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PROGNOSIS OF THE LOAD -BEARING CAPACITY OF DRILLING PILES BY NUMERICAL METHOD OF BOUNDARY ELEMENTS BASED ON THE RESULTS OF ANALYSIS OF THEIR STRESS STATE

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Construction is one of the leading sectors of the national economy in the historical aspect of its development. Prevention of destruction of structures is a very important task of construction, so a quantitative measure of strength of the foundation of the structure is required. The tasks of improving engineering solutions require designers in search of unused reserves for improving the efficiency of construction, introducing the achievements of science in design practice. One of the main areas is the further involvement of mathematical methods and computers in design practice.

Successful construction of buildings requires constant development of the basics of mechanics and geomechanics. The current trend of increasing the number of floors of buildings to 9-12 floors leads to a significant increase in the load on the foundations. For such structures, piles have to be driven in 2-3 rows, the grillage becomes wide, and the cost of reinforcement for it is significant, so the overall effect of using driven piles is reduced.

The solution to the problem of reducing the cost and reducing the time of completion of zero-cycle works is most facilitated by the use of bored piles. This is also facilitated by the transition to building with increased number of floors. Bored piles are characterized by high bearing capacity and their arrangement does not have a dynamic effect on the structures of neighboring buildings and structures. The latter circumstance is important when building within urban areas. The use of bored pile technology also allows the use of deepening to a specific pile mark.

The aim of the work is to conduct numerical simulation of the resistance of a bored pile under conditions of nonlinear deformation of the soil base on a computer.

The growing capabilities of modern computers require constant revision of existing numerical methods for the study of new classes of problems for which there is hope for a solution. One of such topical problems is the nonlinear problem of geomechanics of the behavior of bored piles under load.

***Keywords**. Numerical boundary element method, stress-strain state, bored piles.*

Introduction

The basis of the calculation methods for assessing the bearing capacity of foundations is the theory of limit equilibrium, which is still relevant today, with the availability of computers and numerical methods for analyzing elastic-plastic deformation of foundations. The solutions of the theory of limit equilibrium, which have been repeatedly tested in practice, allow us to reliably determine the magnitude of the ultimate load.

The accumulation of experience in designing bored piles, as well as data from observing the settlements of various structures in different soil conditions, allows us to adjust the areas of their practical use and requires the development of modern nonlinear methods for their calculation. The research methods also include the comparison of the results of experimental and numerical studies in order to confirm the adequacy of the developed methodology. The issue considered in the work is relevant for the further development of soil mechanics and the convergence of calculated data with field data.

Field studies play a controlling role.

The current stage of development of soil mechanics is characterized by an active transition to new computational models that more fully reflect the real properties of soils, because 95% of soil deformations are irreversible. These are plastic flow models. The dispersion of the soil leads to the fact that its state and properties at the moment depend on the entire history of its loading.

The basis for building a soil model is experimental information on the behavior of real soil. At the same time, model equations should not contradict the laws of conservation of motion, mass, and energy. The tasks of improving engineering solutions require designers to search for unused reserves to increase construction efficiency, implement scientific achievements in design practice. One of the main directions is the further involvement of mathematical methods and computers in design practice. When soil is compacted, surface energy decreases. The presence of pores in dispersed soil makes it possible to obtain freedom of movement. Soil particles can move from places of temporary dislocation into pores. The gradual reduction of voids causes a decrease in excess energy.

The paper presents the results of numerical studies of the stress-strain state of bored piles using the modern numerical method of boundary elements (BEM).

The experience of using foundations made of bored piles convincingly demonstrates their significant advantages compared to other types of piles:

- Increased bearing capacity.

- Sharp reduction in reinforcement consumption.
- Reduction in estimated cost.
- Reduction in the volume of excavation work by 70-80%, concrete by 35-40%, labor costs by 45-60%, estimated cost by 50-60%, construction time is reduced by 1.5 times.

At the design stage of bored piles, it is necessary to predict the expected settlement values. The design of this type of piles is associated with the solution of a complex of computational, constructive, and technological problems.

Clarification of computational and constructive issues that arise in the design of bored piles is an urgent task in foundation engineering - improving methods for calculating the bearing capacity of axisymmetric foundations using numerical methods.

The paper uses a method for calculating the bearing capacity of bored piles using a method that combines the calculation of the first and second groups of limit states from the action of vertical loads using the numerical method of boundary elements, taking into account both elastic and plastic work of the soil base.

The method is based on the fundamental laws of soil mechanics - the theory of limit equilibrium, strength laws, and the results of comparing theoretical solutions with experimental research data.

Problem statement. Defining relationships

During the construction of a structure, the gravitational load from the weight of the structure is transferred to the soil base, which compresses it. The soil base will be compacted. At the same time, the rigid contacts between the mineral particles of the soil will be broken, which will cause the rearrangement of the soil particles into a denser or looser packing.

Solid bodies, which are described by the mechanics of solid media, have the strength of the bonds between the mineral particles the same as the strength of the individual particles.

In three-phase dispersed soils, under the action of external forces, both general deformations characteristic of continuous media and deformations caused by the mutual movement of individual soil grains into the pore space with the violation of individual bonds between individual particles occur. Dilatancy effects are characteristic of soils, as well as for porous media that are compacted. Features of their mechanical behavior: hydrostatic pressure affects the shape change, and tangential stresses affect compaction. This leads to a simultaneous change in the volume and shape of soils - the effects of dilatancy and contractancy, which were discovered by O. Reynolds back in 1885 [1, 2].

That is why it is necessary to involve the theory of elasticity, the theory of plasticity, and the mechanics of dispersed media to model the behavior of soil under load.

In the article, to solve the boundary value problem of the equilibrium of a reinforced bored pile in the soil, a numerical MGE is used, one of the largest areas of application of which is the problems of mathematical physics (classical Laplace or Poisson problems) [1, 2], which describe a constant potential flow. Soil mechanics problems are related to Laplace problems.

The MGE uses the fact that for soil mechanics problems, the equations of state of which are a system of 15 partial differential equations, there are fundamental (singular) solutions that correspond to single effects in an unbounded region of the half-space. The implementation of the MGE involves a preliminary transition from the initial boundary value problem to the integral relation obtained by K. Brebbi [2] and which is a synthesis of statics, geometric, and physical equations:

$$\left.\begin{aligned} &\sigma_{ij,j} + b_j = 0 \\ &\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \\ &\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl} \end{aligned}\right\} \Rightarrow C_{ij}(\xi)u_j(\xi) + \int_{\Gamma} p^*_{ij}(\xi,x)u_j(x)d\Gamma(x) = \int_{\Gamma} u^*_{ij}(\xi,x)p_j(x)d\Gamma(x), \qquad (1)$$

where $\sigma_{ij,j} + b_j = 0$ – static equations of equilibrium;

$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$ – geometric equations;

$\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl}$ – physical equations of the medium.

The left-hand side of equation (1) is written in Einstein notation (derivatives are denoted by a comma). When considering a nonlinear problem, the integral equation obtained by K. Brebbia [2, 6] takes the form:

$$c_{ij} \cdot u_j + \int_{\Gamma} p^*_{ij} u_j d\Gamma = \int_{\Gamma} u^*_{ij} p_j d\Gamma + \int_{\Omega} \dot{\sigma}^* \dot{\varepsilon}^p_{jk} d\Omega \quad , \qquad (2)$$

where, u – is the given displacement vector on the contact boundaries of the foundation structure;

p – is the desired stress vector on the boundary;

u^*, p*, σ̇*– kernels of the boundary equation [2,6] or the influence functions of the MGE (fundamental solutions), these are two-point functions, their components are the displacement and stress of an arbitrary point of the half-space field in the direction "i" (observation point) from the force P = 1 applied in the "j" direction (source) – the solution of R. Mindlin for displacements, stresses and derivatives of stresses corresponding to single disturbing influences (P=1) in the half-space [1,2,6] is adopted. The kernels of the integral equation characterize the investigated medium;

c_{ij} – constant, determined from the conditions of motion of the body as a whole, appears when translating the boundary value problem to the integral equation (1,2) to obtain a single solution.;

Г, ξ, x , Ω – respectively: – boundary surface of the foundation structure,

disturbance point, – observation point, – and the boundary of the triangular cells of the active (dilatancy) zone of the soil [2,5].

The last component in (2) includes the integral over the area of the soil mass dΩ, in which the appearance of plastic deformations is expected (the active zone of the soil base). $\dot{\varepsilon}_{jk}^{p}$, $\dot{\sigma}^*$– derivatives of the fundamental solutions of R. Mindlin. The fundamental solutions of R. Mindlin [1,6] turn the integral over the area to zero and thereby reduce the problem to the definition of only boundary functions. The point of application of the unit force ξ and the observation point B are located on the lateral surface and at the tip of the pile.

To obtain a numerical solution of equations (1,2), the boundary of the contact area of the foundation structure with the soil base was discretized by linear boundary elements, Fig. 1.

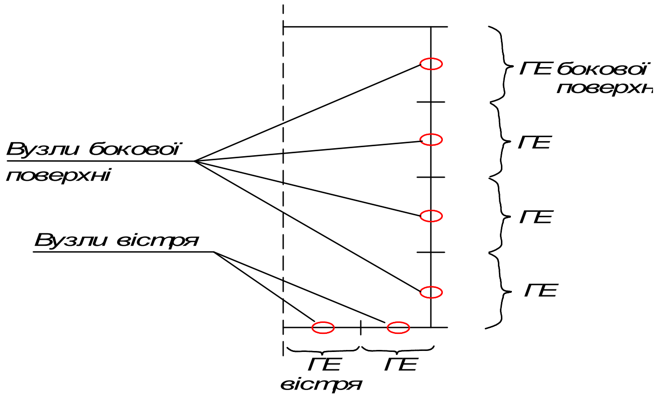

Fig. 1. – Discretization of the lateral surface and tip of a bored pile by constant boundary elements

The active zone of the surrounding soil base was discretized by triangular cells (Fig. 3).

In the mechanics of continuous media, it is customary to consider the behavior of bodies under the action of various influences as a violation of the initial state of equilibrium between interacting internal elements and as its transition to a new state of equilibrium as a result of a change in the forces acting between the elements. That is, the equilibrium conditions for infinitely small elements of the medium must be satisfied. In addition, the condition of the indissolubility of the medium is set and the law of the connection between σ-ε (physical equations) is determined. In the theory of limit equilibrium, which is used in the work, the same equilibrium equations remain, instead of geometric equations, the connection between σ-τ in the limit state is written. As for the physical equations, the plastic flow dependences are used, which model the development of plastic deformations.

The assessment of the process of accumulation of residual volumetric deformations and shear deformations (subcritical deformation of the soil) in the work was carried out according to the unassociated law of plastic flow and dilatancy theory of dispersed media by Nikolaevsky V.M., Boyko I.P. [3,4]:

$$d\varepsilon_{ij}^{p} = \frac{dF}{d\sigma_{ij}}, \quad F \neq f \quad , \qquad (3)$$

where F is the plastic potential (dissipative function of the porous soil medium), f is the criterion for transition to the plastic state, dλ is a scalar factor.

The synthesis of mathematical methods from different branches of mechanics is a progressive method in scientific research.

According to the developed model, the total deformations of the soil were determined:

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \sum \varepsilon_{ij}^{p} + d\varepsilon_{ij}^{p} \cdot \delta_{ij} \ . \qquad (4)$$

The work of stresses on elastic deformations ε_{ij}^e is converted into elastic energy, the work on the increments of irreversible deformations $\sigma_{ij} \cdot d\varepsilon_{ij}^p$ is dissipated [1,2,3].

The increment of plastic deformations consisted of layer and deviator parts:

$$d\varepsilon_{ij}^p = d\varepsilon_{ij}^p{}_{(шар)} + d\varepsilon_{ij}^p{}_{(дев).} \tag{5}$$

where

$d\varepsilon_{ij}^p{}_{(dev)} = D_{ij}\, d\lambda$, D_{ij} - stress deviator , $d\lambda$ - proportionality coefficient.

$d\varepsilon_{ij}^p{}_{(layer)} = \Lambda \cdot d\gamma^p$, where Λ - dilatancy coefficient [1,3,4], $d\gamma^p$ – increment of shear deformations.

The process of plastic deformation of the soil in the model was based on its linearization according to the proposals of O.A. Ilyushin [2] - this is a recurrent sequence of linear problems. The threshold nature of plastic deformations (the boundary of the transition of the soil work to the plastic stage) was determined by the modified Mises-Schleicher-Botkin condition [1,3,6], which assumes failure along octahedral sites. It is assumed that the yield site coincides with the octahedral (site of mobilization of tangential stresses):

$$f = \begin{cases} T + \sigma_m tg\psi - \tau_s = 0 \quad npu \quad \sigma_m \le p_0 \\ T + \rho_0 tg\psi - \tau_s = 0 \quad npu \quad \sigma_m > p_0 \end{cases} \tag{6}$$

where ψ, τ_s – angle of internal friction and specific adhesion on octahedral plane.

p_0 – level of maximum hydrostatic pressure when soil acts as a continuous medium (limit of plastic compressibility).

As function f the modified Mises-Schleicher-Botkin condition [1,3] is used, which takes into account real spatial deformation of soil and

presumes that the shear areas are realized on octahedral areas:

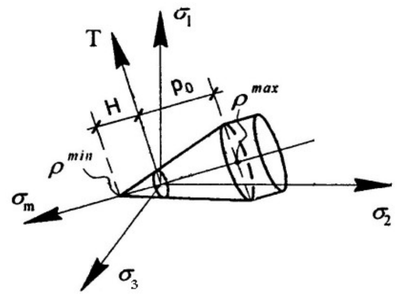

Fig. 2 – Modified Mises-Schleicher-Botkin yield criterion

In the stepwise loading method, the increments of elastic stresses $\Delta\sigma$ in each boundary element were determined. The obtained $\Delta\sigma$ were added to the stresses obtained in the previous step and the total stresses were calculated, the vector of which was compared with the boundaries of the yield surface.

When the acting stresses did not go beyond the boundaries of the yield surface, the soil deformations were considered elastic. When the vector σ was beyond the boundary of the yield surface, the soil deformations were determined by the law of plastic flow.

Construction practice forces us to look for new, more optimal soil models that take into account its nonlinear behavior. One of the directions of scientific and technological progress in foundation construction is the widespread use of computers in calculations.

For this purpose, numerical studies of the stress-strain state (SSS) of bored piles [5] with a diameter of:

– 40 cm (Fig. 4) and

– 50 cm (Fig. 5)

with a pile length of 7 m were carried out using the numerical method of boundary elements (MFE) according to the given nonlinear dilatancy model.

The layering of the base of the construction site is

– rigid plastic loam,

– dense sand,

– hard clay [5].

The accuracy of mathematical models used in calculations of foundations and soil structures and describing the mechanical behavior of soils depends on the most significant features of soil deformation.

The discretization of the lateral surface and tip of the experimental bored piles was carried out by constant boundary elements, Fig. 1, the discretization of the active zone is presented in Fig. 3

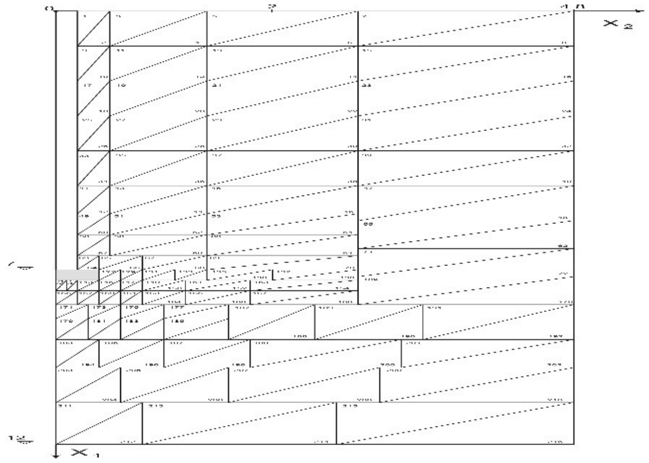

Figure 3 – Discretization of the surrounding pile space of the active soil zone

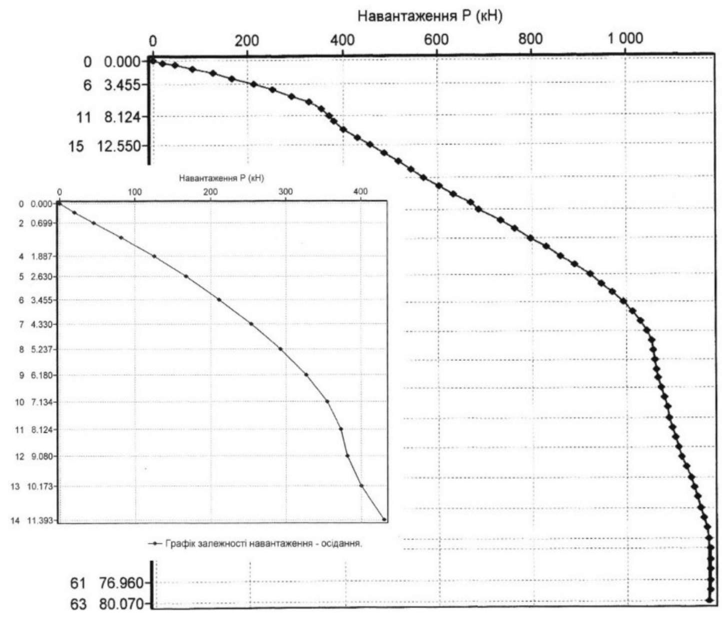

Figure 4 – Load-settlement graph for a bored pile with a diameter of 40 cm and a length of 7 m

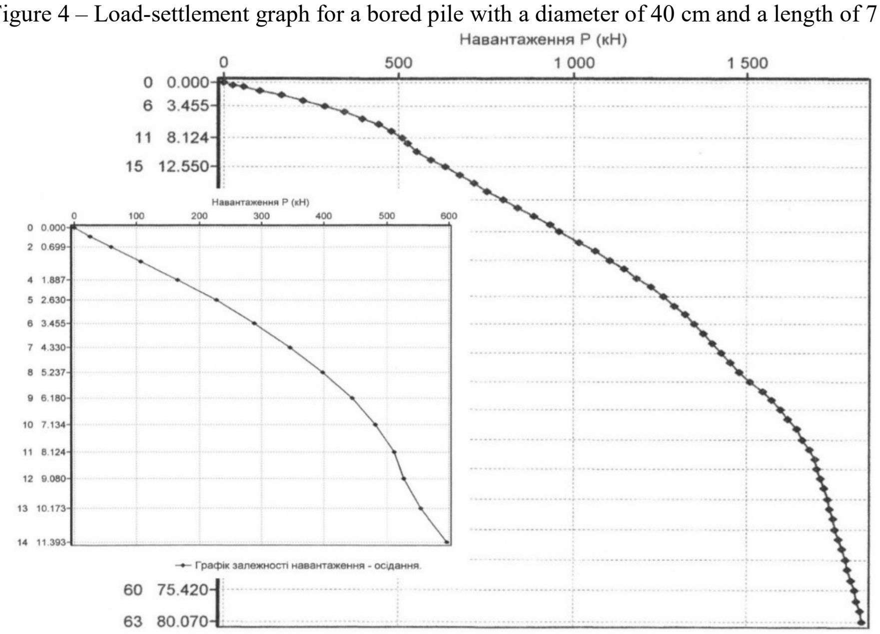

Figure 5 – Load-settlement dependence graph for a bored pile with a diameter of 50 cm, a length of 7 m

Analysis of the load-settlement graphs (Fig. 4, 5) shows that at low loads (i.e., up to a settlement of about 11 mm, in the left part of the graphs) an almost linear pattern is observed. With increasing load magnitude, the dependence becomes nonlinear, due to the significant development of zones of plastic deformation in the base of the piles.

The results of numerical modeling of the process of deformation of the elastic-plastic base of building piles according to the proposed method correspond to generally accepted ideas and data from experimental studies. The experimental value of the bearing capacity of bored piles with a diameter of 40 and 50 cm was, respectively, 380 and 520 kN [5]. The forecast for MGE is 390 and 510 kN, respectively (Fig. 4, 5).

With an increase in the diameter of bored piles, their bearing capacity for vertical loads increases. From the point of view of the value of the bearing capacity, we can speak of the absolute advantage of piles of large diameters.

Conclusions

1. Modern numerical modeling allows us to determine the NDS of bored piles with an accuracy sufficient for design and to identify their bearing capacity. Knowing the NDS of the pile-soil system, we can make a forecast of the development of events.
2. The use of elastic-plastic models with the unassociated law of plastic flow and dilatancy relations of V.N. Nikolaevsky and I.P. Boyko in the calculations of soil foundations is a starting point for solving a wide range of problems that have direct engineering applications.
3. The calculations are based on the theory of limit equilibrium, which considers the limit stress state. MGE is a progressive method, a new way of solving boundary value problems of foundation construction.

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ПРОГНОЗУВАННЯ НЕСУЧОЇ ЗДАТНОСТІ БУРОВИХ ПАЛЬ ЧИСЕЛЬНИМ МЕТОДОМ ГРАНИЧНИХ ЕЛЕМЕНТІВ НА ОСНОВІ АНАЛІЗУ ЇХ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ

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Будівництво є однією з провідних галузей національної економіки упродовж історичного розвитку. Запобігання руйнуванню споруд є надзвичайно важливим завданням будівництва, тому необхідна кількісна оцінка міцності основи споруди. Завдання вдосконалення інженерних рішень зобов'язують проектувальників шукати невикористані резерви для підвищення ефективності будівництва та впроваджувати досягнення науки у проектну практику. Одним з головних напрямів є подальше залучення математичних методів і комп'ютерних технологій у проектування.

Успішне зведення будівель потребує постійного розвитку основ механіки та геомеханіки. Сучасна тенденція збільшення поверховості будинків до 9–12 поверхів призводить до значного зростання навантаження на фундаменти. Для таких споруд палі доводиться занурювати у 2–3 ряди, ростверк стає широким, а витрати на його армування значні, тому загальний ефект від використання забивних паль зменшується.

Ключові слова: чисельний метод граничних елементів, напружено-деформований стан, бурові палі.

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