International Journal of Engineering & Technology, 7 (4.8) (2018) 48-52

International Journal of Engineering & Technology

Website:www.sciencepubco.com/index.php/IJET

Research paper

Deformation Modeling of Pyramidal Piles Base at Petroleum Industry Facilities

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Abstract

Utilizing the comparison of results of mathematical modeling by the finite element method and from the field and laboratory studies, it has been determined that the compaction zone diameter of the short pyramidal piles by the exponential function is impacted by the internal friction angle of a soil. Within the limits of the axisymmetric spatial problem, the task was solved in a geometrically non-linear setting. It has been proved that utilizing the 8-nodal iso-parametric axisymmetric finite elements allows using both rectangular and curvilinear finite element grid. The elements varied in shape and volume, and accounting for these variations enables determining the displacements, stresses, and described soil properties at each stage of the piles' construction (or a cone head digging-in). It also has been established that the natural soil properties and geometrical size of operating devices do not have a significant influence on the modeling accuracy.

Keywords: *soil, cone head, penetration, influence zone, short pyramidal pile, finite element method, axisymmetric problem.*

1. Introduction

It has been experimentally established that the regularities of the interaction of foundations with a densified base during creation and operation are determined by the natural state of the massif, the structural and technological parameters of its construction and the conditions of operation [1, 2]. Empirical and theoretical methods for determining the parameters of densified zones are sufficiently precise for certain types of foundations and artificial bases but are not universal. A more general methodology should be applied with the use of mathematical modeling taking into account the features of compaction methods. Finite Element Method (FEM) is better suited for problems with the developed heterogeneity of characteristics [3, 4].

The possibility of obtaining the above-mentioned characteristics of the environment after the formation of foundations (piles) in it and foundations with a consolidation of soil opens the simulation of fast-moving processes, which include various technologies of soil consolidation. The greatest difficulties of numerical studies are related to [4 - 14]:

- considerable physical nonlinearity (mainly, compressibility) of soils, caused by the problems of accounting for the nature and speed of its loading. It complicates the choice of an adequate phenomenological model of the mechanical behavior of the environment, and hence the relatively simple (preferably - laboratory) method of determining its parameters;
- significant geometric nonlinearity (large irreversible deformations and local displacement of soils), through which the numerical implementation of tasks is accompanied by a significant distortion of the finite elemental grid, hence the need for its irregular rearrangement, which creates technical difficulties and increases the errors of numerical solutions;
- an unknown contact area of the working body (piles, foundations) with the soil.

For these reasons, solutions based on the traditional geomechanics of small deformations, are largely unsuitable for the simulation of rapid processes. Thus, the question of a universal method is not resolved for modeling the latter in soils. Usually, they are modeled by FEM within the axisymmetric spatial problem [4].

The numerical solutions of the spatial problems of the FEM with the use of elastic-plastic soil models to some extent adequately reflect the stress-strain state (SSS) of the massifs when they are located in separate types of foundations (piles) with a compaction of soil, including obtaining the indicated density and porosity of soils [4 - 14].

The most common class of bases and foundations that cause the removal of soil from the working body or foundation in different directions [4], in particular, include short pyramidal piles. Because of the abundance of types and standard sizes of these foundations, soil conditions of its application at the objects of the oil and gas industry, the use of analytical methods for their calculation is associated with certain assumptions, and therefore - errors. Every time there is a need for experimental substantiation of the project variant, which increases its cost.

Under these conditions, it is advisable to use mathematical modeling of the processes of arrangement and subsequent work of such bases and foundations using the software complex "PRIZ-Pile" [4, 15 - 17], in which the solution of the axisymmetric problem of FEM by stepwise-iterative methods in a physical and geometrically nonlinear formulation is realized. Utilizing the 8-nodal iso-parametric axisymmetric finite elements allows using both rectangular and curvilinear finite element grid. The elements varied in shape and volume, and accounting for these variations allows determining the displacements, stresses, and described soil properties at each stage of the piles' construction. The simulation of the base of foundations (piles) consists in the task of moving the nodes of a finite elements grid of with the estimation of the SSS of the massif. At the stage of its operation, the further consolidation of the soil, its transition into the plastic state, the possibility of slipping the lateral surface of the foundation on the soil are taken into account.

The purpose of the work is to determine the simulation features of SSS of short pyramidal piles bases, by comparing their results with the corresponding experimental research.

2. Main Body

2.1. Calculation scheme and its numerical realization

Creating the bases and foundations of the class "The work of the soil with the possibility of squeezing out of the working body or foundation in different directions" is modelled by the task of forced displacement of soil in various directions [4, 16]. The task of immersing (pushing) a standard conic penetration tip into the soil was adopted as a test [17].

The methodology of laboratory research on soil SSS from squeezing of the conical tip in it is based on the effect of the walls of the ring during penetration tests. The effect is that when immersing a conical tip, bounded by a metal ring, into a soil the invariance of penetration resistance q ($q=F/h^2$, where F is a penetration force, h is an emersion depth of a conical tip) is violated (sharply increases) on a certain depth h_k ("characteristic" or so-called "critical") for clays or penetration indicator U ($U=F/h^3$) for sands, which definitely indicates that the border of the conical tip influence zone has reached the ring wall.

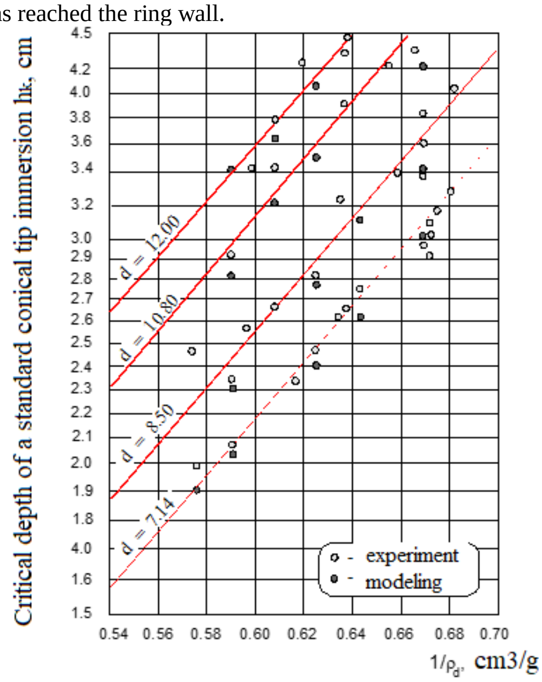

Fig. 1: Comparison of experimental and simulated correlation graphs $h_k = f(1/\rho_d; d_k)$

The studies included several series of penetration tests with the laboratory penetrometer LP-1 with a conical tip, which had an opening angle at the top $\beta = 30^\circ$ and height of h_{con}= 6.0 cm. The studies were conducted on the fine dry sand of disturbed structure laid and compacted ($\rho_d = 1.50 \ldots 1.75$ g/cm3) into the rings with the diameter of d=7.14; 8.50; 10.80; 12.00 cm. There was established a correlation between h_k and d and the characteristic of the soil density $1/\rho_d$: $h_k = f(1/\rho_d;\ d_k)$. The critical depth value h_k was increasing with the increase of d and decreasing of ρ_d. That is the "influence zone" diameter increased in denser soils. After structuring the research results into "lg h_k – $1/\rho_d$" chart, the following correlation was obtained (fig. 1).

The graph is described analytically by the formula:

$$1/\rho_{d\,i} = 1/\rho_{d\,0} + 1/\alpha \cdot \lg\left(h_{k\,i}/h_{k\,0}\right) \qquad (1)$$

where $1/\rho_{d0}$ and h_{k0} are the coordinates of the boundary point on the line; $1/\alpha$ is angular coefficient of linear equation.

In simulating the task of injecting into the soil of the described tip, the calculated region was taken as a cylinder with a diameter equal to the inner diameter of the ring and a height of 60 mm. Number of rectangular FE is 108 (9x12) and 367permanent nodes and varying number of fixed nodes (48…58) in each calculation scheme. The height of all FE is constant – 5 mm. The width of FE that are directly adjacent to the vertical axis is 10…22 mm, the width of all the other FE is 3…5 mm (constant for each scheme).

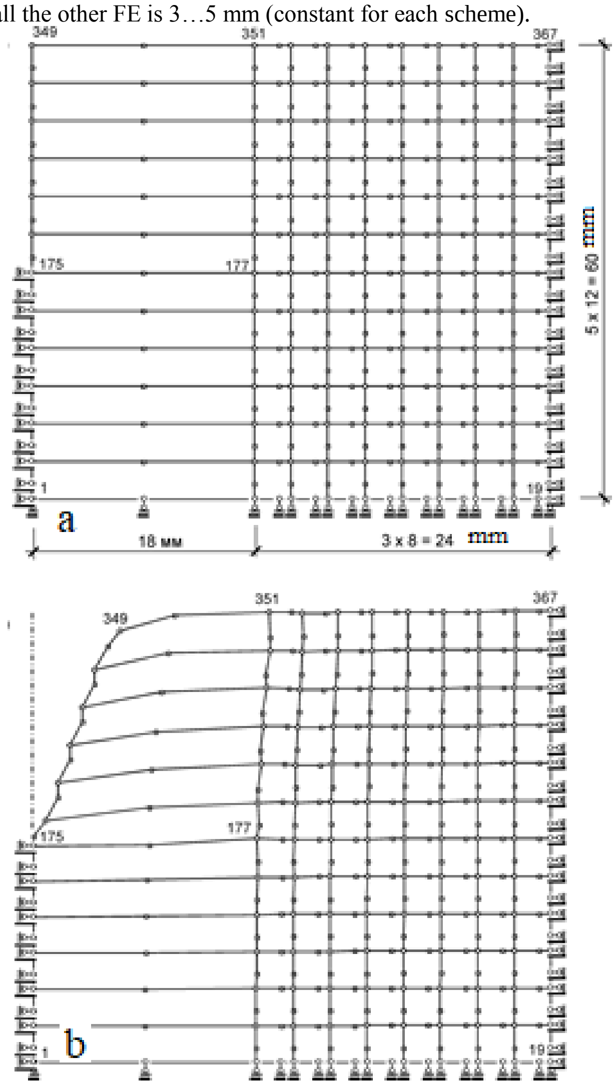

Fig. 2: An example of the calculation schemes of the ITU of the problem of immersion into the ground of a conical tip (d=8.50 cm; ρ_d =1.5 g/cm^3; h_k = 3.6 cm): a – initial; b – deformed

An example of the characteristic (d=8.5 cm, ρ_d =1.5 g/cm^3) initial calculation scheme for the problem of immersion of conical tip into a soil is shown in figure 2, a. Horizontal and vertical forced displacements were set only for the nodes of the FE network, which lie on the vertical axis of the symmetry of the calculated area. The scheme of soil deformation from the conical tip immersion (when h_k=3.6 cm) is shown in figure 2, b.

Examples of isolines of horizontal and vertical displacements of soil, based on the data of this example of the mathematical modelling of injecting a penetration tip into it, are shown in Figure 3, and an example of consolidating the soil around this cone is shown in Figure 4.

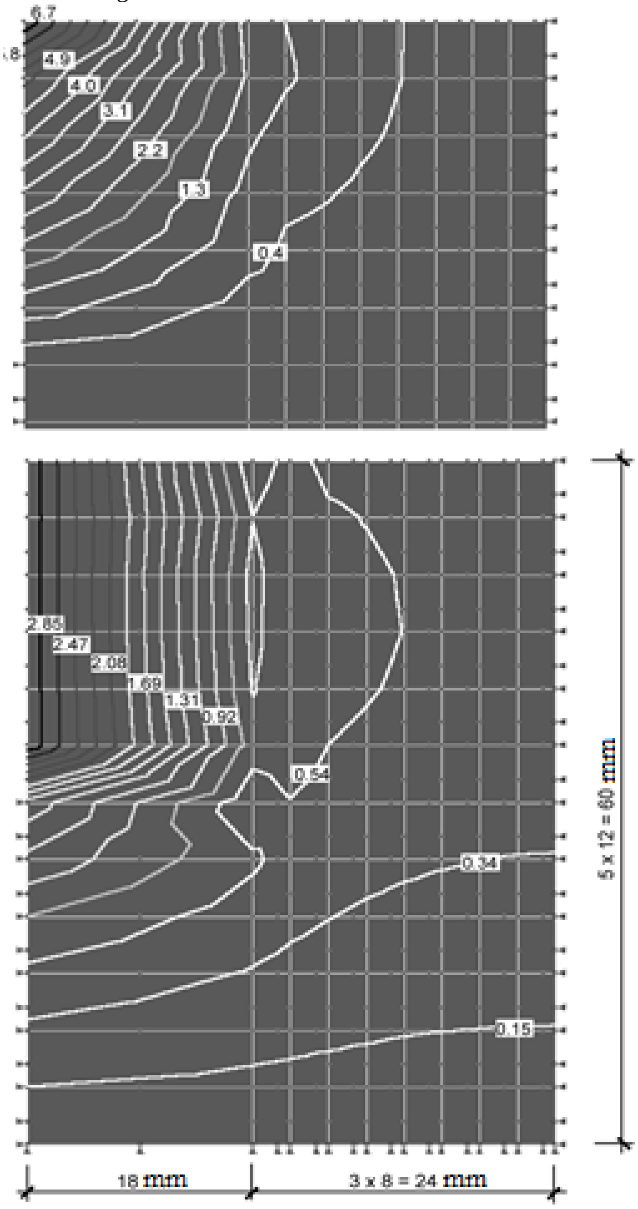

Fig. 3: Isolations of soil movements in a ring with a diameter of d=8.5 cm from immersion of the penetration tip for modelling: a - in the horizontal; b - in the vertical direction

From the last figure, in particular, one can see that:
– the maximum value of the density of the dry ground 1.8 g / cm^3 is fixed at the lateral surface of the cone. With the distance from it, the consolidation of the soil decreases with a certain dependence;
– compared to the original value of ρ_d on the boundary with the wall of the ring increased by 0.02 g / cm^3, which is usually taken beyond the boundary of the distribution zone of the seal. That is, by modelling it is possible to determine the size of the "zone of influence" from the immersion of the tip into the soil.
Comparison of experimental and simulated graphs $h_k=f(1/\rho_d; d_k)$ is given in Figure 1. We have a satisfactory convergence of the simulated and experimental values of the critical depth h_k of immersion of the tip (the relative difference does not exceed 7%), although almost always the measured values were less than those obtained in the experiment.

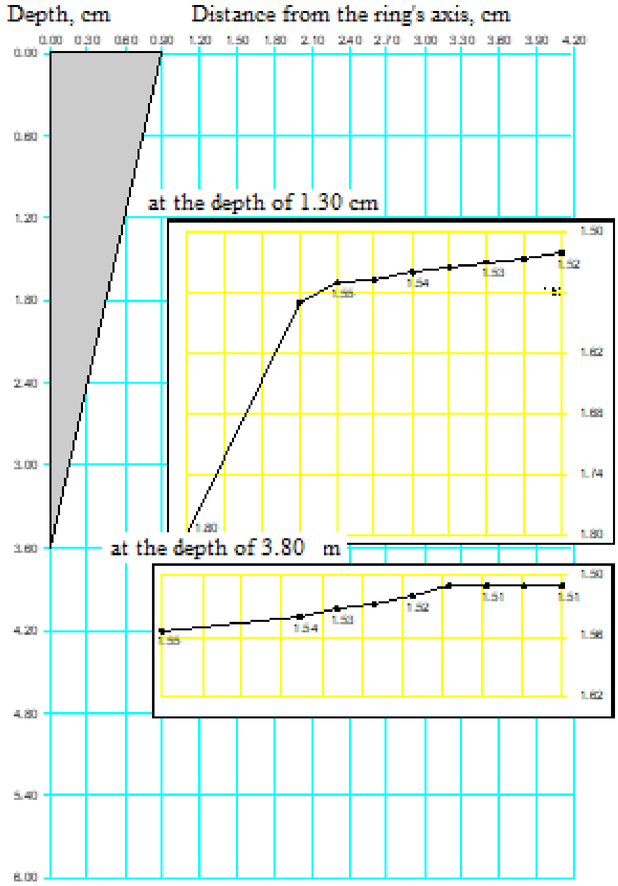

Fig. 4: Sealing the sand of the disturbed structure, enclosed and compacted to ρ_d =1.5 g/cm^3 in a ring with the diameter of d = 8.5 cm, as a result of immersion of the conical tip to the depth of h_k = 3.6 cm according to the modelling results

2.2. Driven short pyramidal piles

As it was experimentally established, the short pyramidal piles of square cross-section (with the maximum head size of 90x90 cm and the tip size of 7x7, 10x10 cm) and a length of 1.5 – 4.0 m with the angle between the vertical axis and the side surface $\alpha = 4 \ldots 12.5^\circ$, due to the considerable conicity of the shaft, short pyramidal piles, when immersed, form a more developed zone of compacted soil around the lateral surface compared to the piles of uniform cross-section.
The compacted area under the tip of the pyramidal (conical) piles does not exceed 10 - 20 cm, which is significantly less than for piles with a uniform cross section.
Simulation features of the pyramidal piles immersion are as follows:
– the calculated area combines the lower cylinder and the upper cut cone;
– the original form of finite elements is not only rectangular but also rectangular trapezoidal and parallelogram;
– the forced displacements direction of the pile’s axial nods of the finite element grid are usually taken perpendicular to a side surface of the pile.
The example of a base deformation scheme from a short pyramidal pile driving is given in Figure 5. The site consists of a loess loam with a natural density of a dry soil ρ_d=1.44 g/cm^3. A short pyramidal pile 40 by 40 cm in top and 7 by 7 cm in the bottom surface was driven to the depth of 134.6 cm. The initial calculation scheme included 200 FE (rectangular from 0.1 by 0.2 to 0.4 by 0.4 m in size, rectangular trapezoid from 0.1 by 0.2 to 0.357 by 0.2 m in size, and parallelogram from 0.1 by 0.2 to 0.4 by 0.2 m in size) and 661 nods 87 of which were fixed ones.

The maximum horizontal forced displacements of FEM grid nods on the vertical symmetry axis of a calculation area were set to be 200 mm for nod 641, and minimal displacements were 35 mm for nod 417 (fig. 5).

The soil displacements isolines are presented in figure 6 according to the pyramidal pile driving simulation. The displacements range from 9 to 172 mm in the horizontal direction (the maximum displacements are registered around the pile head) and in the vertical direction the displacements range from 5 to 95 mm (the highest concentration of displacements was registered under the pile bottom).

The analysis of soil compaction modeling around the pile surface and the field observations reveal its satisfactory similarity (fig. 7).

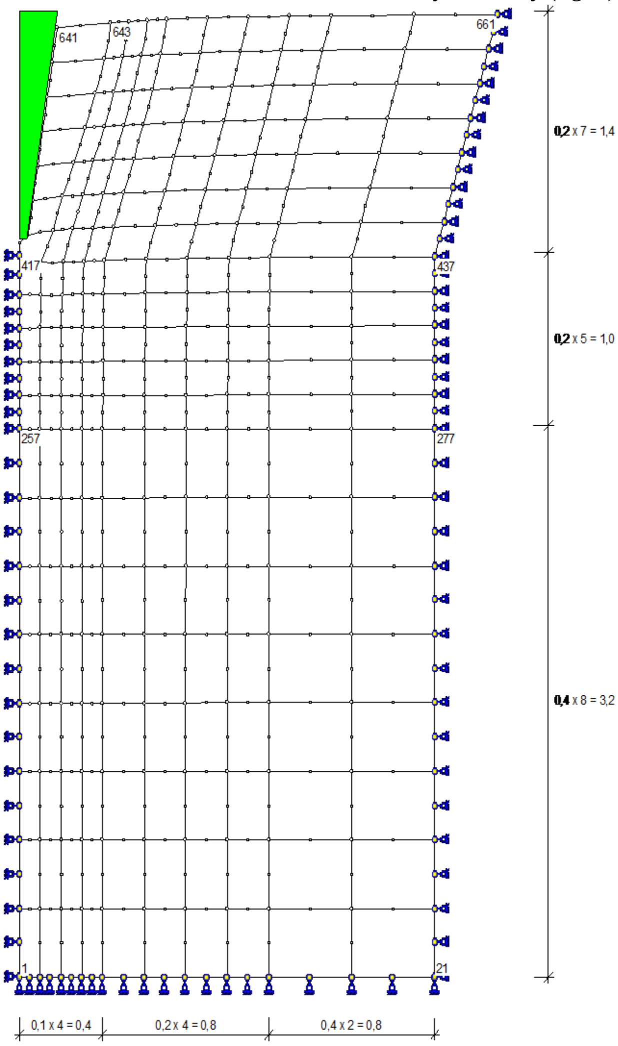

Fig. 5: The base deformation scheme caused by the short pyramidal pile driving according to the simulation data

The conventionally simulated values of a dry soil density are slightly higher than the ones of experimental analogs at the side surface of a pile (within a "soil jacket"). The opposite situation is observed at a distance of b…2b (where b stands for the cross section diameter at a particular depth) from the vertical axis of the pile. The further results of the mathematical and field experiments are virtually similar.

The parameters of densified zones around short pyramidal piles of various sizes in sandy and clay soils were compared based on modelling data and field experiments.

The latter were obtained by the methods of penetration, static soil probing with the expanded cone and cutting rings.

The analysis of numerical simulation data and field results on the parameters of soil sufficient compaction zone D around the short pyramidal piles are summarized in table 1 and figure 7. In addition, the D/b_p ratio correlates with the soil internal friction angle φ by the exponential function. The $D/b_p = f(\varphi)$ function is given by the following expression for simulation results:

$$D/b_p = 1.58 \cdot \exp(0.023 \cdot \varphi) \quad (2)$$

where the correlation index is r=0.92 and variation coefficient is V=0.07. The relative error between the data of modeling and physical measurements (Table 1) usually does not exceed 6% and only in two cases is slightly more than 10%, that is, we have a completely satisfactory convergence.

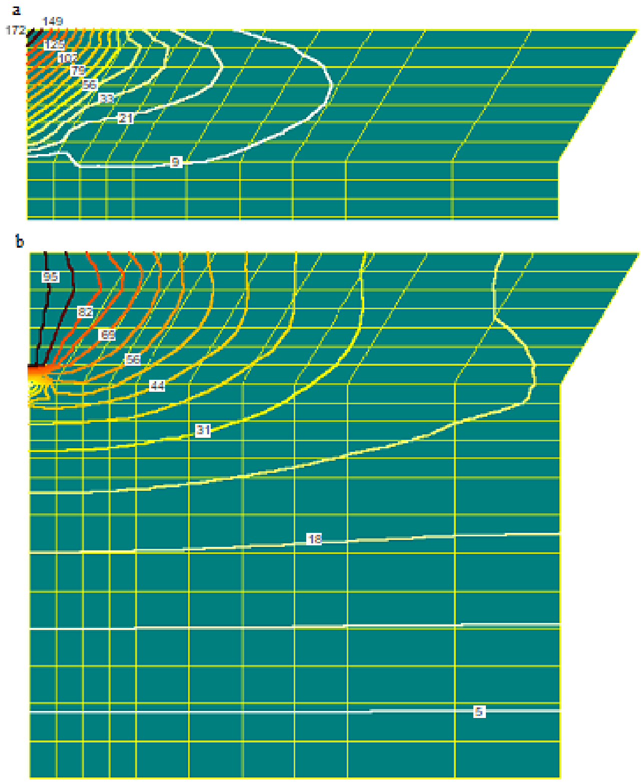

Fig. 6: Isolines of soil displacements caused by the short pyramidal pile driving according to the simulation data: a – in horizontal direction; b – in vertical direction

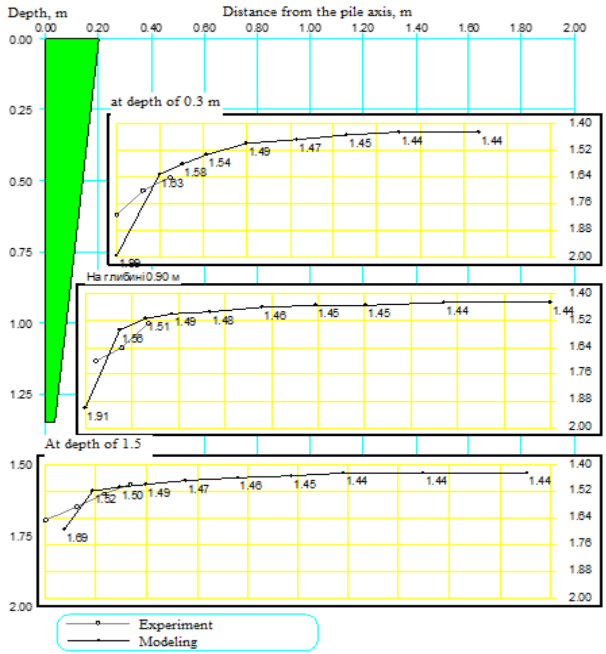

Fig. 7: The comparison of the soil density ρ_d around the pyramidal pile according to simulation and field experiment

Consequently, in numerical simulation, the values of the soil characteristics around the short pyramidal pile are significantly influenced by the natural density of the soil and the geometric parameters of the pile.

Table 1: Comparison results of simulation and field data on the compaction zones size for short pyramidal piles

#	Soil and pile parameters					D, m		D/b_p		relative error δ, %
	ρ_d, g/cm^3	φ °	b_p, m	h, m	α°	sim.	field	sim.	field	
1	1.35	22	0.8	1.6	12.5	2.025	1.96	2.53	2.45	-3.16
2	1.355	22	0.8	3.6	5.55	2.08	2.20	2.60	2.75	5.45
3	1.355	22	0.8	3.6	5.55	1.92	2.20	2.40	2.75	12.73
4	1.355	22	0.9	2.0	11.3	2.23	2.36	2.48	2.62	5.34
5	1.355	22	0.9	2.0	11.3	2.29	2.36	2.54	2.62	3.05
6	1.53	30	0.7	2.0	9	2.24	2.30	3.20	3.29	2.74
7	1.505	34	0.67	1.9	9	2.12	2.10	3.16	3.13	-0.95
8	1.59	36	0.7	2.0	9	2.36	2.64	3.37	3.77	10.61

The comparison of compacted areas sizes around the piles with a constant section of the shaft reveal that conical piles with a small angle of conicality and short pyramidal piles has shown that at close transverse dimensions, the diameter of compacted zones increases with the increase of the angle of the conical pile and the angle of internal friction of the soil, and the height of these zones under the pile edge, on the contrary, decreases with the increase of the angle of the conical pile.

3. Conclusions

Thus, it is proved that the reliability of the solutions obtained by modeling is ensured by the properties of finite elements, the size of the calculated area, the choice of computational schemes of soil compaction, and compliance with the parameters of the soil state model. The convergence of mathematical and physical experiments in determining the zones of deformation and compaction and the indicated parameters of the soil is significantly influenced by: adequacy of the design scheme to the actual work of the soil in the massif during the piling (or immersion of a conical tips); model parameter describing changes in the deformation module depending on the porosity change in the soil and the pressure transfer rate. The natural characteristics of the soil and the geometric dimensions of the piles (conical tips) do not significantly affect the accuracy of the modeling.

It has been established that the above-mentioned soil parameters, the compaction zones sizes, and the base deformation are influenced by all four factors of the previous conclusion. In particular, the sufficient compaction zone size of the short pyramidal pile depends on the internal friction angle of the soil and the base area.

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