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Nonlinear numerical analysis of foundations on basis of plate load test results

Analyse numérique non linéaire des fondations sur la base du résultat du test de charge sur plaque

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ABSTRACT: The nonlinear analysis method for shallow foundations is presented in the article. The study of more than 50 results of plate load tests on sandy and clayey soils allow the improvment of the settlement computation of the shallow foundation by the numerical method with the nonlinear dependence between stresses and deformations. Comparison of calculation data with the field test results showed that the proposed nonlinear numerical method provides the necessary accuracy of settlement computation in the nonlinear range of stresses up to $0.5q_{ult}$ in sand and up to $0.6q_{ult}$ in clay. The proposed method of nonlinear settlement calculation significantly reduces the impact of the difference between the behaviour of real soil and the ideal material assumed in the theory on the accuracy of computation.

RÉSUMÉ: La méthode d'analyse non linéaire par approximation successive pour les fondations superficielles est présentée dans l`article. L'étude de plus de 50 résultats d'essais de plaques de charge sur sols sableux et argileux nous permet d'améliorer le calcul du tassement des fondations superficielles par la méthode numérique avec la dépendance non linéaire entre contraintes et déformations. La comparaison des données de calcul avec les résultats des tests sur le terrain a montré que la méthode numérique non linéaire proposée fournit la précision nécessaire pour le calcul du tassement dans la gamme non linéaire de contraintes allant jusqu'à 0,5 q_{ult} dans le sable et jusqu'à 0,6 q_{ult} dans l'argile. La méthode proposée de calcul du tassement non linéaire réduit l'influence significative des différences entre le comportement du sol réel et le matériau idéal supposé dans la théorie.

Keywords: Shallow foundation; nonlinear numerical analysis; plate load test.

1 NONLINEAR COMPUTATION OF SHALLOW FOUNDATION

In theory, the key point in shallow foundation design is to determine the allowable bearing capacity based on the ultimate bearing capacity and settlements of the footing, and the calculated settlement is usually the determining factor. In fact, the task is to determine the required range of bearing capacity as the difference between the ultimate bearing capacity and the allowable bearing capacity. This is essentially the reserve bearing capacity of the foundation, which is the main determinant of the safety of the foundation design. However, foundation construction costs are significant, so the value of the reserve bearing capacity of the foundation directly affects the economic efficiency of construction, especially in difficult soils. The analyses carried out show that application of non-linear methods of settlement calculation and, as a consequence, justified increase of loads on spread footings from 1 m to 5 m in width and from 1 m to 5 m in depth on sand and clay contributes to cost savings ranging from 12 to 47%. Footings of medium dimensions (from 2 m to 3 m in width) rested on medium dense sand and stiff cohesive soils have greater cost savings than footings of larger and smaller dimensions (Kirichek and Tregub, 2015).

1.1 The purpose of the research

A reliable nonlinear method for computing the settlement of shallow foundation makes it possible to reasonably reduce the reserve bearing capacity of the foundation, which allows reducing the cost of construction with guaranteed reliability of the foundation. The purpose of this research is to improve the settlement computation process of the shallow foundation by the mixed numerical-experimental technique with the nonlinear dependence between loads and deformations.

1.2 Accuracy assessment of engineering nonlinear settlement methods

The nonlinear calculation methods of spread footings based on experimental studies of settlements had recently been developed by many authors, and this paper has used the results of some plate load tests: Cimbal and Sheikhnazari (2011), Kusner (2008), Klepikov (1996), Malyshev (1982, 1996), Shvets (2002) and Timchenko (2009). The size of the plates allows the plate load tests to be considered as full scale load tests, and field test results from real sites have also been used.

The computed settlements based on engineering methods were compared with the test results on sandy and clayey soils. Figure 1 shows a comparison of the results of the settlement calculation according to the nonlinear models and PLAXIS with the results of full scale load test on dense silty sand f`=36˚, c`=10kPa, E=34.7 MPa, γ=16.6 кN/m^3, R=0.53 MPa, P_u=4.65 MPa, (Kushner, 2008) and Figure 2 for full scale test on stiff loam, f`=23˚, c`=43 kPa, E=19MPa, γ=18.7kN/m^3, R=0.54 MPa, Pu=1.09 MPa, (Klepikov, 1996).

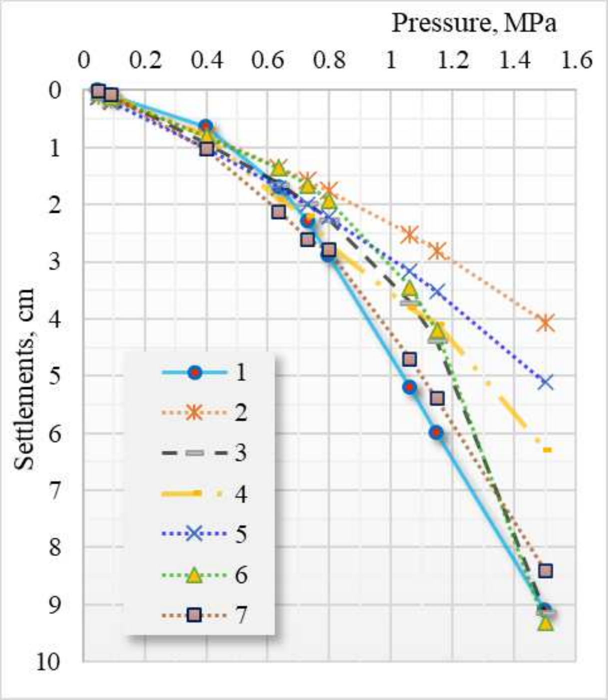

Figure 1. Comparison of computed settlements and test result for the plate of 1x1m, and 2.2 m depth on dense silty sand: 1 - the test; 2 - Klepikov's method; 3 - Malyshev's method (1982); 4 - Kushner's method; 5 - Popov's method; 6 - Malyshev's method (1996); 7 – PLAXIS 3D.

The results of numerical modelling of settlements in PLAXIS 3D of the considered experimental foundations at the applied pressure on the soil $R<P<P_u$ corresponding to the nonlinear deformation stage are shown in Figures 3 and 4, where R (MPa) is the computed resistance of the foundation according to Ukrainian State Building Standard DBN V.2.1-2018, as linear limit in the applied pressure-settlement relationship and P_u is the ultimate bearing capacity (MPa).

The considered nonlinear models for calculating settlements were applied to homogeneous soil massifs within the depth of soil deformation zones, which, according to the results of calculations in Figures 3 and 4, ranged from 2.8B to 3.2B, where B is the width of the footings.

Engineering calculation methods showed a deviation of the calculated settlements from the test data of approximately 19% at the linear stage of settlement, and up to 45% beyond the linear stage of settlement as a function of load, with the error increasing as the load increases.

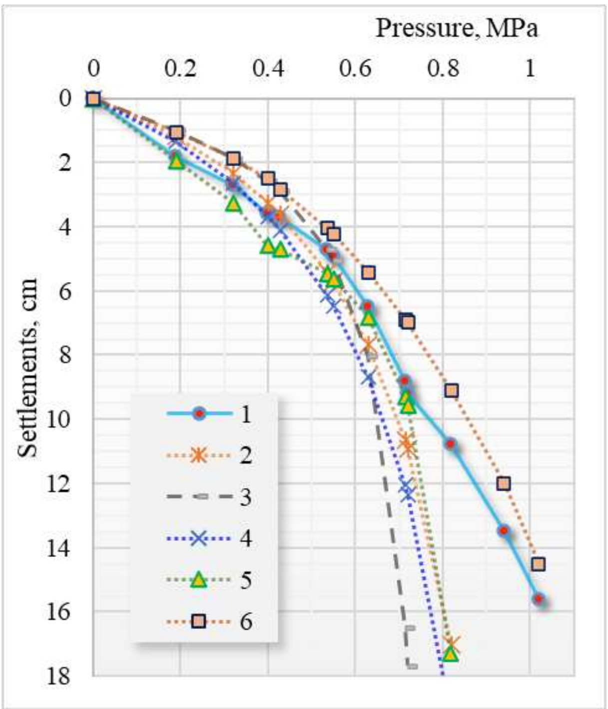

Figure 2. Comparison of computed settlements and test result for the plate of 1.4x1.6 m, and 0 m depth on stiff loam: 1 - the test; 2 - Klepikov's method; 3 - Malyshev's method (1982); 4 - Popov's metod; 5 - Malyshev's method (1996); 6 – PLAXIS 3D.

The calculation by the numerical finite element method in PLAXIS 3D using the the linear-elastic perfectly-plastic Mohr-Coulomb model showed the best convergence with the settlement curve of the full scale load test, compared to analytical methods. The deviation of PLAXIS 3D data from the full-scale settlement at pressures $R < P \leq 1.5R$ was 16-21%.

Insufficient accuracy of nonlinear methods for settlement calculations is obviously one of the reasons for limiting the loads on foundations to 1.2R in the State building codes of Ukraine. The engineering method of Malyshev (1996), which is an improvement of the previous method (1982), can be further developed by the use of the empirical relationship between settlements, loads, soil properties and foundation dimensions on the basis of the comparison of test results and calculated settlements with different nonlinearity parameters.

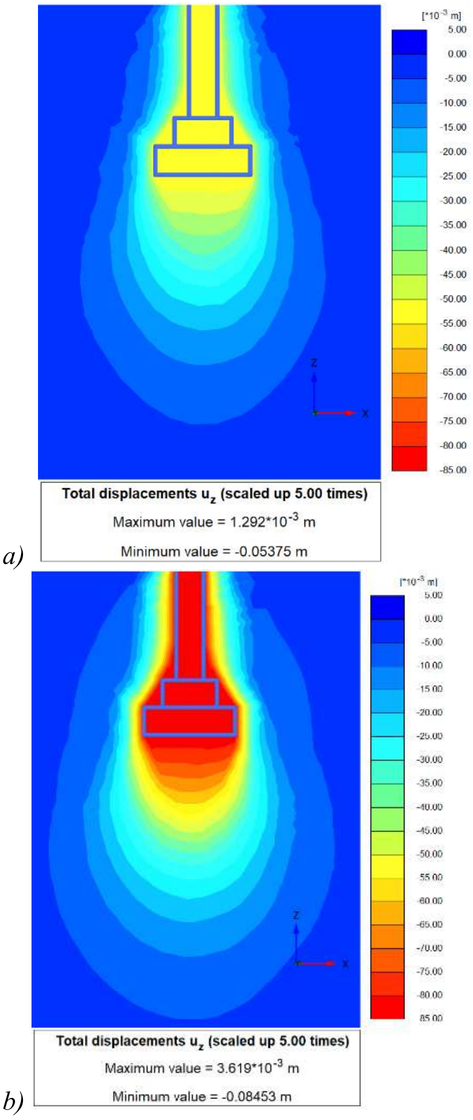

Figure 3. Numerical modelling of the settlement of 1x1m plate at the depth of 2.2m on dense silty sand:
a - pressure P=1.15 MPa, settlements S=5.4 cm; b - P=1.5 MPa, S=8.5 cm.

1.3 Improving the method of the nonlinear settlement computation

In this research, the use of the Malyshev (1996) method for calculating settlements with a non-linearity parameter has been substantiated. In order to make more rational use of the bearing capacity reserves of the shallow foundations in the design, it is necessary to obtain pressure-settlement dependencies from the full scale test data in the formula:

$$S = S_R\left\{1 + \left(\frac{P_u - R}{P_u - P}\right)^n \cdot \frac{P - R}{R - \sigma_{zg,0}}\right\} \qquad (1)$$

where S_R (cm) is the settlement of the footing under pressure corresponding to the computed resistance of the foundation R (MPa), as linear limit in the applied pressure-settlement relationship;

P is the applied pressure on the soil (MPa);

$\sigma_{zg,0}$ is overburden pressure (MPa);

n is a nonlinearity parameter which characterizes the nonlinear dependence of the settlement on the applied pressure, and which can be established empirically.

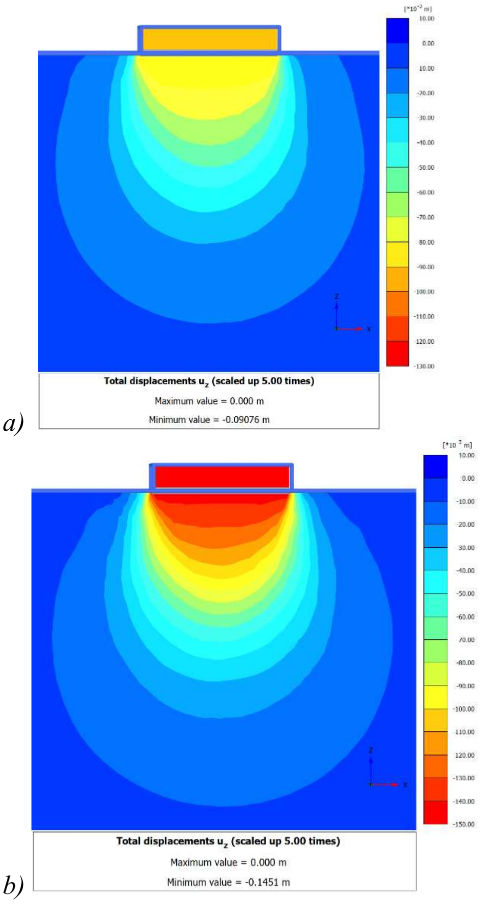

Figure 4. Numerical modelling of the settlement of 1.4x1.6 m plate at the depth of 0 m on stiff loam: a - P=0.82 MPa, S=9.1 cm; b - P=1.02 MPa, S=14.5 cm.

1.4 Determination of empirical parameters of the nonlinear model

The study of pressure-settlement curves for full scale load tests on different types of soil was carried out to determine the dependence of the nonlinearity parameter n on the characteristics of the foundations. The nonlinearity parameter values were determined by comparing the calculated settlements with the test results. In total, more than 50 data from field tests and full-scale load tests were examined. Some results presented in Figures 5-8 were used in the nonlinear model calculation.

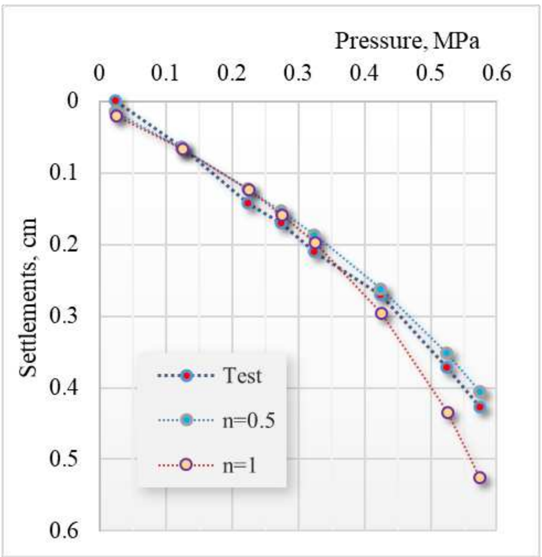

Figure 5. The nonlinearity parameter n for a round plate with diameter of 1 m, and 0.5 m depth on dense fine sand: f`=36*$^{0}$*, c`=4 kPa, E=86 MPa, γ=17.99kN/m^{3}*, n=0.5 (Shvetz, 2002).*

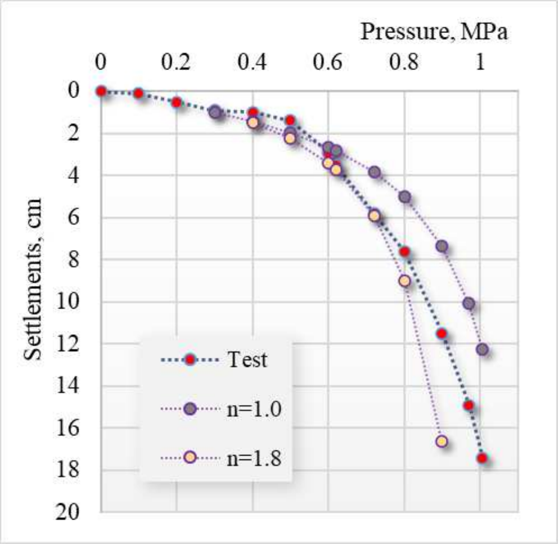

Figure 6. The nonlinearity parameter n for plate of 1.2 x 2.4 m and 0 m depth on semi-solid loam: f`=32.2, c`=20 kPa, γ=19.6 kN/m^{3}*, n=1.8 (Timchenko, 2009).*

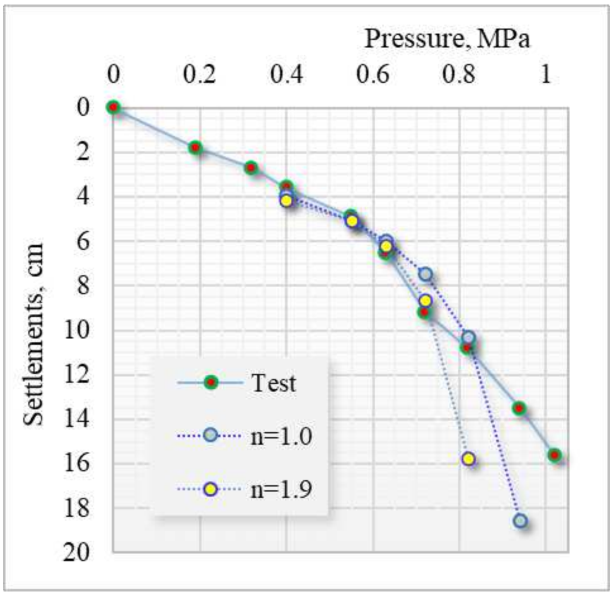

Figure 7. The nonlinear parameter n for the plate of 1.4 x 1.6m, and 0 m dept on semi-solid loam: f`=23*$^{0}$*, c`=43 kPa, E=13.1 MPa, γ=18.7 kN/m^{3}* n=1.9, (Klepikov, 1996).*

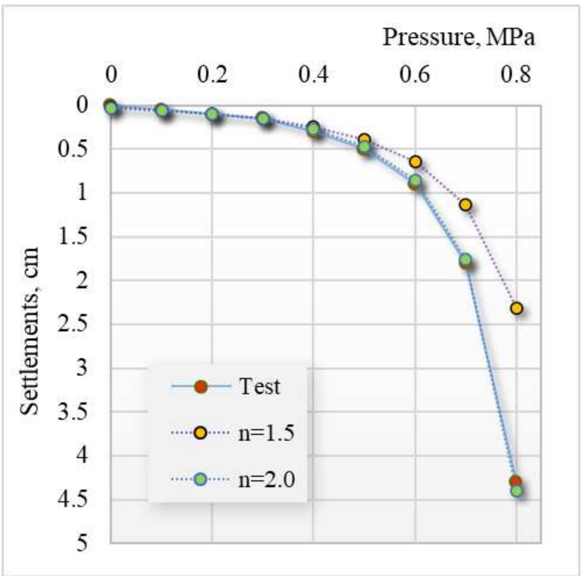

Figure 8. The nonlinearity parameter n for the plate of 1x1m, and 0.9 m depth on dense coarse sand: f=33^{0}*, E=20.7 MPa, γ=20 kN/m*^{3}*, n=2.0 (Cymbal, 2011).*

The factors influencing the adopted computational model were determined using the method of correlation analysis. On the basis of these data, regression equations were obtained that reflect the dependencies of the nonlinearity parameter n on the characteristics of the foundations and the relative foundation depth D/B. The non-linearity parameter equation was obtained:

$$n = -0{,}306 + 1{,}175\frac{P_u}{P_{u0}} + 0{,}177\frac{D}{B} -$$
$$-0{,}052\left(\frac{P_u}{P_{u0}}\right)^2 - 0{,}051\frac{P_u}{P_{u0}}\frac{D}{B} + 0{,}055\left(\frac{D}{B}\right)^2, \quad (2)$$

where: P_{u0}=1MPa;

D is footing depth;

B is footing width.

The determination coefficients of the equations were r^2 = 0.7 – 0.9, which indicates a sufficiently satisfactory agreement between the computed data and the field test results.

Figure 9 shows the dependences n=f(Pu, D/B), calculated using formulas (1, 2). It is noted that with an increase in the relative depth of foundation D/B and the value of the bearing capacity of the foundation, the nonlinearity parameter on the settlement-load diagrams increases.

Figures 10-13 show the results of comparing the calculated settlements according to the proposed nonlinear model for the calculation of settlements of spread foundations using the obtained empirical equation with the field data and full scale load test results on sandy and clayey soils.

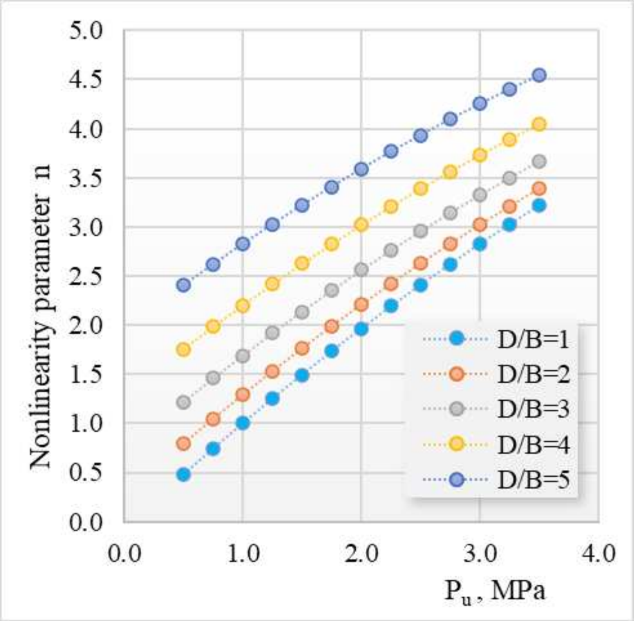

Figure 9. Dependences of the nonlinearity parameter n on the ratio of the depth of embedment to the width of the foundation D/B and the ultimate bearing capacity P_u.

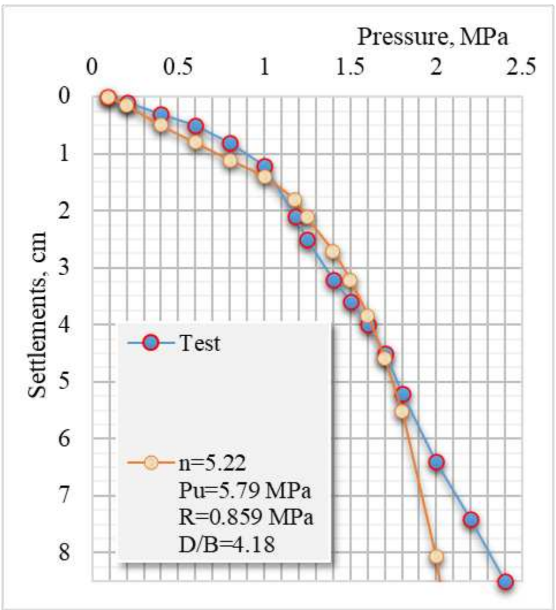

Figure 10. Comparison of computed settlements and full scale load test result for the plate of 1.0 x1.0 m, and 4.18 m depth on the medium dense silty sand: f`=37*$^{0}$*, c`=10kPa, E=53 MPa, γ=16.8 kN/m^{3} *(Kushner, 2008).*

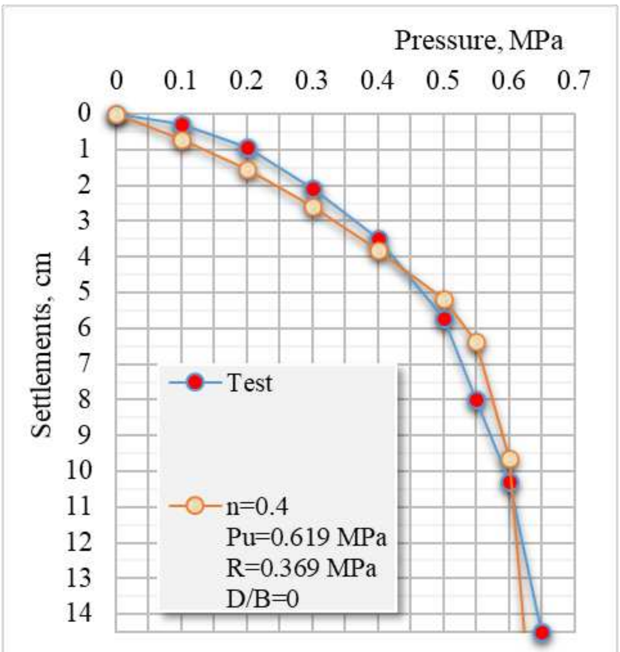

Figure 11.Comparison of computed settlements and field test result for the plate of 1.2 x 1.4 m, and 0 m depth on the firm clay: f`=24*$^{0}$*, c`=45 kPa, E=20 MPa, γ=19.6 kN/m^{3}*, (Timchenko, 2009).*

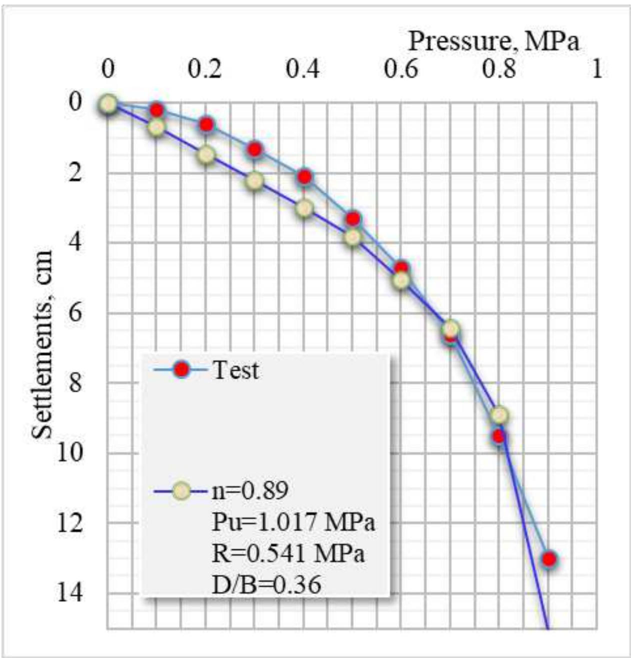

Figure 12. Comparison of computed settlements and field test result for the plate of 1.4 x 1.6 m, and 0.5 m depth on the stiff loam: $f`=27^{0}$, $c`=57$ kPa, E=24 MPa, $\gamma=19.8$ kN/m^{3} (Timchenko, 2009).

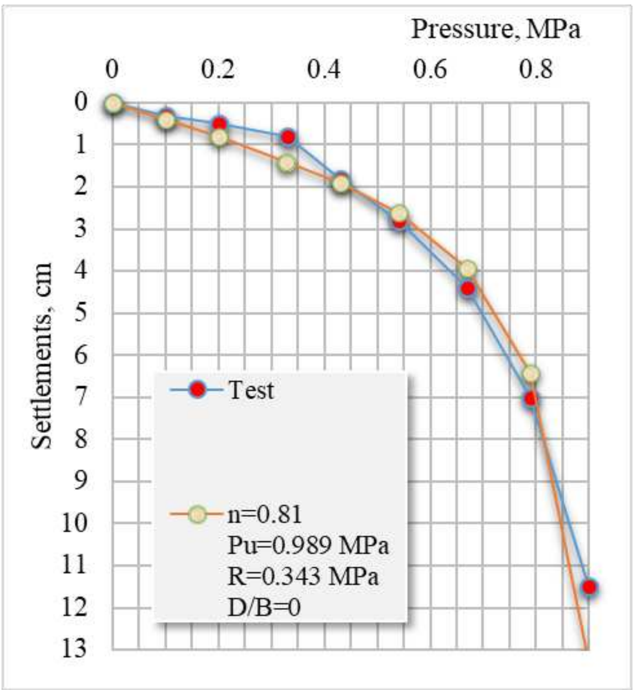

Figure 13. Comparison of computed settlements and field test result for the plate of 1.2 x 2.4 m, and 0 m depth on the stiff loam: $f`=35^{0}$, $c`=28$ kPa, E=34MPa, $\gamma=19.2$ kN/m^{3} (Timchenko, 2000).

The comparative analysis indicated that the adopted nonlinear model allowed performing calculations of settlements of spread foundations with sufficient accuracy for practical use in the pressure range of up to $0.4P_u$ on sandy soils and up to $0.6P_u$ on clayey soils.

4. CONCLUSION

The conducted research makes it possible to propose mixed numerical-experimental technique for computing settlements of spread foundation on the basis of full scale test results characterizing the non-linear relationship between loads and settlements.

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REFERENCES

Cimbal, S.Y., Sheikhnazari, H.R. (2011) Static testing of pad foundations on soil of Iran, In: *Foundation,* v.32, KNUBA, Kyiv, Ukraine, pp. 159-164.

Kirichek, Y., Tregub, A., (2015) Limit Sate Design of Shallow Foundation in *Fifth International Symposium on Geotechnical and Risk (ISSGR*), Rotterdam, The Netherlands, pp. 374 – 379.

Klepykov S.N., (1996), *Calculation of the constriction on deformable soil*, NIISK, Kyiv, Ukraine, 202 p.

Kushner, S.G., (2008), *The computation of the foundation deformation*, IPO Zaporozhye, Ukraine, 496 p.

Malyshev, M.V., Nikitina, N. S., (1982) Computation of foundation settlements with nonlinear dependence between stresses and deformations in soils, *Foundations and soil mechanics,* 2, pp. 21–25.

Malyshev, M.V., (1996) Prognosis of foundation settlements of shallow deposits with the use of both criteria of limit states, *Foundations and soil mechanics*, 1, pp. 2–4.

Shvetz, V.B. (2002) On the issue of assessing the stressed deformed state of layered soil foundations, In: *Construction, materials science, mechanical engineering,* PDABA, Dnipropetrovsk, Ukraine pp. 34-38.

Timchenko, R.A. (2009) Interaction of mat foundation with a non-uniformly deformable base under complex loading: In *Thesis of Doctor of Engineering Sciences,* Dnepropetrovsk, Ukraine, 387 p.