

Limit State Design of Shallow Foundations

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Abstract. The paper contains the analysis 86 field tests and calculations conducted by the authors for predicting the safe bearing capacity of shallow foundations. Limit state design of shallow foundation is studied. The allowable plastic shear zones were estimated by elasto-plastic FE analysis.

Keywords. Limit-state method, safe bearing capacity, bearing failure, finite element modeling, plastic shear zone

1. Introduction

According to Eurocode 7 two types of limit state have to be considered for selecting dimensions of foundations. The most common limit states for shallow foundations are bearing failure and excessive settlements.

The bearing capacity equations developed by Terzaghi, Hansen, Meyerhoff, and Vesic (Gunaratne 2006) are used for determination of ultimate bearing capacity. If the contact ground stress imposed by the structural load exceeds the ultimate bearing capacity, the shear stresses induced in the ground would cause large plastic shear deformation within the influence zone. Such overloading condition leads to shear failure. One of key questions concerning limit state of shallow foundation is its safety. The uncertainties in geotechnical engineering are very large because of variability on natural soils in the ground and loading, the complexity of theoretical soil mechanics. To take into account all such uncertainties it is common to apply a safety factor. The safety factor can be applied as partial factors to reflect the various uncertainties. The National Annex may contain the information on values for partial factors, which are open in the Eurocode for national choice, known as Nationally Determined Parameters.

Second limit state for shallow foundation is excessive settlements of the foundation. The settlements depend on dimensions of shear plastic zones under footings as well. If the shear zones are spacious the settlements became too

large because of the vast horizontal plastic deformation in soil under the footing.

2. Application of the results of the plate load tests for the bearing capacity prediction for shallow foundations

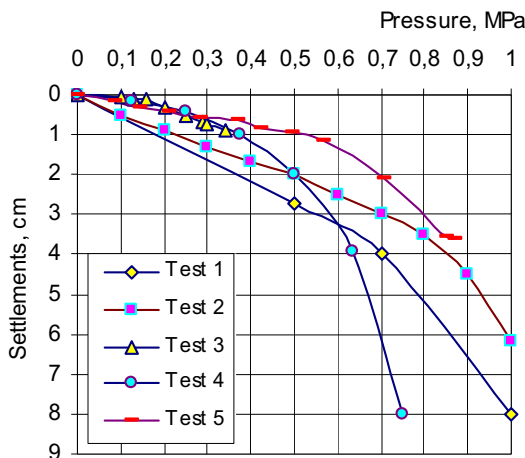
In this paper the field data are studied for comparison of bearing capacity analyses utilizing two methods - safe bearing capacity using the safety factor and calculated resistance of the foundation given by the Ukrainian norms DBN B.2.1-10.2009. Tables 1 and 2 describe some of 86 plate load test results (Alyohin 2004; Berezancev et al. 1958; Cimbali & Sheyhnazari 2011; Drukovaniy et al. 2006; Klepikov 1996; Kushner 1990; Skoromin & Malishev 1970; Timchenko 2009; Tugaenko 2003)

The plate load tests were performed with square, rectangular and circular plates. Width (diameter) of the plates ranged from 0.5 to 3.3 meters and depth of embedment was in the range between 0 m and 4.18 m. Table 1 presents type of soil, width B and length L of the plates used in the plate load tests, depth of embedment of the plates D. Table 2 contains the soil properties modulus of elasticity E, friction angle φ , cohesion C, unit weight γ and voids ratio e.

Figures 1-6 show the load-settlement curves of rested on a homogeneous soil shallow horizontal plates of various shapes and sizes in case of the load increase. These figures depict the results of plate load tests performed on sand

Table 1. Soils and plate dimensions used in plate load tests

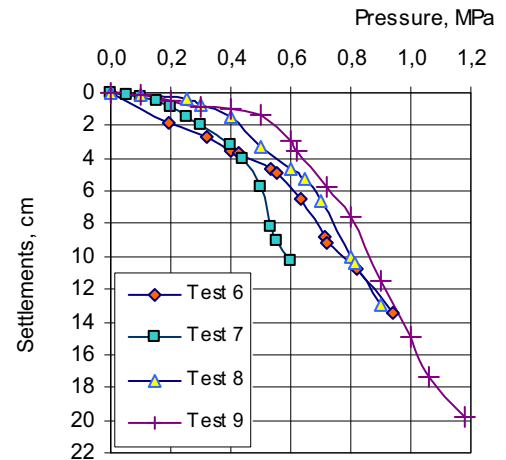
№ test	Soils	With and length of plate, m	Depth of embedment of plate, m
1	2	3	4
1	Medium dense fully saturated silty sand	1x1	0
2	Medium dense silty sand	2x0.52	0
3	Medium dense partially saturated medium sand	Ø0.6	0
4	Medium dense partially saturated silty sand	Ø0.63	0
5	Medium dense partially saturated silty sand	Ø 0.63	0
6	Stiff loam	1.4x1.6	0
7	Stiff clay	1.2x2.4	0
8	Stiff loam	1.4x1.6	0
9	Stiff loam	1.2x2.4	0
10	Stiff loam	1.4x1.6	0
11	Stiff loam	1.2x2.4	0
12	Stiff loam	1.2x2.4	0
13	Stiff clay	2x2.5m	0
14	Stiff clay	1x1	0
15	Medium dense partially saturated medium sand	1x1	0.5
16	Dense partially saturated fine sand	2x0.52	0.5
17	Medium dense partially saturated silty sand	Ø0.628	0.63
18	Stiff loam	0.5x0.5	0.7
19	Stiff clay	1.0x1.0	0.8
20	Stiff clay	1.0x1.0	1.2
21	Medium dense partially saturated silty sand	1.0x1.0	4.18
22	Medium dense fine sand	2x0.52	1.17
24	Medium soft eluvial loam	Ø0,7	2,8
25	Medium soft eluvial loam	Ø0,7	5

**Figure 1.** Plate load tests 1-5 for plates with depth of embedment $D/B=0$ rested on sand.

and cohesive soil with embedment depth of the plates D/B in the range from 0.0 to 7.14.

Table 2. Soil properties at the sites of plate load tests

Test №	E, MPa	ϕ , degree	C, KPa	γ , KN/m ³	e
1	2	3	4	5	6
1	8	35	3	19.2	0.77
2	15	35	3	16.1	0.77
3	53.1	36	1	16.6	0.62
4	21.8	35	3	16.2	0.7
5	22.6	36	5	17.9	0.63
6	19	23	43	18.7	0.75
7	19.7	24	45	19.6	0.68
8	16.8	27	57	19.8	0.62
9	46.7	32	20	19.6	0.68
10	23.3	27	57	19.8	0.62
11	34.3	35	28	19.2	0.72
12	36.7	18	32	19.1	0.68
13	4.5	15	38	18	1.0
14	3.3	15	38	18	1.0
15	54	35	8	18.2	0.6
16	35	34	8	17.8	0.64
17	22.6	35	3.0	16.1	0.7
18	6	24	18	17.3	0.9
19	4.8	15	38	18	1.0
20	17	19	49	19.3	0.7
21	53.4	37	10	16.8	0.7
22	34.7	36	10	16.6	0.72
23	30.3	34	8	17.8	0.64
24	15.7	26	30	17.2	0.65
25	18.5	26	30	17.2	0.65

**Figure 2.** Plate load tests 6-9 for plates with depth of embedment $D/B=0$ rested on stiff loam.

The result shows the ratios of calculated resistances of the soils to the ultimate bearing capacity for medium dense sands and dense sands which are in the range between 0.1 and 0.21. For clayey soils from medium soft to very stiff consistency the ratios are between 0.21 and 0.59. These ratios correspond to the range of safety factor from 4.8 to 10 for sand, and from

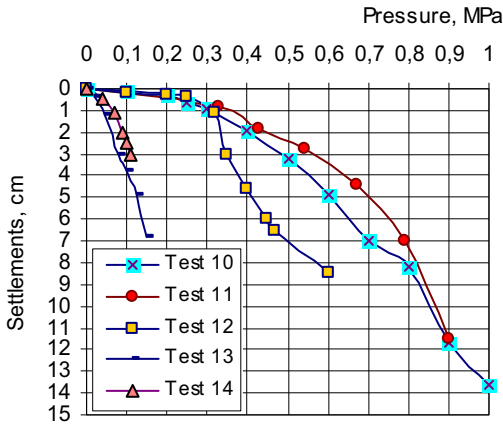


Figure 3. Plate load tests 10-14 for plates with depth of embedment $D/B=0$ rested on stiff loam.

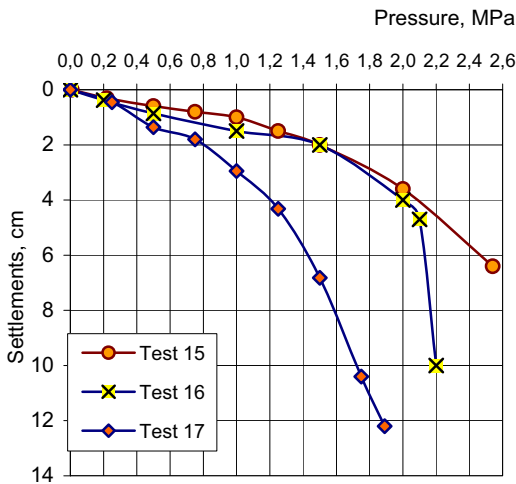


Figure 4. Plate load tests 15-17 for plates with depth of embedment D/B from 0.5 to 1 rested on sand.

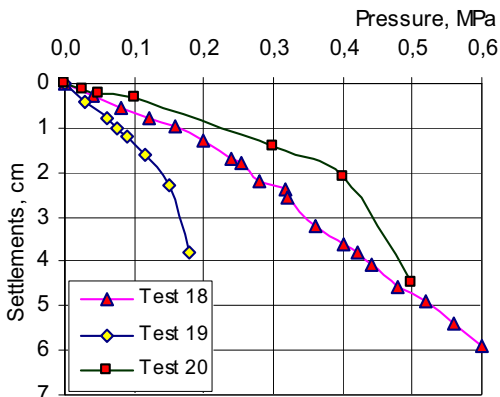


Figure 5. Plate load tests 18-20 for plates with depth of embedment D/B from 0.8 to 1.4 rested on stiff loam and clay.

1.7 to 4.8 for clayey soils. It can be seen that the resistance is not fully used for maximum values of the factors and safety is not ensured for minimum values of the factors. Furthermore the resistances are not used completely for middle dense sand, stiff and medium stiff cohesive soils.

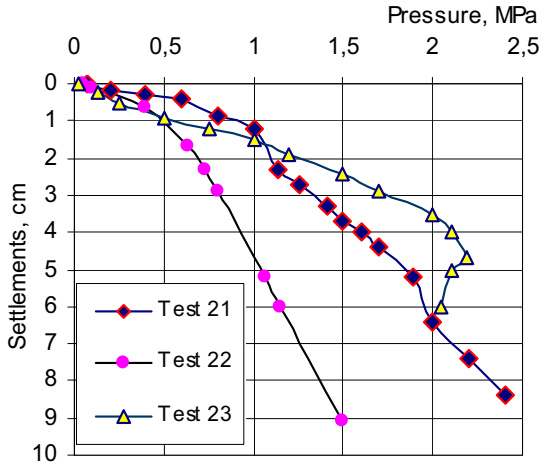


Figure 6. Plate load tests 21-23 for plates with depth of embedment D/B from 2.16 to 4.18 rested on sand.

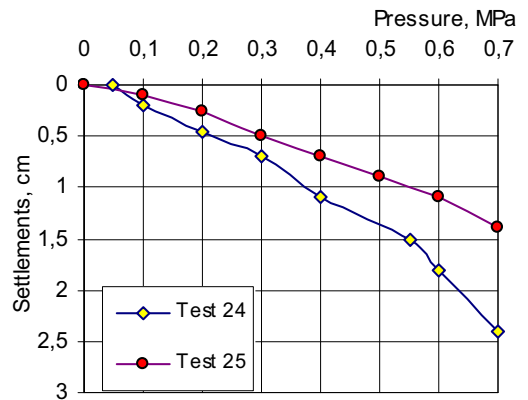


Figure 7. Plate load tests 24-25 for plates with depth of embedment D/B from 4 to 7.14 rested on soft eluvial loam.

The calculated resistances R are within the range between $0.1q_u$ and $0.65q_u$, where q_u is the ultimate bearing capacity. The settlements of the plates under pressures equal in value of calculated resistances of the foundations are in the range from $0.01S_s$ to $1.25 S_s$, where S_s are the safe settlements. At the same time the corresponding safety factors are in the range

from 1.5 to 10. The safety factors are deviating from ultimate limit state of the structure. Therefore minimum experimental values of the safety factors are insufficient and maximum values are excess.

Experimental settlements under corresponding to calculated resistance of the foundation pressure are much less as well as greater than ones given by the norms.

The analysis of computed results shows that the safe bearing capacity given by Eurocode 7 is some bigger that one provided by the Ukrainian norms. At the same time Eurocode 7 has a range of partial factors and other reliability parameters that ensure safety.

The experimental settlement-load dependences are compared with ones obtained by Plaxis modeling. Discrepancies between the predicted and experimental values of settlements are in the range from 2.6% to 16.4% under pressure $1.2R < P \leq 2R$ for silty sands and 10.2% for stiff loam under pressure $R < P \leq 1.2R$. Discrepancies of the other comparisons are greater and the predicted settlements are always greater than experimental ones.

3. Plastic shear zones in soil

As it is known, under increasing vertical load shear zones appear and grow in soil under footing. Researches of mechanism failures of soil make it possible to estimate the safety of the foundation. An increase of load on foundation greater than corresponding first critical pressure is accompanied by increase of dimension of plastic shear zone in the soil. The local shear failure in the soil will gradually extend outward from the foundation.

The result of plate load test (Skoromin & Malishev, 1970) and FE analysis depicting the shear plastic zones is presented on the left side of Figure 8. The field test was performed on a circular plate with diameter $D=0.6\text{m}$ on dense medium sand ($e=0.62$; $\gamma=16.6$; kN/m^3 ; $\varphi=36^\circ$). In this case first critical pressure equal to 11.3 kPa, $R = 33$ kPa and $q_u=274$ kPa. The axisymmetric FE-analysis (Mohr-Coulomb model) is given on the right side of Figure 8. The plastic shear zone in the soil is appeared under pressure 20 kPa. Under pressure equal to

calculated resistance the depth of plastic shear zone is some greater than a quarter of the plate diameter. Two plastic shear zones are joined under pressure 100 kPa at the depth 1.2D. The failure in the soil took place when the plastic shear zone reaches the critical dimensions under the pressure equal to $q_u=230$ kPa. In this case failure surface in the soil is extended to the ground surface and both zones under the edges of the foundation are connected under the centre of the footing.

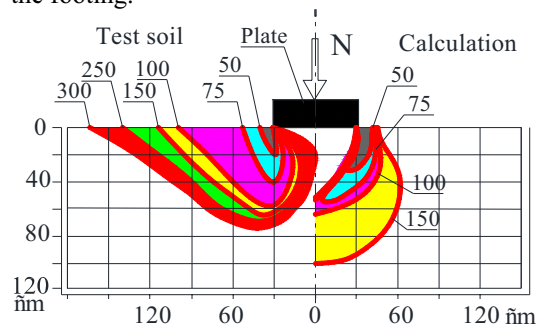


Figure 8. Load plate test on the left and FE analysis on the right

Safety of shallow foundation depends on dimension of the shear zones, which can be found using numerical simulation. Spread of plastic shear zones in soil was studied using PLAXIS 8.2 for the purpose of estimation of plastic shear zones in soil and safety of shallow foundation.

Figures 9 shows results axisymmetric load plate test and describes the spread of plastic shear zones. The increases of load on footing greater than corresponding first critical pressure accompanied by increase of plastic shear zones in the soil. The local shear failure in the soil gradually extended outward from the footing. When plastic shear zones reached the critical dimension sudden failure in the soil took place. In this case failure surface in the soil extended to the soil surface, and both zones below the edges of footing joined below the centre. That load per unit area corresponds with ultimate bearing capacity.

The finite element modeling showed that the joining of both plastic shear zones on axis of foundation took place at the depth equal to $(1.2-1.25)b$, where b is width of footing. Forming the

packed core of the soil $0,9b$ in the width and 0.4 m high corresponded to ultimate bearing pressure.

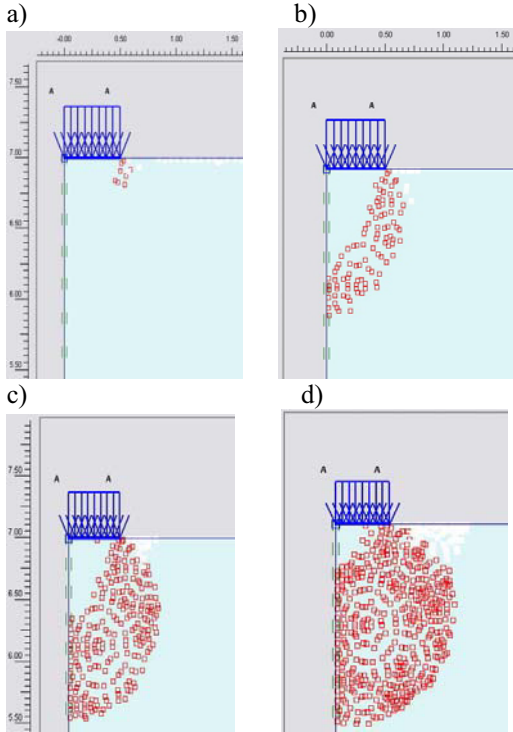


Figure 9. The plastic shear zones

According to the Ukrainian norms the depth of plastic shear zones is practically limited by one quarter of the footing width for engineering purposes. The comparison of numerical and experimental results shows that safe dimensions of plastic shear zones can be some greater than $\frac{1}{4}$ of the footing width and they can be limited by load within the range of $0.27 q_u$ to $0.36 q_u$.

Results of the numerical analysis allow us to determine the footing loads per unit area P_c under which the two plastic shear zones joined in soil on the axis of symmetry. Spread of plastic shear zones in soil was studied under a circular footing. The increasing of the plastic shear zones in soil was studied under different loads on the ground under footings of various dimensions and depths. The analysis shows that with increase in diameter of the footing (B) relative value of the depths of the of plastic shear zones (Z/B) decreases. Consequently decreases influence of footing depth D on the dimensions of plastic shear zones (Figures 10, 11).

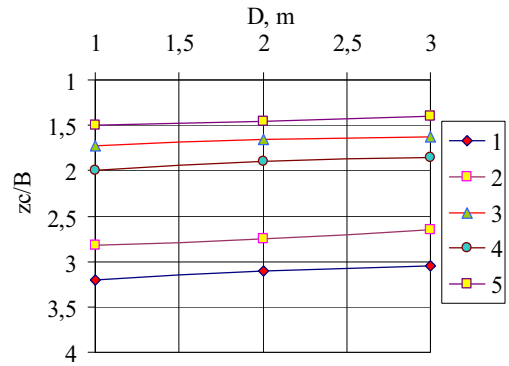


Figure 10. Relationship between relative value of the depth of the plastic shear zone and footing depth in: 1- dense fine sand, 2 – dense silty sand, 3 - firm sandy loam, 4 - stiff loam, 5 - stiff clay

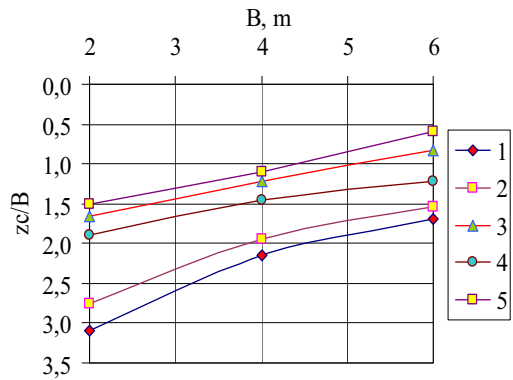


Figure 11. Relationship between relative value of depths of the plastic shear zones and width of the footing in: 1- dense fine sand, 2 – dense silty sand, 3 - firm sandy loam, 4 - stiff loam, 5 - stiff clay

Comparison experimental results with the numerical ones showed that predicted by Plaxis dimension of the shear zones in soil were 20% bigger, than experimental dimension. At the same time predicted by Plaxis ultimate bearing capacity of foundations were less of experimental ultimate bearing capacity.

4. Cost savings in foundation design

It is significantly important to take into account the economical and safety factors during the foundation design. The safe bearing pressure of footing given by Eurocode 7 is generally greater than one given by the Ukrainian norms. Therefore, a footing designed using the

Ukrainian norms, has greater dimension and consequently is more expensive than one designed using Eurocode 7. Figures 12 and 13 show an analysis of costs for square footings from 1 m to 5 m in width and from 1 m to 5 m in depths rested on sand and loam, respectively. The cost saving is in the range between 12 and 47%. Foundations with middle dimension (from 2 m to 3 m in width) rested on middle dense sand, stiff and medium stiff cohesive soils have greater cost savings than foundations with larger and smaller dimensions.

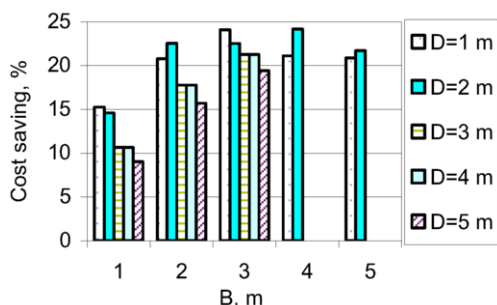


Figure 12. Analysis of cost savings of foundations rested on a sand.

The safe bearing pressure according to Eurocode 7 is greater than the one given by the Ukrainian norms. It is found out that the implementation of Eurocodes in Ukraine will effectively save about 20 - 40% of total costs for shallow foundation construction and at the same time sustain the high level of safety.

It is very important to harmonize the safety and economical profit, but many important problems remain unsolved in the limit state design of footing in weak soil.

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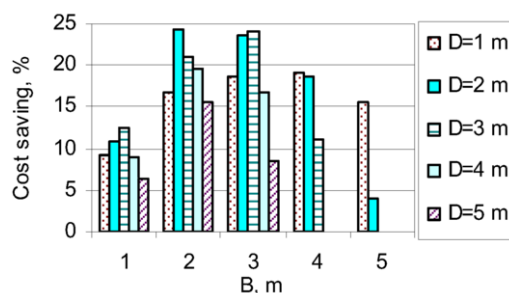


Figure 13. Analysis of cost savings of foundations rested on a loam.

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