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Comparative analysis of calculation models of soil behavior on the example of the tray experiment`s modeling

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Graphs of settlements of stamp experiment in the modeling of the tray experiment with variable reinforcement parameters to determine the effect of reinforcement with vertical soil-cement elements (SCE) of weak clay bases of strip foundations of buildings are shown. The simulation results of the experiment using the Mohr-Coulomb ideal elastoplastic model of soil behavior and the Hardening soil model isotropic compaction model of soil behavior by the finite element method for estimating the stress-strain state of the "soil-cement base – rigid strip stamp" system when using different models of the SCE assignment are presented. A comparison of the methods of modeling the stress-strain state with the capabilities of the Plaxis 3D software package is carried out. The most optimal models of soil behavior for the simulation of SCE under existing soil conditions have been determined

Keywords: vertical soil-cement element, soil base, settlement, comparison of calculation methods, finite element method, tray experiment

Порівняльний аналіз розрахункових моделей поведінки ґрунту на прикладі моделювання лоткового експерименту

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Наведено графіки залежності «тиск на основу – осідання жорсткого стрічкового штампу» за результатами математичного моделювання та лоткового експерименту при варіативних параметрах армування глинистої основи для визначення впливу армування вертикальними ґрунтоцементними елементами (ҐЦЕ) слабких глинистих ґрунтів в основі стрічкових фундаментів будівель і споруд. Порівняно результати моделювання лоткових випробувань з використанням двох раніше вже апробованих моделей поведінки грунту: ідеальної пружно-пластичної моделі Мора-Кулона та моделі ізотропного ущільнення (зміцнення) Hardening soil model, - методом скінченних елементів (МСЕ) у просторовій (3D) постановці для оцінювання напружено-деформованого стану (НДС) системи «грунтовий масив – ґрунтоцементна основа – жорсткий стрічковий штамп» при використанні різних моделей імітації ҐЦЕ, зокрема, об'ємними грунтовими елементами за моделлю поведінки linear elastic та пальовими елементами, так званими embedded beam. Оцінено різні способи моделювання ҐЦЕ відповідно до можливостей програмного комплексу (ПК) Plaxis 3D Foundation. Визначено найоптимальніші моделі поведінки ґрунту для моделювання роботи ҐЦЕ за умов слабких глинистих ґрунтів. При цьому в якості вихідних параметрів використано наступні характеристики грнту: щільність; модуль деформації; кут внутрішнього тертя; питоме зчеплення; коефіцієнт Пуасона. Доведено коректність результатів ПК Plaxis 3D при застосуванні пружно-пластичної моделі Мора-Кулона та моделі ізотропного ущільнення для аналізу деформованого стану системи «грунтовий масив – ґрунтоцементна основа – жорсткий стрічковий штамп». Рекомендовано для подальшого практичного використання в геотехічній практиці модель Hardening soil model, як більш коректну в лінійній стадії роботи ґрунту, а для моделювання ҐЦЕ використовувати об'ємні елементи, як більш достовірні. Підтверджено ефективність методу армування основ вертикальними ҐЦЕ для поліпшення основ, складених з ґрунтів з низьким модулем деформації

Ключові слова: вертикальний ґрунтоцементний елемент, ґрунтова основа, осідання, порівняння моделей розрахунку, метод скінченних елементів, лоткове дослідження

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Introduction

More than three-quarters of the territory of Ukraine, including Poltava Region, has difficult engineering and geological conditions for the construction of buildings and structures (for example, subsidence and weak soils, layers of anthropogenic sediments, flooded areas, areas under which there are underground workings and siting of karst etc.).

The central parts of cities are usually also characterized by dense buildings. Of course, the listed factors significantly complicate the process of designing, arranging and operating soil bases and foundations of buildings and structures [1, 2].

Review of the research sources and publications

Therefore, under such conditions, geotechnicians have to use a whole set of already tested measures in order to comply with sufficiently strict limits of absolute and relative settlements of foundations of buildings and structures [1-5]. Some of these measures are: cutting through a layer of soil with special properties; complete or partial elimination of such properties (for example, through compaction or strengthening of soils); justification of the relevant constructive measures (in particular, increasing the rigidity of the structure or, conversely, its flexibility); application of certain water protection measures, etc.

And when designing [1-5], it is necessary to evaluate the stress-strain state (SSS) of the entire system "soil base – foundation – building" not only its parts, after which the parameters of its components are changed (improved) accordingly.

Thus, to reduce the settlements of highly compressible massifs in geotechnics the method of their reinforcement with vertical soil-cement elements (SCE), in particular, by drilling-mixing technology, has already been well tested. This method is technologically simple and economical due to use of local soil as a material for creating elements [6-10].

For visually obtaining SSS parameters while designing the system "natural soil massif – base reinforced by SCE – strip (or slab) foundation of the building" was tested by the spatial (3D) version of the finite element method (FEM) using an elastic-plastic soil model [11-15].

Definition of unsolved aspects of the problem

However, further comparative research is needed to develop the optimal method of calculating the soil bases of strip and slab foundations reinforced with soil cement, and to improve the method of predicting their settlements under conditions of weak, highly compressive soils.

Problem statement

One of the reliable ways to solve this problem is to compare the values of settlements of artificial soil basese of buildings based on the results of field or tray experiments and numerical modeling.

Therefore, the aim of the work is FEM simulation in a 3D setting of the deformed state of a clay base with variable parameters of reinforcement in a tray under a rigid strip stamp, the analysis of the obtained values of deformations of this base, the comparison of the results of the FEM calculation when simulating soil cement with so-called pile elements and soil volumetric elements with the data of the tray experiment performed by the authors earlier [9], as well as the substantiation of the most reliable methodology for predicting settlements of bases reinforced with SCE of strip foundations.

Basic material and results

So, in order to achieve the set goal, the following tasks were solved:

– by FEM simulation in a 3D setting using an ideal elastic-plastic soil model with the Mohr-Coulomb strength criterion to investigate the development of deformations of a rigid strip stamp on an unreinforced base and a base reinforced with vertical SCE;

– by FEM simulation in a 3D setting using the Hardening soil model to evaluate the development of deformations of a rigid strip stamp on an unreinforced base and a base reinforced with vertical SCE;

– to compare the deformed state of the reinforced and natural bases of the rigid strip stamp according to the FEM calculation with the data [9] of the tray experiment.

The well-known geotechnical software complex Plaxis 3D Foundation [11-15] was chosen for the stress-strain state FEM simulation in the 3D setting of system "soil massif – soil-cement base – rigid strip stamp".

The same parameters of the tray, soil base, soil cement and reinforcement percentages as in the tray experiment [9] were selected for the simulation of tray stamp investigations. The dimensions of the calculation area in the plan were 580×530 mm, the depth – 560 mm. A rectangular steel stamp measuring 420×35 mm in plan was imitated by a plate element with the characteristics of S245 steel.

For the mathematical modeling of the stamp tests in the tray the same characteristics of the reinforcement percentages as in the tray experiment were chosen. Modeling of bases without SCE reinforcement and with different percentages of reinforcement with element depth of 100 mm and their diameter of 6 mm was carried out. Variation of the value of the reinforcement percentage at three levels of 2.1%; 4.4% and 7.1% are accepted.

In the first version, the soil-cement elements were modeled by volumetric elements (Fig. 1). Excavation of soil for the installation of a buffer crushed stone cushion, SCE, filling of wells with soil cement, installation of a cushion, stamp and gradual loading were gradually considered. SCE was modeled as a volumetric soil body with appropriate characteristics according to the linear elastic behavior model.

In the second calculation, a certain simplification was performed – the SCE was modeled as a pile with the appropriate characteristics (Fig. 2), and the step-by-step modeling was limited to the stages of pile installation and load application. The SCE was modeled with pile elements, the so-called embedded beam. The type of behavior is a pile, the connection with the foundation is loose, the behavior of the material is linear elastic. The parameters required to specify the element as pile axial skin resistance and base resistance are calculated according to norms [1], as for bored piles. The correctness of this approach is described in the previous work of the authors [14].

In each case, the pressure on the soil was applied in accordance with that obtained in the tray experiment. Also, for both variants of SCE modeling, calculation was performed using different models of soil behavior: ideal elastic-plastic model with Mohr-Coulomb strength criterion and isotropic compaction model (Hardening soil model). Tables 1 and 2 present the characteristics of the materials (density ρ, modulus of deformation E, angle of internal friction φ, specific adhesion c and Poisson's ratio υ), which were specified during modeling according to both models of soil behavior, respectively.

A mesh of finite elements was created for which the very fine density level was adopted due to the low density of the soil layers (actually, only soil clay paste artificially placed in the tray), the presence of insignificant amount of SCE, the simple rectangular shape of the stamp, and, therefore, the relatively high speed of the problem calculation. The mesh of volumetric finite elements in the form of triangular prisms was automatically generated by the program, their thickening was also performed automatically at the piles and the base of the stamp, additional thickening was not specified.

The number of FE varied depending on the complexity of the calculation scheme: for the simulation of SCE with embedded beam pile elements – from 7819...22315 units and for modeling with volumetric soil elements – from 55757 to 145947 units.

The following assumptions and parameters are used in the calculations. The iterative procedure provided for: a relative error equal to 0.05; the maximum number of iterations does not exceed 60; the maximum number of steps in each phase is 250.

Table 1 – Parameters of the Mohr-Coulomb soil model when modeling the stress-strain stateof the "soil-cement base – rigid strip stamp" system

Element	ρ, g/cm^3	E`, MPa	φ,°	c, kPa	υ
Soil paste	1,85	0,7	0	15,8	0,35
Crushed stone	2,00	40	40	1,0	0,25
Soil cement	2,00	300	-	-	-
Soil-cement elements	2,00	300	-	-	0,25

Table 2 – Parameters of the Hardening soil model when modeling the stress-strain state of the "soil-cement base – rigid strip stamp" system

Element	ρ, g/cm^3	E_{oed}, MPa	E_{ur}, MPa	φ,°	c, kPa	υ
Soil paste	1,85	0,7	3,5	0	15,8	0,35
Crushed stone	2,00	40	-	40	1,0	0,25
Soil base	2,00	300	-	-	-	-
Soil-cement pile elements	2,00	300	-	-	-	0,25

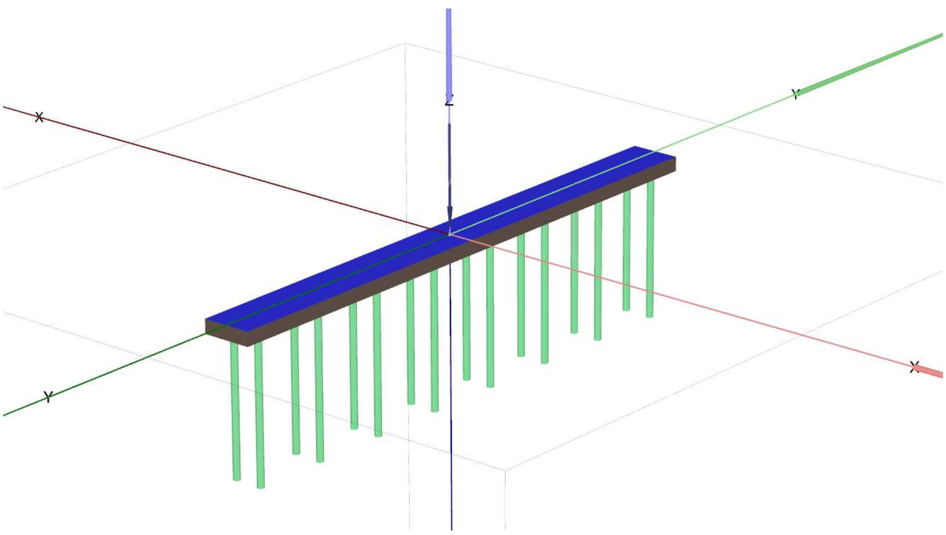

Figure 1 – Soil-cement elements formed by volumetric soil elements

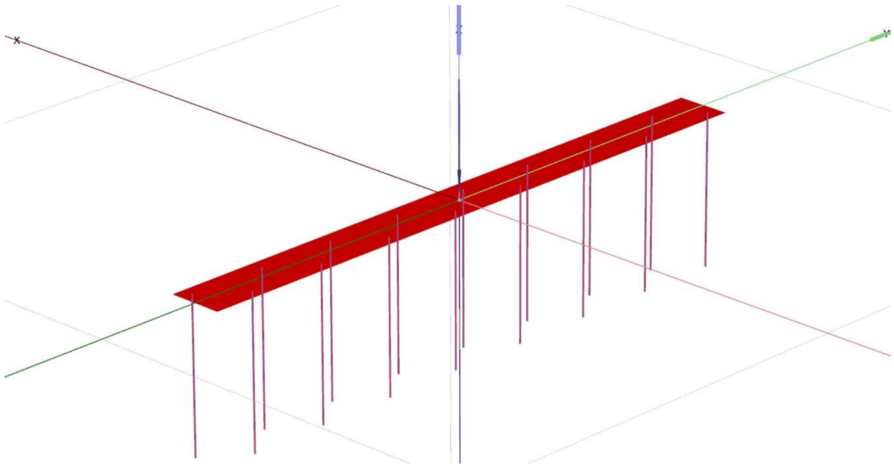

Figure 2 – Soil-cement elements formed by pile elements “embedded beam”

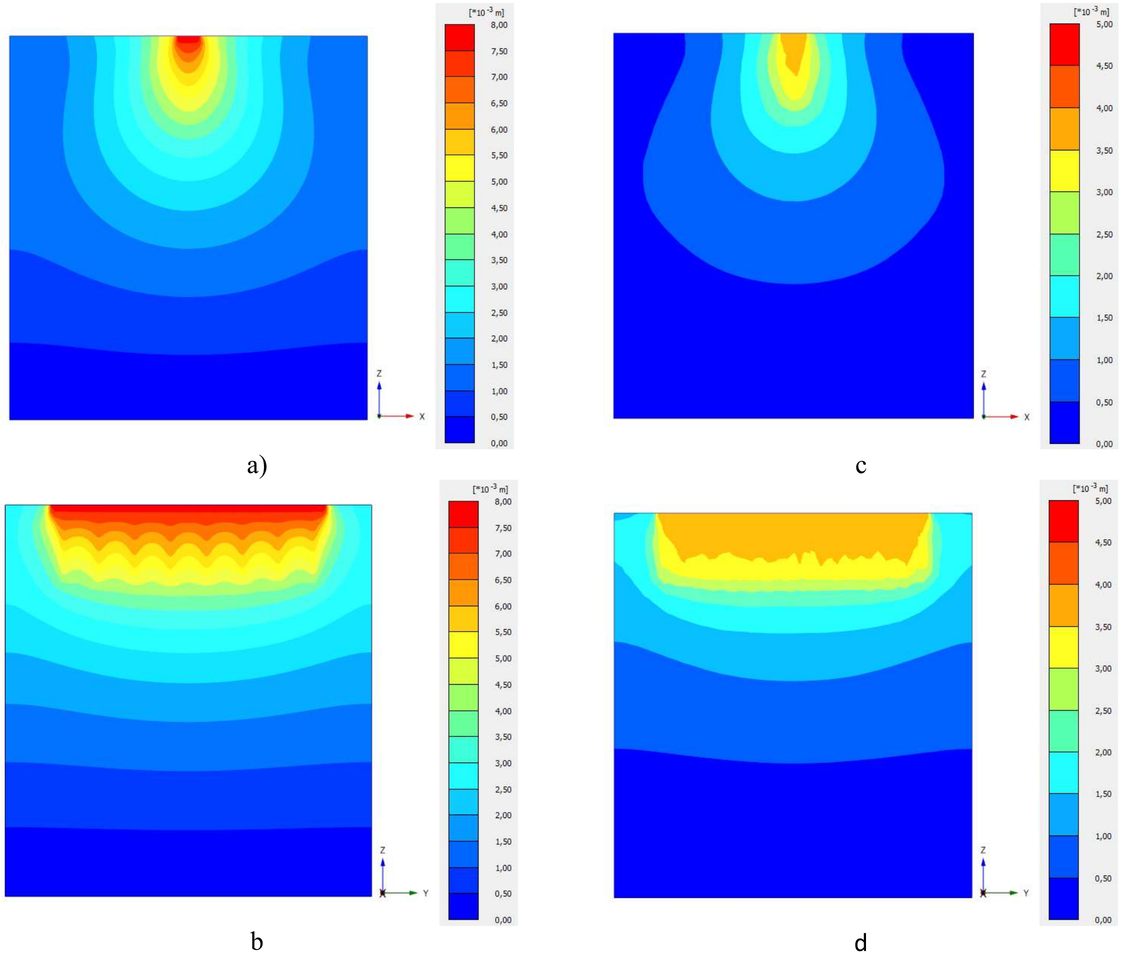

Figure 3 – Settlements of soil base with reinforcement percentage of 2,1% under a load of 1,5 kPa:
a, b – SCE formed by volumetric soil elements; c, d – SCE formed by pile elements

In fig. 3 shown vertical cross-sections according to soil models with the results of vertical movements of FE (soil settlements) under the same conditions (pressure on the base, percentage of reinforcement, soil models) under different parameters of SCE modeling. Fig. 3a and 3b shows settlements according to modeling with volumetric soil elements and in Fig. 3c and 3d – piled. On the vertical cross-section along the axis of the SCE placement, it is clearly visible that when modeling with piles, the soil under the stamp settles uniformly, regardless of the placement of the SCE, while when modeling reinforcement elements with volumetric bodies, the soil settlements is the smallest in the middle between the piles, and the largest is in the center of the SCE in the middle of the stamp , which is closer to reality.

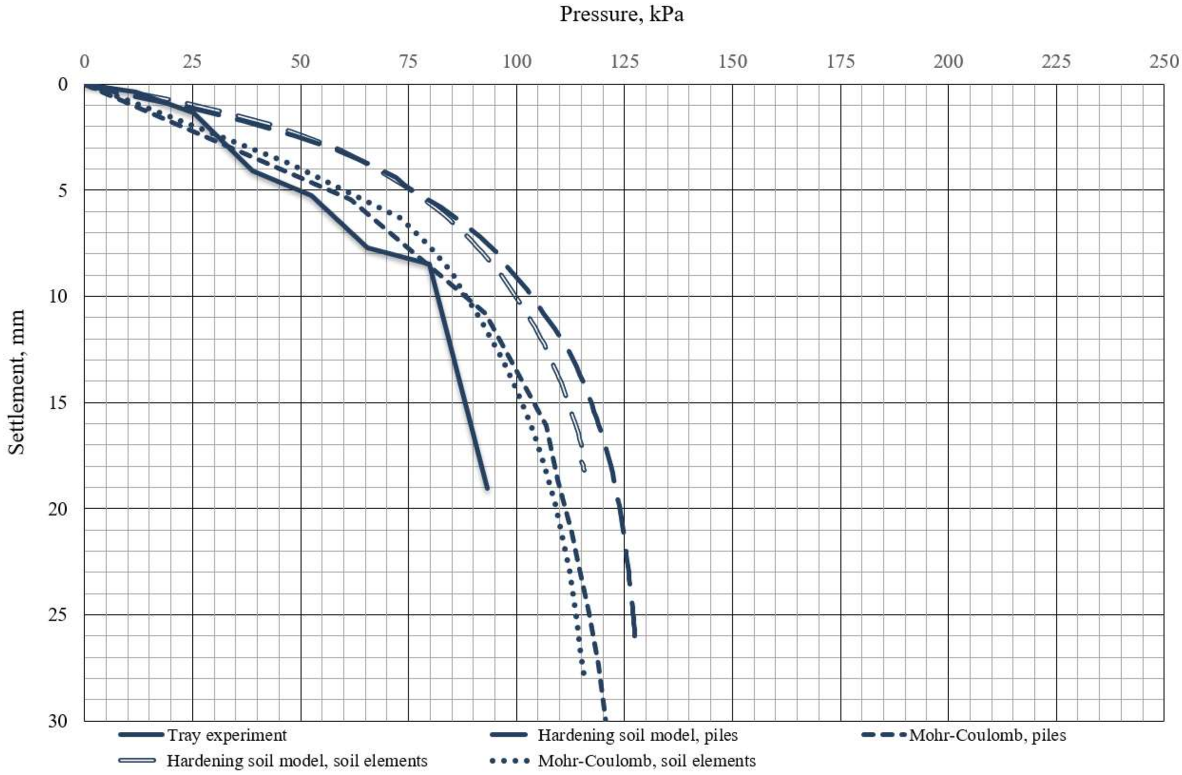

Figure 4 – Results of the tray experiment and the FEM numerical modeling in 3D setting of stamp tests of unreinforced soil base in a tray

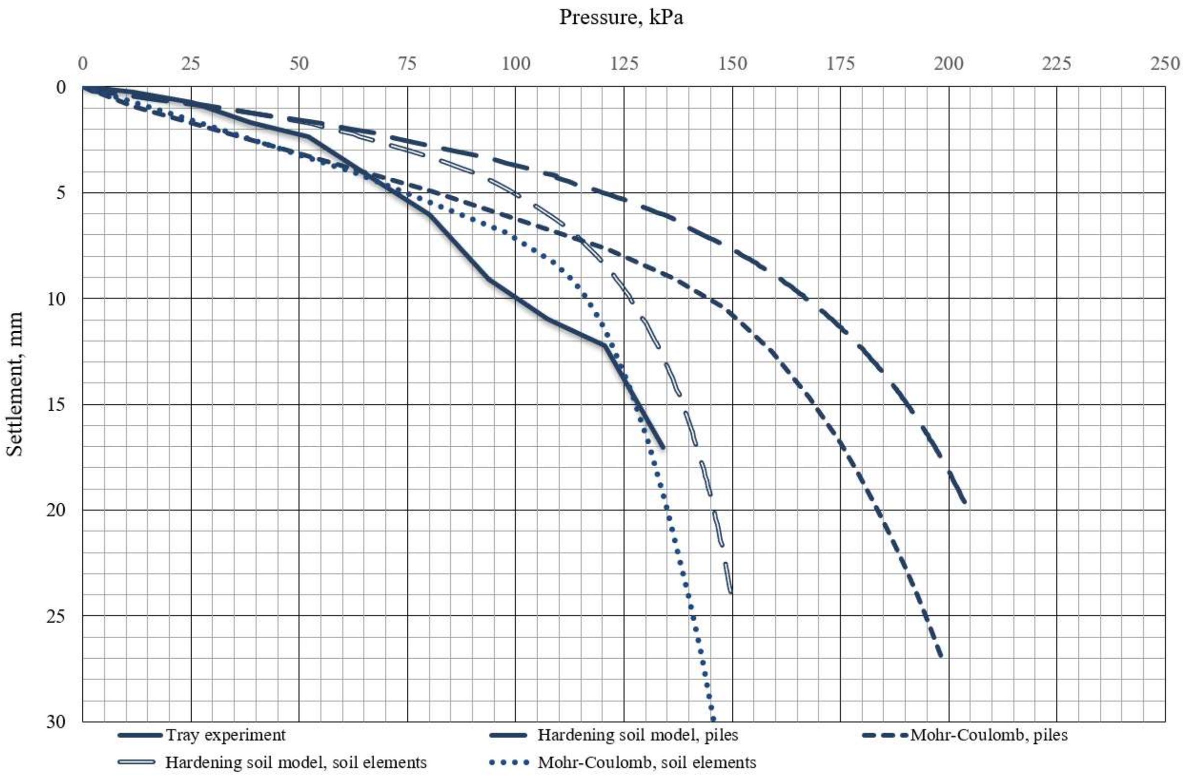

Figure 5 – Results of the tray experiment and the FEM numerical modeling in 3D setting of stamp tests of soil base in a tray with a reinforcement percentage of 2.1%

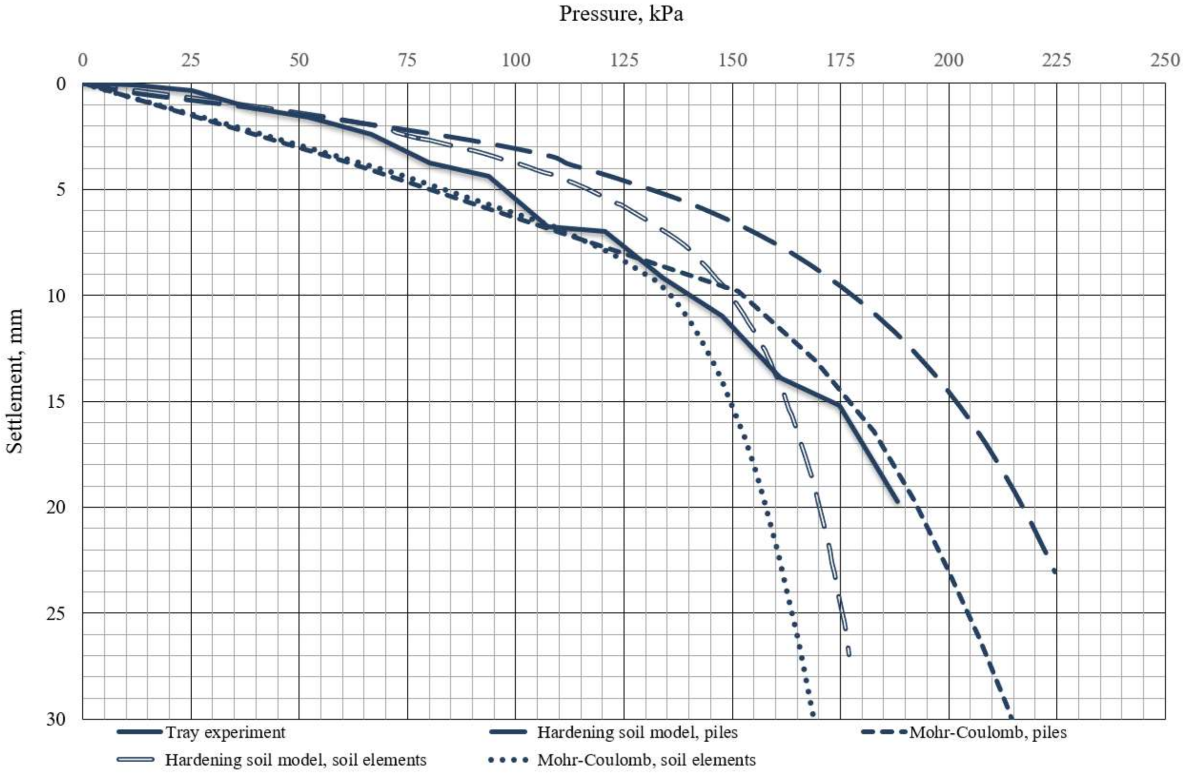

Figure 6 – Results of the tray experiment and the FEM numerical modeling in 3D setting of stamp tests of soil base in a tray with a reinforcement percentage of 4.4%

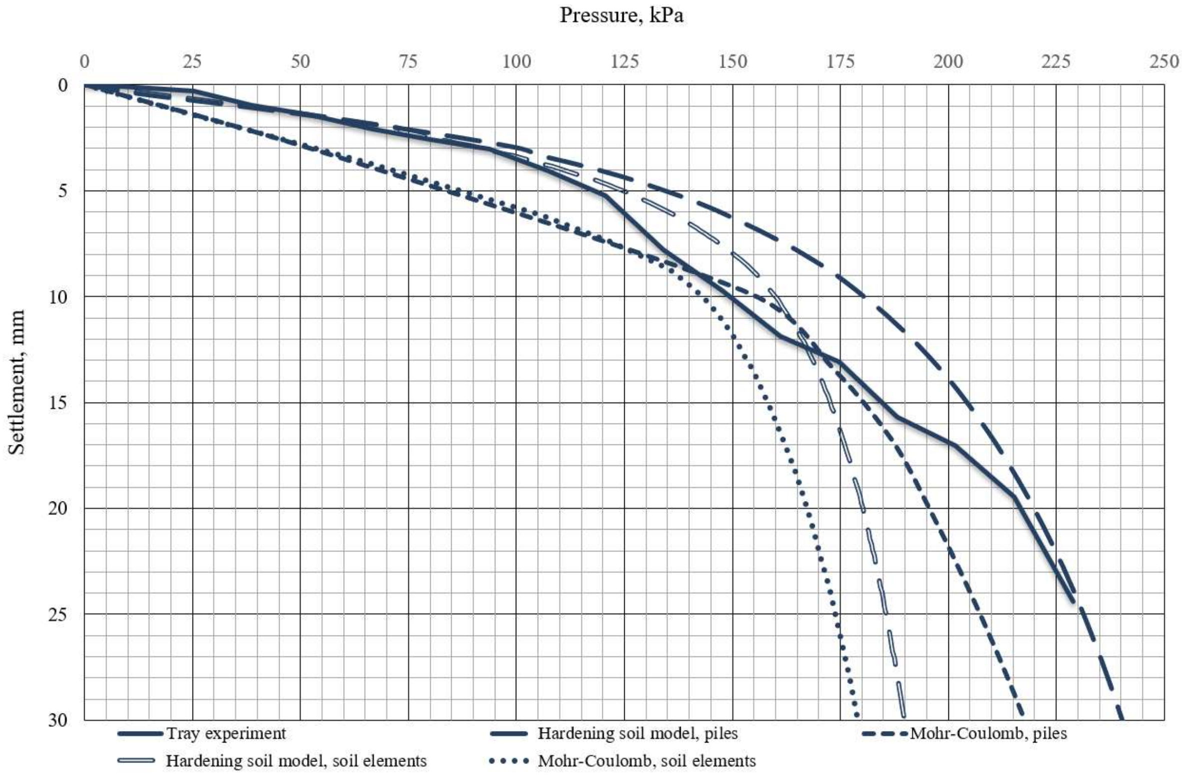

Figure 7 – Results of the tray experiment and the FEM numerical modeling in 3D setting of stamp tests of soil base in a tray with a reinforcement percentage of 7.1%

In fig. 4 – 7 compared graphs obtained experimentally and numerical modeling according to the MC and HSM models for unreinforced stamp base and reinforced bases with reinforcement percentages of 2.1%; 4.4%; 7.1%. For the possibility of evaluating the reliability of the results obtained by FEM modeling in a 3D setting in fig. 4 – 7 also shown the graphs of the experimental tray research.

In particular, these graphs demonstrate a sufficiently high correspondence between the tray and theoretical dependences when using the values of soil specific adhesion previously obtained by the authors [9] according to formulas based on the known theoretical solution [1] for the second critical pressure of the soil.

Comparing the work of the soil in the linear (elastic) stage until the moment of reaching the first critical pressure, it is clearly observed that for HSM the coincidence is almost perfect both for modeling with volumetric elements and for pile elements. According to the Mohr-Coulomb model in the same stage of soil work, FEM modeling in 3D overestimates subsidence. At the same time, the linear dependence for this model of soil behavior is longer, as it should be theoretically.

Note that the Mohr-Coulomb models correspond to the unlimited development of deformations even beyond the second critical pressure while the HSM models of isotropic compaction correspond to the exhaustion of the bearing capacity of the soil when the second critical pressure is reached, for which the strength characteristics were actually determined.

If we compare the settlements results after the first critical pressure is reached and the transition from elastic to plastic behavior of the soil – FEM modeling in 3D setting with pile elements slightly underestimates the settlement of the base of rigid stamps.

In general, all four options sufficiently adequately describe the behavior of the soil during the tray static experiment under rigid strip stamp. On the experimental graph, there are areas that deviate from the ideal elastic-plastic dependences of the tested soil behavior models. These effects can be explained by the different duration of action of the pressure levels during the tests, the difficulty of obtaining a homogeneous soil paste on the entire height of the tray, etc.

Conclusions

Thus, analyzing the obtained dependences it is possible to conclude about the correctness of the application of the considered soil models for predicting the settlements of weak clay soil bases reinforced with vertical SCE under strip foundations (in the tray experiment – with rigid strip stamps).

So, by comparing the data of 3D FEM simulation using the Mohr-Coulomb and Hardening soil behavior models of the deformed state of the unreinforced and reinforced with vertical SCE clay bases of the rigid strip stamp, as well as with the results of settlements of this stamp during the tray experiment, the following was established:

1. The correctness of the SC Plaxis 3D results of modeling when applying the Mohr-Coulomb elasto-plastic model and the isotropic compaction (hardening) model for the analysis of the deformed state of the system "soil massif – soil-cement base – rigid strip stamp" has been proven.

2. It is recommended for further practical use in geotechnical practice the Hardening soil model as more correct in the linear stage of soil work, and for the modeling of SCE to use volumetric elements as more reliable.

3. The adequacy of the description of soil behavior according to all models of soil behavior and SCE modeling analyzed in this work, at least, when performing approximate engineering calculations, was confirmed.

4. The effectiveness of the method of reinforcing foundations with vertical SCE for improving bases made of soils with a low deformation modulus has been confirmed.

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