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Mathematical modeling of the folded foundation interaction with the base by varying the structure stiffness

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The article describes a practice of using software system based on the finite element method for calculating shell foundations. It considers the peculiarities of the folded foundation interaction with subsoil mathematical modeling . It is found that during modeling, special attention should be paid to a purpose of the system initial parameters, to a choice of finite elements type, and to an optimal model of subsoil. Mathematical modeling of the folded foundation interaction with subsoil is performed under conditions of a plane problem. The foundation operation under various conditions of interaction with subsoil and with different stiffness parameters of the foundation is analyzed. Correlation between stiffness of a foundation structure and resulting equivalent stresses in subsoil under different conditions of interaction is determined. It is concluded that the obtained results represent a benchmark for subsequent calculations and modeling the interaction between a foundation and subsoil under a volumetric stressed condition.

Key words: shell foundation, finite element method, mathematical modeling, coulomb-mohr model

Математичне моделювання взаємодії складчастого фундаменту з основою при варіюванні жорсткості конструкції

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В статті наведено досвід використання програмних комплексів на основі методу кінцевих елементів при розрахунках фундаментів-оболонок. Зазначено, що активне використання методу кінцевих елементів пов'язане поєднанням трьох факторів: особливостями самого методу, наявністю сучасної обчислювальної техніки, розробкою математичних моделей досліджуваних явищ, що адекватні до реальних процесів із високим ступенем точності. Наведено приклади найрозповсюдженіших програм для вирішення геотехнічних задач, при цьому зазначено, що вони відрізняються способами завдання моделі ґрунтової основи, та мають свої певні інструменти для зміни та коригування вихідних параметрів та аналізу. Розглянуто особливості математичного моделювання взаємодії фундаментів та ґрунтової основи. Встановлено, що при моделюванні особливу увагу слід звертати на призначення початкових параметрів системи, на вибір типу кінцевих елементів і оптимальної моделі ґрунтової основи. Було виконано моделювання взаємодії складчастого фундаменту з основою в умовах плоскої задачі за допомогою програмного комплексу LiraSapr-2013. Проаналізовано характер роботи фундаменту при різних умовах взаємодії з основою та при різних параметрах жорсткості фундаментної конструкції. Було встановлено залежність між жорсткістю фундаментної конструкції та виникаючими еквівалентними напруженнями в ґрунтовій основі при різних умовах взаємодії. Встановлено, що саме у випадку із використанням гнучкої складки, яка працює як оболонка, і, залучаючи до роботи більше об’єму ґрунту у порожнину, досягається ефект перерозподілу напружень по всій ґрунтовій товщі. Зроблено висновок, що отримані результати слугують орієнтиром для послідуючих розрахунків та моделювання взаємодії фундаменту та основи при об’ємному напруженому стані.

Ключові слова: фундамент-оболонка, метод кінцевих елементів, математичне моделювання, модель Кулона-Мора

Introduction. Finite Element Method (FEM) is actively used to solve various engineering tasks, geotechnical ones in particular. The development of technology along with a wide software use when designing and calculating engineering systems urges the integration of software systems based on FEM in subsoil modeling, its interaction with foundation, and in the system analysis in general [1-3].

There are various software systems based on the finite element method, for example: Feadam, SageCrisp, Plaxis, Ansys, LiraSapr, Nastran, ABAQUS, etc. They differ in methods of subsoil modeling, and have their own specific tools for changing and adjusting source parameters and analysis. At the same time, the application of a software system for modeling foundation structures of off-standard forms and types is also relevant, i.e. stamps modeling. Today, the practice of using software systems for modeling complex foundation systems in conjunction with subsoil is not studied sufficiently [4-6].

Analysis of the latest research findings and publications. The finite element method is widely used due to a combination of three factors: the features of the method itself, the availability of modern computer technology, the development of investigated phenomena mathematical models that comply with the real processes with a high degree of accuracy.

National and foreign scientists actively use software systems based upon the finite element method for solving geotechnical problems in their research [1-10]. First of all, in research analysis, attention is paid to the study of software systems application in mathematical modeling of different types of shell foundations while interacting with subsoil. Mahmoud Samir El-kady and Essam Farouk Badrawi conducted experimental and numerical studies applying five square foundations, one of them was a flat-shaped foundation used as a reference sample and four shell foundations of a folded shape [1]. ABAQUS software was used for mathematical modeling. In a numerical model, a body of sandy soil is described by an 8-node brick element of a trilinear displacement. The sandy soil is modeled as a resilient plastic material model with a non-associated flow rule using the Coulomb-Mohr plasticity model. Foundation supports are modeled as a plastic material using an 8-node linear brick element with reduced integration (fig. 1). The minimum deviation of experimental and numerical results was found in conclusion.

Nisha P. Naik and Sabna Thilakan [5] investigated the operation of a column type shell foundation analyzing various angles of lateral surfaces inclination. The models of a foundation strain and soil properties were numerically modeled with OptumG2 software using finite elements. The Coulomb-Mohr sand model available in OptumG2 was used to simulate three soil conditions: loose, medium, and dense states. The models were subjected to a multiplier resilient and plastic analysis. As a result, general stresses, maximum vertical displacements were obtained. The results showed that the foundation with shell configuration had a greater bearing capacity than conventional flat slab foundation.

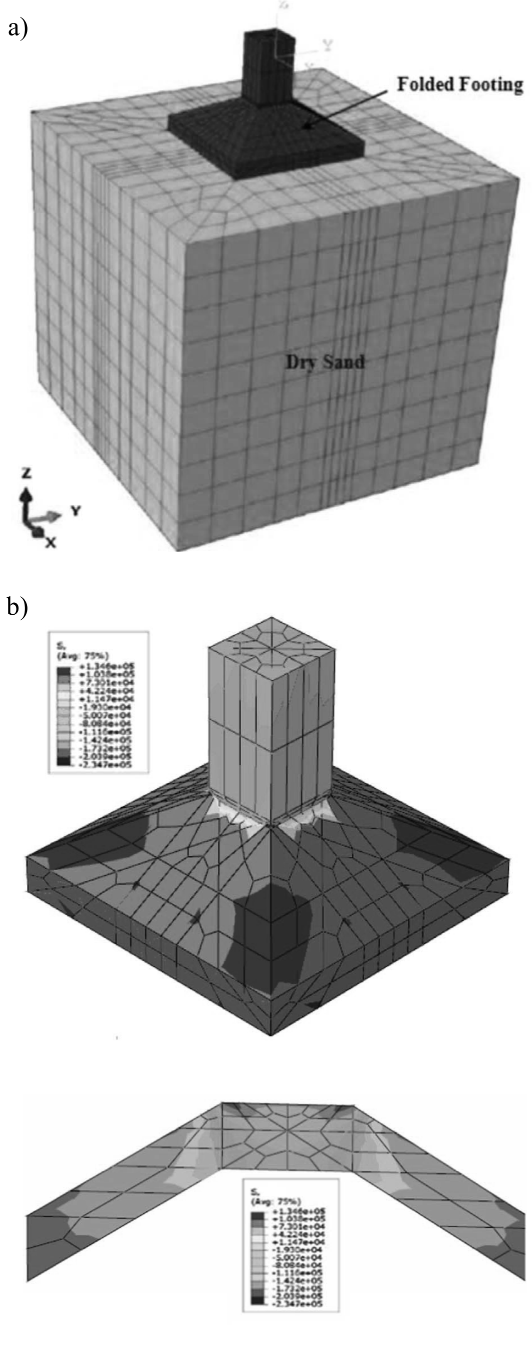

Figure 1 – Modeling of foundation and subsoil:
a) – finite element mesh of subsoil and foundation;
b) – shading contours of stresses
for 30° folding angle

Mohammed Y. Fattah analyzed the operation of a conical shell foundation using ANSYS software system [7]. A three-dimensional brick element (Solid 65) was used to simulate concrete with or without reinforced bars. Steel reinforcing bars were represented using a 2-node bar (Link8 in ANSYS) and included in the property of 8-node brick element. The type of a

45 finite element is normally used for 3D modeling of solid structures. The element is determined by eight nodes with three degrees of freedom at each node. Using load symmetry, geometry and distribution of reinforcement, RPC-conical foundations were considered in the analysis of the finite element method. The selected segment was modeled using Solid 65 isoparametric hexahedral brick elements.

Chinese scientists Dongxue Hao, Rong Chen and Guangsen Fan were engaged in research on the ultimate bearing capacity of the foundations for power transmission towers on structurally unstable soils [9]. Mathematical modeling of subsoil and foundation was carried out in ABAQUS software system. The monolithic reinforced concrete foundation was modeled as a linear plastic material with a modulus of elasticity of 40 GPa and a Poisson coefficient of 0.2. The subsoil is considered as a homogeneous resilient and plastic material, which is described by the Drucker-Prager model. Resilient parameters: E = 30 MPa, ν = 0.3, γ=17 kN/m^3. The parameters of the Coulomb-Mohr subsoil model in a tensile stress state, specific soil cohesion and the angle of internal friction can be transformed into the parameters of the Drucker-Prager model. While conducting a finite element analysis of a deepened foundation with an extended basement near an enlarged base, large displacements and strains are inevitable. An application of traditional Lagrange elements in these areas may cause a decrease of their accuracy [10]. In contrast to the Lagrangian, Euler's analysis is a technique of finite elements in which material can flow through the boundaries of elements in a rigid mesh. Thus, Euler's technique can be very effective in processing tasks involving very large strains, material destruction, and liquid materials. In this paper, the Euler’s method was used to study soil.

Determination of the unsolved parts of the general problem. One of the difficulties about mathematical modeling of folded foundations for power transmission lines is the modeling of joint operation of a foundation structure of a complex shape and subsoil, as it is necessary to choose a relevant subsoil model, consider all output parameters, simulate the operation of a foundation up to full involvement of soil into the operation.

Task setting. The research task is to analyze the operation and to select the optimal parameters of a folded foundation (stiffness) and subsoil (model choice) during mathematical modeling in LiraSapr-2013 software system.

Basic material and results. The research subject is a stressed and strained state of a foundation structure and subsoil under their contact interaction in specific operational conditions. A folded foundation is selected as a prototype of a new foundation shaped as separate thin-walled reinforced concrete folds joined with each other by a steel or reinforced concrete beam [11]. A folded foundation with an improved system of bearing beams and hinges is proposed as a new alternative solution [12].

Mathematical modeling of the interaction between a foundation structure and subsoil is carried out in the LiraSapr-2013 software system. As a test model, one of the foundations prismatic folds with known geometric parameters and physical characteristics was modeled [12], further on one typical prismatic stamp operation was studied under altered operational conditions and interaction with subsoil. To study the stress-strain state of subsoil under different interaction types of "foundation-subsoil" system, the task was solved in a plane formulation.

A finite element of type 2, corresponding to the finite element (FE) of the flat frame, was used for modeling a prismatic fold (there are 3 degrees of freedom in each node: X – displacement along X axis; Z – displacement along Z axis; UY – rotation around Y axis). Finite elements 21 and 22, which are rectangular and triangular FE of a plane problem (beam-wall), were used to model subsoil. This finite element is intended for a strength calculation of the plates loaded in their X1OZ1 plane; a priori this FE allows modeling a plane stress state. At the same time, the lower part of 1/3 soil thickness was modeled by finite elements of a larger size to optimize the calculation process.

Two conditions of a foundation structure and subsoil interaction were compared. In the first case, a prismatic folded plate contacts subsoil only within the horizontal bearing flanges. In the second case, subsoil is fully incorporated into the operation by filling the fold cavity. Silty sand was chosen as a reference soil sample having the following characteristics: c = 2 kPa, e = 0.75, E = 11 MPa, φ = 26°.

It is common knowledge that structures the outlines of which are similar to the arched ones transmit horizontal loads to the bearing parts, which in turn provokes tensile stresses at the base of a fold. In order to reduce the spill negative impact, which is transmitted to the soil, the rigidity ribs (diaphragms) are arranged in the fold. To simulate the operation of the folds with diaphragms and a step of their arrangement, calculations with different stiffness of the fold for both cases of interaction were performed.

To determine the main and equivalent stresses, the Coulomb-Mohr theory was chosen (a subsoil model) as a strength theory for assessing a bearing capacity of subsoil. The calculation results of the mathematical models are shown in Fig. 2 and 3.

As it can be seen in Figure 2, in the case where the prismatic fold rests on the soil only through the horizontal bearing flanges and the load is transmitted to the soil through them, the stiffness of the fold increases while the equivalent stresses reduce. This is explained by the fact that, when the stiffness of the fold increases, it ceases to operate as a thin-walled structure losing the properties of a shell, and its operation with the increased stiffness is similar to the operation of a conventional hard stamp (a slab).

However, in the second case (Fig. 3), when the soil is fully integrated into the operation by filling it into the fold cavity, the stiffness of the fold increases along with the increase of the equivalent stresses. It suggests that the application of a flexible fold operating as a shell and the integration of a larger soil amount in the cavity lead to the redistribution of stresses throughout the soil stratum.

The graphs of equivalent stresses values dependence from the alteration of the foundation structure stiffness (Fig. 4) clearly shows the consistent pattern of operation under different conditions of interaction between the foundation structure and subsoil.

Conclusion. The scientific novelty of the research is in determining the correlation between the stiffness of a foundation structure (folds) and values of equivalent stresses under different conditions of interaction between a foundation structure and subsoil. In turn, this affects the bearing capacity of a foundation and subsoil in general. The best results are demonstrated during co-operation of a foundation and soil. It can be explained by the fact that soil and foundation in this case act as a whole. The obtained results represent a benchmark for subsequent calculations and modeling of the foundation and subsoil interaction under a volumetric stressed state.

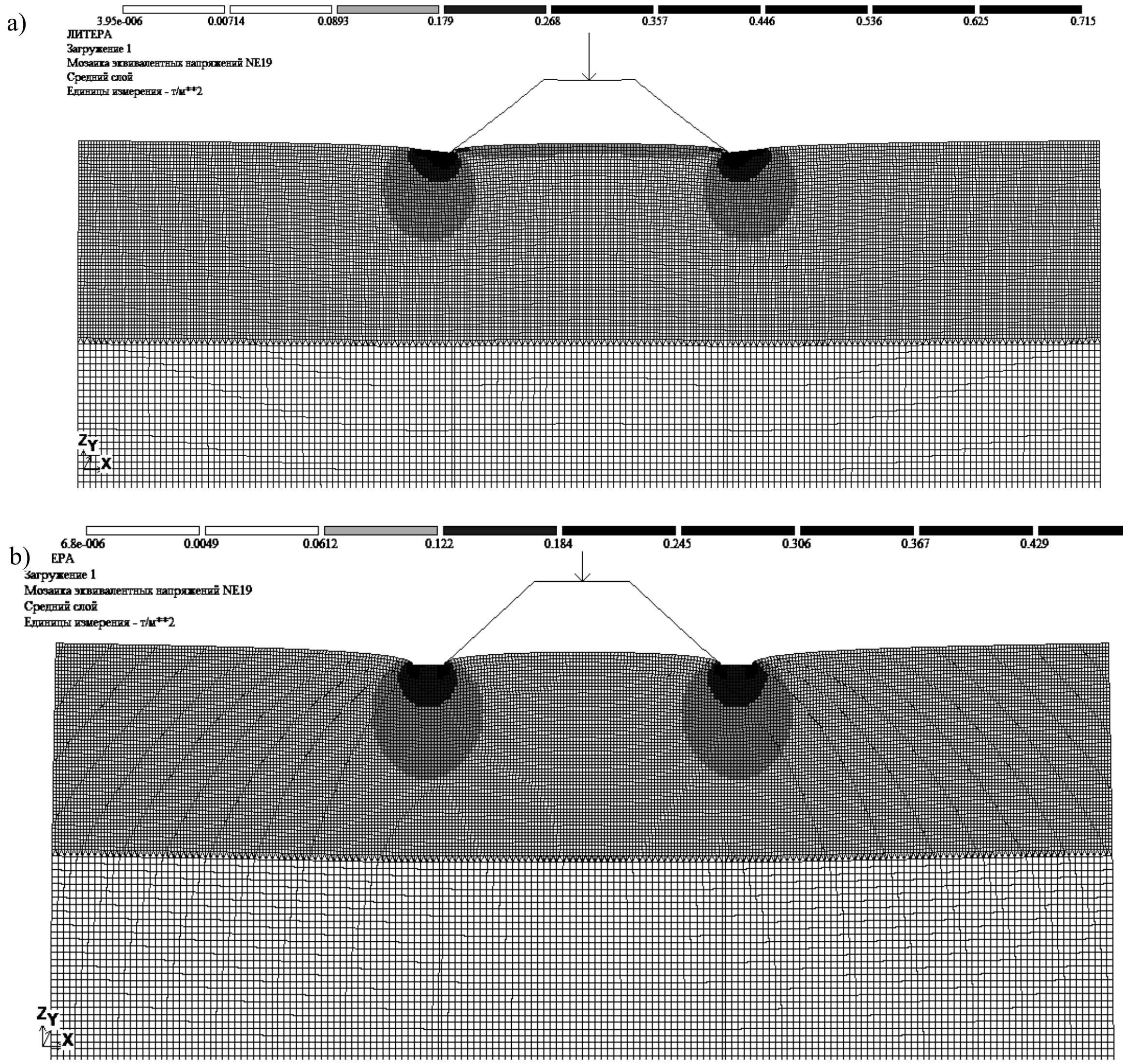

Figure 2 – Stresses shading contours under incomplete interaction of the foundation and the ground:

a) – the value of equivalent stresses at a coefficient of stiffness N=1;
b) – the value of equivalent stresses at a coefficient of stiffness N=4

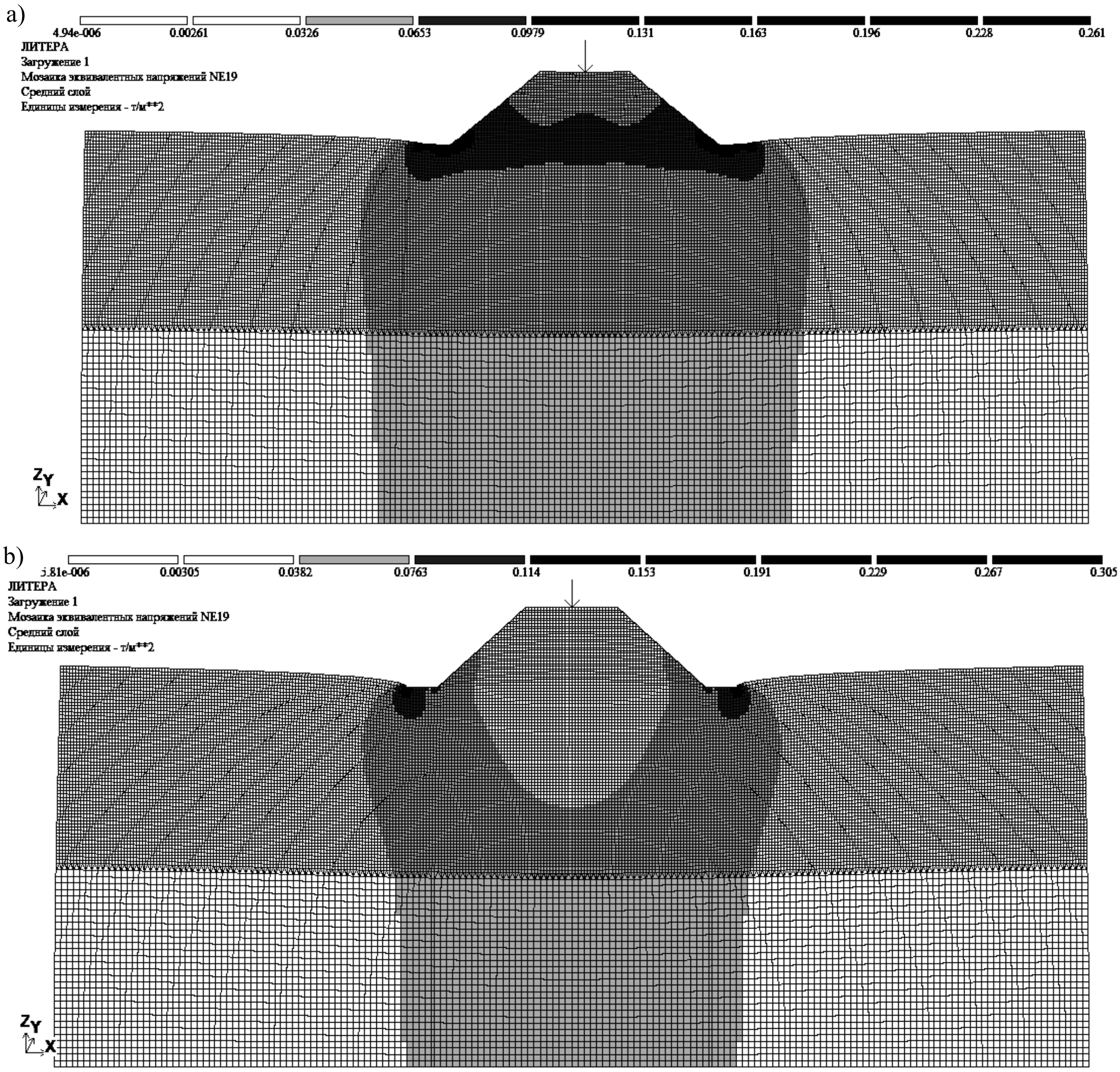

Figure 3. Stresses shading contours under complete interaction of the foundation and the ground

а) – the value of equivalent stresses at a coefficient of stiffness N=1;

б) – the value of equivalent stresses at a coefficient of stiffness N=4

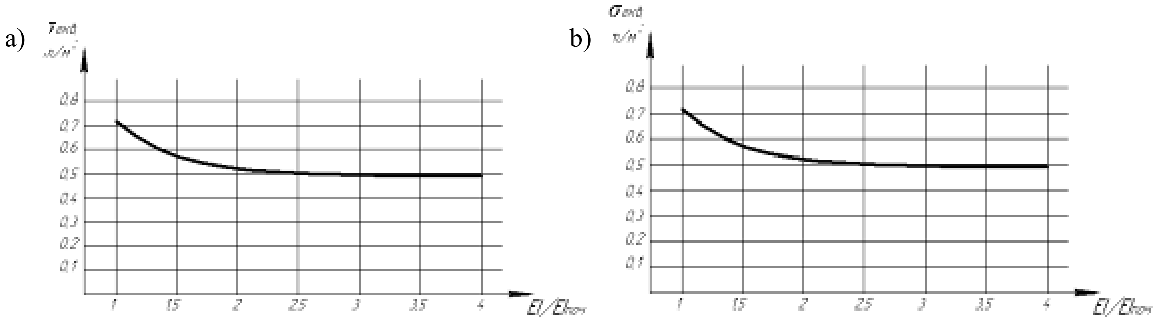

Figure 4. The graphs of equivalent stress values dependence from the stiffness change of the foundation structure

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