 1{,}95\ t/m^3$, c=18,1 kPa, $\varphi = 0{,}193\ rad.$, $p_0 = -1800\ kPa$, $\rho_s = 2{,}717\ t/m^3$.

Under the influence of load soil base under the structure is deformed within the active zone (zone of the active influence of additional load). Discretization of the active zone of the foundation base under 12-storied building is shown in Fig. 2. The mathematical model is known to give ground for numerical analysis of the object under study, which enables obtaining data of not only descriptive, but also of predictive character.

Complex stress-strain condition of the soil is considered (compression with a shift). Physical state equations are described by elastic-plastic Prandtl diagram with strengthening with boundary proportionality according to Mises – Schleicher – Botkin [2, 3], where maximal attained stresses of the base are registered.

The proposed nonlinear mathematical dilatancy model is based on the following assumptions:

1. Equilibrium equation of the plate, which is immersed into soil medium, satisfies Laplace differential equation.
2. As geometric equations, small-strain tensor of Cauchy is used.
3. Physical state of the soil work in linear region is described by Hook's law.
4. At the plastic deformation stage vectors of stress tensor and deformation rate tensor are not coaxial. Precise differential equations of the foundation plate behavior in the soil are non-linear.
5. In order to simplify the problem, in the proposed mathematical model non-linear equations at each loading step are linearized using step procedures of A. A. Iliushin.

Transition from the boundary problem of equations of the foundation plate equilibrium in the soil to integral equations is performed by means of the numerical boundary element method.

Main calculation equation of the soil work model, which is the analog of the system of 15 differential equations (static, geometric and physical), is the integral equation proposed by K. Brebbia [4]:

$$c_{ij} \cdot u_j + \int_{\Gamma} p_{ij}^{*} u_j \, d\Gamma = \int_{\Gamma} u_{ij}^{*} p_j \, d\Gamma + \int_{\Omega} \dot{\sigma}^{*} \dot{\varepsilon}_{jk}^{p} \, d\Omega, \tag{1}$$

where u – given displacement vector at the boundary of foundation structure; p – the required vector of stresses at the boundary; u^*, p^*, σ^* – kernels of the boundary equation (1) – R. Mindlin solution for displacements, stresses and derivatives of stresses, which correspond to the unit disturbing forces (*P* = 1) in half-space [4]; c_{ij} – constant, which is determined from the body motion condition (body as a whole) and appears in transition from boundary problem to integral equation (1) for obtaining the unique solution; B, Ω – boundary surface of the foundation structure and boundary of the soil triangular cells respectively.

Notion of "system" is widely used almost in all fields of science and engineering. System response to external influences was considered in the work as a dynamic change of the system state, in the process of which it tries to minimize a certain potential function. Solution of these problems of the soil base behavior under load has both scientific and practical importance.

In the paper equation (1) is solved mainly by the boundary element method. In accordance with the regulations, which are given in the normative documents, boundary resistance of the foundation structure is determined by the soil resistance to destruction under the lower edge and shear resistance along the lateral surface. In the paper this boundary surface of the plate was discretized by boundary elements while active zone of the soil was discretized by triangular cells. To investigate stress-strain state of the plate, a spatial elastic-plastic dilatancy model of porous media is used [2].

The dilatancy model application makes it possible

a) to schematize the process, breaking it into successive stages of forming and compaction;

b) to make use of the plasticity theory for incompressible bodies, which has been adequalely developed for today;

c) to perform the analysis of non-linear problem solved by the method of elastic solutions of A. A. Illiushin;

d) to take into account the loading trajectory, misalignment of the stress tensor vectors and deformation rate tensor.

e) to make a transition to the computer-aided calculation of the foundation structure behavior by discretizing the calculation model and performing computations by the boundary element method (BEM).

Instead of the orthogonality requirement to the increment of plastic deformation vector $d\varepsilon_{ij}^p$ to the plasticity surface f, the non-associated law of plastic flow, complemented by dilatancy relation of V. M. Nikolayevskiy and I. P. Boyko is used in the paper:

$$d\varepsilon_{ij}^p = \Lambda(\chi)\cdot d\gamma^p, \quad (2)$$

where $d\gamma^p$ – scalar equivalent of shear plastic deformation increment on the octahedral plane; $d\varepsilon_{ij}^p$ – increment of non-elastic volume changes, which accompany the shift; Λ – dilatancy rate; χ – soil medium strengthening parameter (soil density ρ is adopted).

As a strengthening parameter, soil density, which is a peculiar memory of the soil, is adopted. Increasing soil density means changing yield point of the soil material.

In accordance with the elaborated model, total deformations were determined as

$$d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p , \quad (3)$$

where $d\varepsilon_{ij}^e$ – increment of elastic deformations; $d\varepsilon_{ij}^p$ – increment of plastic deformations.

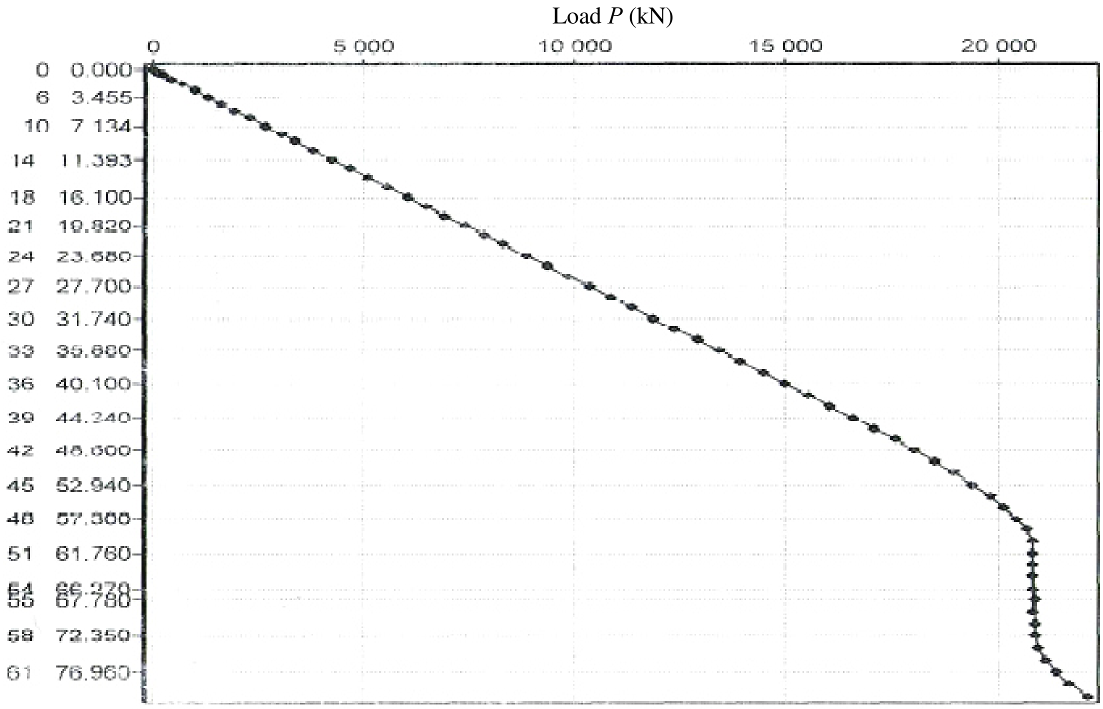
In the model, which was used for numerical investigation of stress-strain state of the foundation plate, additional kinematic dilatancy conditions were introduced (2).

Determination of the plate bearing capacity and foundation subsidence due to the influence of vertical loads was performed by solving the problem in elastic-plastic statement by the following sequence of steps:

- discretization of the boundary surface of the plate and active buffer zone;

- composing calculation influence matrix of BEM on the basis of R. Mindlin solutions;
- obtaining design equation system;
- solution of the obtained system of linear algebraic equations, fixation of the stress-strain state at each loading step;
- building plastic regions;
- taking and substantiation of the design decision about the possibility of application of additional loads.

Fig. 2 presents the graph of "loading – subsidence" dependence, predicted by BEM, for the entire loading interval of the raft foundation structure with the height of 0,7 m for 12-storey building.



Tne loading step number, displacement *U* (mm)

Fig. 2. Graph of the "loading *P* – subsidence s" dependence

Graph of Fig. 2 makes it possible to determine subsidence s for different loads *P* and to select the most feasible and cost-effective conditions of the plate foundation work, which will ensure stability and reliability of the 12-storey building, that stands on this raft foundation. The proposed model combines calculation of the "base – foundation – plate" system for both boundary states. Analysis of the system stress-strain state is conducted in the entire loading range. The foundation plate is capable of compensating for uneven subsidence due to re-distribution of the loads.

Conclusions

1. In high-rise building construction there is a possibility of predicting the foundation base stress-strain state with the application of modern methods of applied geomechanics and numerical methods – FEM and BEM.
2. In order to determine bearing capacity of the foundation plate and the base of the building, the theory of dispersed mediums and associated tensor calculus issues are used.
3. The research results have significant practical orientation with the possibility to achieve economic effect due to taking into account plastic work of the soil base.

REFERENCES

1. Определяющие законы механики грунтов / [под ред. В. Н. Николаевского, ред. серии А. Ю. Ишлинский, Г. Г. Черный]. – М. : Мир, 1975. – 231 с.

2. Бойко І. П. Напружено-деформований стан ґрунтового масиву при побудові нових фундаментів поблизу існуючих будинків / І. П. Бойко, О. В. Сахаров // Основи і фундаменти: Міжвідомчий науково-технічний збірник. – 2004. – Вип. 28. – С. 3 – 10.

3. Моргун А. С. Метод граничних елементів в розрахунках несучої спроможності кільцевих та круглих в плані фундаментних конструкцій / А. С. Моргун, О. В. Франчук // Вісник ВПІ. – 2012. – № 5. – С. 11 – 14.

4. Бреббия К. Методы граничных елементов / К. Бреббия, Ж. Теллес, Л. Вроубел. – М. : Мир, 1987. – 525 с.

5. Голубков В. Н. Исследование процесса формирования зоны деформации в основаниях одиночных свай / В. Н. Голубков, Ю. Ф. Тугаенко, Б. О. Хуторянский // Основания и фундаменты: Республиканский межведомственный научно-технический сборник. – 1971. – Вып. 4. – С. 9 – 13.

Morgun Alla – Dc. Sc. (Eng.), Prof., Head of the Department of Industrial and Civil Engineering of the Faculty of Civil Engineering, Thermal Power Engineering and Gas Supply.

Shvets Anna – Master's course student of the Faculty of Civil Engineering, Thermal Power Engineering and Gas Supply.

Shevchenko Oleksiy – Master's course student of the Faculty of Civil Engineering, Thermal Power Engineering and Gas Supply.

Vinnytsia National Technical University.