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BEARING CAPACITY OF FOOTINGS AND STRIP FOUNDATIONS COMPARISON OF MODEL TESTS RESULTS WITH EUROCODE 7

CAPACITE DE SUPPORT DES PILIERS ET MOULAGES DE FONDATION I COMPARAISON DES RESULTATS DES TEST MODELES AVED I EUROCODE 7

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SYNOPSIS: The bearing capacities of footings and strip foundations obtained from 1 g model tests and from calculations according to the traditional solutions which are basic to national standards and will be basic to Eurocode 7 show some scatter, those derived from model and field tests being greater than those predicted by theoretical methods. This is caused by the fact that none of the traditional calculation methods is kinematically possible. Soil does not know that it is expected to behave according to a logarithmic spiral simply because it is easier to find a solution for such a model. It has been known for long time that Balla's (1962) theory is closer to the real behaviour of soil and thus closer to the model test results, although it is not used in any foundation engineering standard. In this situation it is appropriate to look at a new calculation method which can accommodate a high non-linearity of stress-strain relations (e.g. FEM). Model tests are necessary to confirm the qualitative and quantitative correctness of this method.

The basic part of this paper is devoted to the authors' own 1 g model tests carried out at the Geotechnical Laboratories of Tampere and Gdansk Technical Universities and to the analysis of different traditional calculation methods. Model tests were carried out under three dimensional and plane strain conditions using rigid circular and rectangular footings or strip foundations resting on homogenenous subsoils of the following kinds: till, gravel and dry or fully saturated sand. Single or repeated static loads were applied.

The scope, main results and analyses of these model tests are presented, special attention being paid to the effects of shape, depth, initial void ratio and foundation base roughness on bearing capacity. Comparisons are made to find out the internal safety of the traditional calculation methods, which still seem to form the basis for the proposed Eurocode 7.

INTRODUCTION

In most national foundation engineering standards the bearing capacity q_u of shallow strip foundations is represented by following expression:

$$q_u = c \cdot N_c + \gamma' \cdot D \cdot N_D + 0{,}5 \cdot \gamma' \cdot B \cdot N_B$$

where

c	=	cohesion
γ'	=	effective unit weight
D	=	depth of foundation
B	=	width of foundation
N_c, N_D, N_B	=	bearing capacity factors, generally functions of the friction angle φ

In most standards N_c and N_D are given according to Prandtl's and Reissner's solution, in which the bearing capacity factors are:

$$N_c = (N_D - 1) \cot \varphi$$
$$N_D = e^{\pi \cdot \tan \varphi} \cdot \tan^2 (45 + \varphi/2)$$

These formulae are based on Prandt's (1920) plastification zones (Fig. 1), which leave a great deal of internal safety in the dimensioning method

- Firstly; When a logarithmic spiral is not kinematically possible internal friction occurs inside Prandtl's radial zone.
- Secondly; When the system of zones is not kinematically possible friction occurs also between Prandtl's radial zone and Rakine's active and passive zones.
- Thirdly; The roughness of the foundation base is not taken into consideration.
- Fourthly; The shear strength of the soil above the foundation level is not taken into consideration.

There are some differences concerning factor N_B

- Brinch Hansen's formula $N_B = 1{,}5\ (N_D - 1) \tan \varphi$ is used in the Nordic countries, Poland and Canada.
- Caquot and Kerisel's formula $N_B = 2\ (N_D + 1) \tan \varphi$ is used in the United States.
- The formula $N_B = 2\ (N_B - 1) \tan \varphi$ is used in the DIN standards. This same formula is also proposed for Eurocode 7.

It has been known for a long time that this dimensioning method contains a great deal of internal safety (Hartikainen 1969), but it is not known how much. For that purpose we analyzed the results of two series of tests performed at the Technical Universities of Tampere and Gdansk.

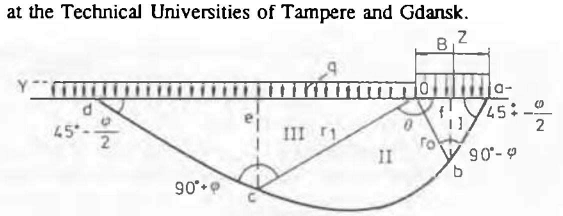

Figure 1. Prandtl's (1920) plastification zones.

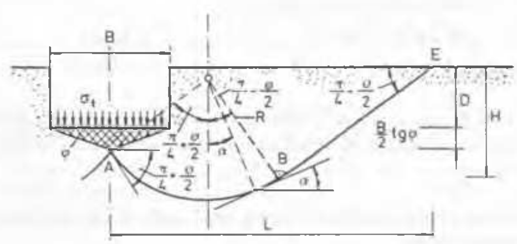

Figure 2. Balla's (1962) plastification zones.

It has also been known for a long time ago that Balla's (1962) theory gives good results by comparison with model test results (Hartikainen 1969, Ingra & Baecher 1983), because Balla has corrected some errors in earlier theories:

- Firstly; Balla's plastification zone (Fig. 2) is circular and thus kinematically possible.
- Secondly; The roughness of the foundation base is taken into consideration.

Thirdly; The shear strength of the soil is taken into consideration as far as the ground surface

Balla's theory is still on the safe side, however, as the junction between his plastification zone and Rakine's passive zone is not kinematic, which means that there will be friction between the zones. It is nevertheless worthwhile to compare the model test results with Balla's theory.

MODEL TESTS AT TAMPERE UNIVERSITY OF TECHNOLOGY

The test series consisted of 54 test loadings, 18 on till, 18 on sand and 18 on gravel (Fig. 3). The test foundations were 150 x 1500 mm and 300 x 1500 mm rectangular footings and a ø 300 mm circular footing, of depths D = 0 and 150 mm. The test loadings were performed on three densities of soil D_r = 85 %, 90 % and 95 %. The material parameters for the densities as determined with triaxial equipment are given in Table 1 (Rantaniemi 1992).

When test loadings were performed at optimum water content, this means that there was some cohesion in the till and also a small apparent cohesion in the sand. This cohesion was not taken into consideration in the comparisons. Only in the gravel was cohesion close to zero.

Table 1. Material parameters of the ground beneath the test-loaded foundation.

Degree of density	Till		Sand		Gravel	
%	φ	γ	φ	γ	φ	γ
85	35	19.4	36	17	36	19.3
90	37	20.5	39	18	40	20.5
95	39	21.7	42	19	44	21.6

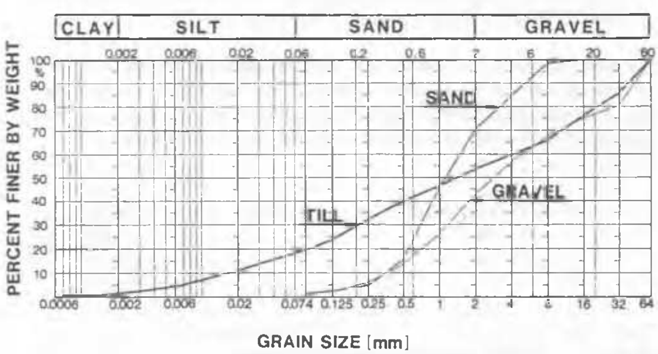

Figure 3. Test loaded ground materials; sand, gravel and till.

TEST RESULTS

Three parts of the load-settlement curve in which the soil behaves differently should always be distinguised, when analyzing test loadings of foundations, namely (Fig. 4):

- rectilinear section with low proportional strain, where soil behaviour is mainly elastic
- curved section, where the soil is starting to plastify, and
- approximately rectilinear section corresponding to the final plastic state.

Depending on the density, the load settlement curves for gravel were of the looked out appearance (Fig. 5), while on till it was difficult to reach a clear failure state (Fig. 6) and the failure load was determined from the load settlement curves using the clear failure load or the second clear turning point. The failure loads determined in this way were checked to give settlement in the right order.

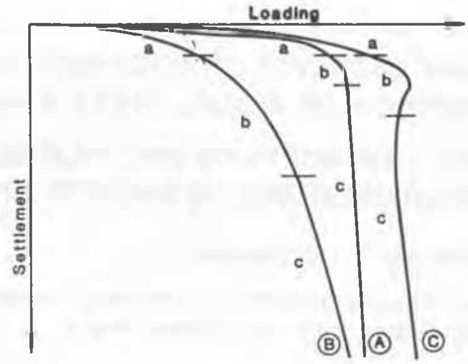

Figure 4. Basic types for load-settlement diagrams for a) loase, b) medium dense and c) very dense ground.

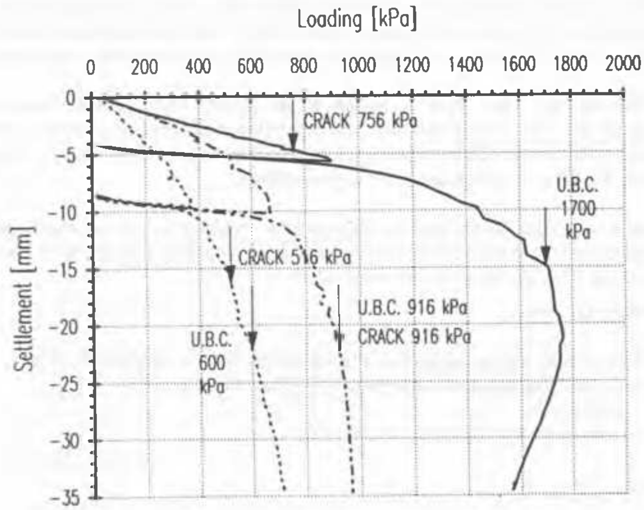

Figure 5. Load settlement curves of 150 x 1500 strip foundation with 150 mm foundation depth on loose, medium dense and dense gravel.

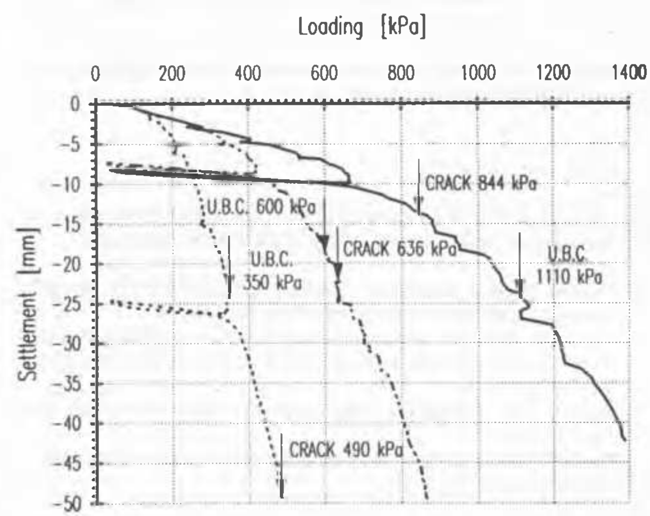

Figure 6. Load settlement curves of 150 x 1500 strip foundation with 150 mm foundation depth on loose, medium dense and dense till.

The results were compared with the Finnish codes, which are actually the same as the Danish and Polish ones, with the proposed Eurocode 7, which is actually the same as DIN 4017 and with Balla's theory (comparisons in Figures 7 and 8). The internal hidden safety factors in the proposed dimensioning methods are given in Tables 2, 3 and 4. Gravel was the only material in the tests without cohesion. It can be seen that there is no extra internal safety in Balla's theory, whereas but the internal hidden safety in the proposed Eurocode 7 is around F = 2 and that of the Finnish and Polish codes even greater.

This is also in good agreement with the Polish test loading results, which are compared with Balia's theory, which again seems to have no internal hidden safety, and with the DIN standard, which is actually the same as the proposed Eurocode 7, in table 5.

The Polish test loadings were done performed under plane strain conditions with a 500 mm long strip foundation between two thick glass plates. The foundation width varied from 100 to 200 mm. The material was uniform model sand with friction angle φ = 32.5 and dry density γ = 16 kN/m^3. The effect of friction against the glass plates is estimated to increase the ultimate bearing capacities in the test loading by 15 % at most.

Table 2. Finnish test loading results in compared with the Finnish and Polish codes.

Loading	Till	Sand	Gravel
90A0	5.6	4.6	3.4
95A0	6.4	6.2	3.4
90A15	3.2	3.4	2.4
95A15	4.2	4.4	2.4
90B0	3.2	4.6	2.3
95B0	3.8	6.4	2.6
90B15	2.1	3.0	2.1
95B15	2.7	3.8	2.5
Average m	3.9	4.5	2.6

$m = Q_m/Q_c$
Q_m = ultimate bearing capacity from model tests
Q_c = ultimate bearing capacity from calculations

Numbering of the test loadings: The first number denotes the degree of density D, the letter the foundation type, where A is strip foundation 150 · 1500 and B strip foundation 300 · 1500, and the final number the foundation depth in centimetres.

Table 3. Finnish test loading results in compared with the DIN standard and proposed Eurocode 7.

Loading	Till	Sand	Gravel
90A0	4.0	3.3	2.5
95A0	4.6	4.5	2.5
90A15	2.9	3.0	2.1
95A15	3.6	3.8	2.1
90B0	2.2	3.2	1.6
95B0	2.6	4.4	1.8
90B15	1.7	2.5	1.7
95B15	2.2	3.0	2.0
Average m	3.0	3.5	2.0

Table 4. Finnish test loading results in compared with Balla's theory.

Loading	Till	Sand	Gravel
90A0	2.0	1.6	1.2
95A0	2.3	2.3	1.4
90A15	1.5	1.5	1.0
95A15	1.7	2.0	1.1
90B0	1.2	1.5	0.8
95B0	1.3	2.2	1.0
90B15	1.0	1.2	0.8
95B15	1.0	1.6	1.0
Average m	1.5	1.7	1.0

Table 5. Comparison of ultimate bearing capacities in Polish test loading results.

Width [cm]		Finnish and Polish Code	DIN and Eurocode 7	Balla's theory	Polish model tests
B = 20	Q [kN] m	3.5 2.83	4.7 2.12	9.1 1.10	10.0 -
B = 15	Q [kN] m	1.9 2.86	2.6 2.14	4.9 1.11	5.5 -
B = 10	Q [kN] m	0.9 2.53	1.2 1.90	2.3 0.98	2.2 -

$m = Q_m/Q_c$
Q_m = ultimate bearing capacity from model tests
Q_c = ultimate bearing capacity from calculations

The Polish test loadings also showed that for eccentric loadings the use of an effective surface area which is symmetrical to the loading resultant is in good agreement with the test results (Table 6).

There seems to be some more internal hidden safety in the load inclination factors according to the Polish test loading results, but the averages of many results collected by Ingra and Baecher (1989) seem to be in reasonably good agreement with the DIN standard coefficients and the proposed Eurocode 7.

Table 6. Influence of eccentricity e/B on ultimate bearing capacity reduction.

Eccentricity e/B	0	1/12	1/8	1/4
Polish experiments	1.0	0.57	0.39	0.23
Ingra and Baecher	1.0	0.73	0.50	0.31
Existing codes	1.0	0.69	0.44	0.25

Table 7. Influence of load inclination δ on ultimate bearing capacity reduction.

Load inclination (δ)	0°	10°	20°	30°
Polish experiments	1.0	0.72	0.63	0.23
Ingra and Baecher	1.0	0.62	0.30	0.08
Finnish code	1.0	0.46	0.16	0.03
DIN standard	1.0	0.55	0.25	0.08

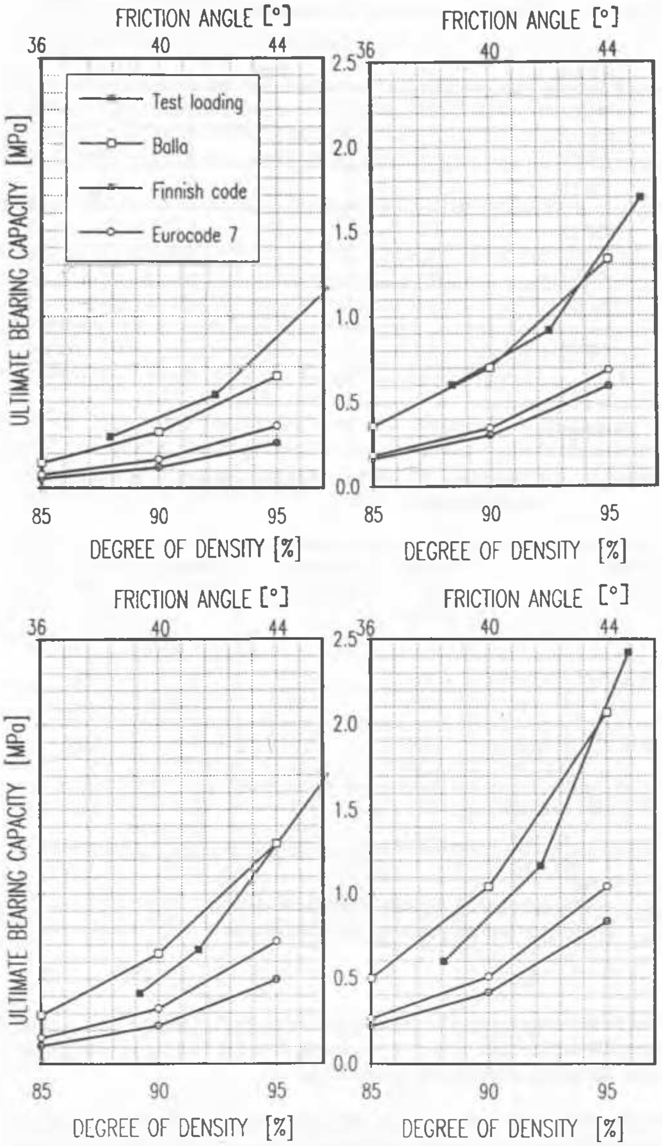

Figure 7. Comparison of test loading results of strip foundations on gravel
a) size 150 x 1500 and depth 0, b) size 150 x 1500 and depth 150, c) size 300 x 1500 and depth 0, and d) size 300 x 1500 and depth 150.

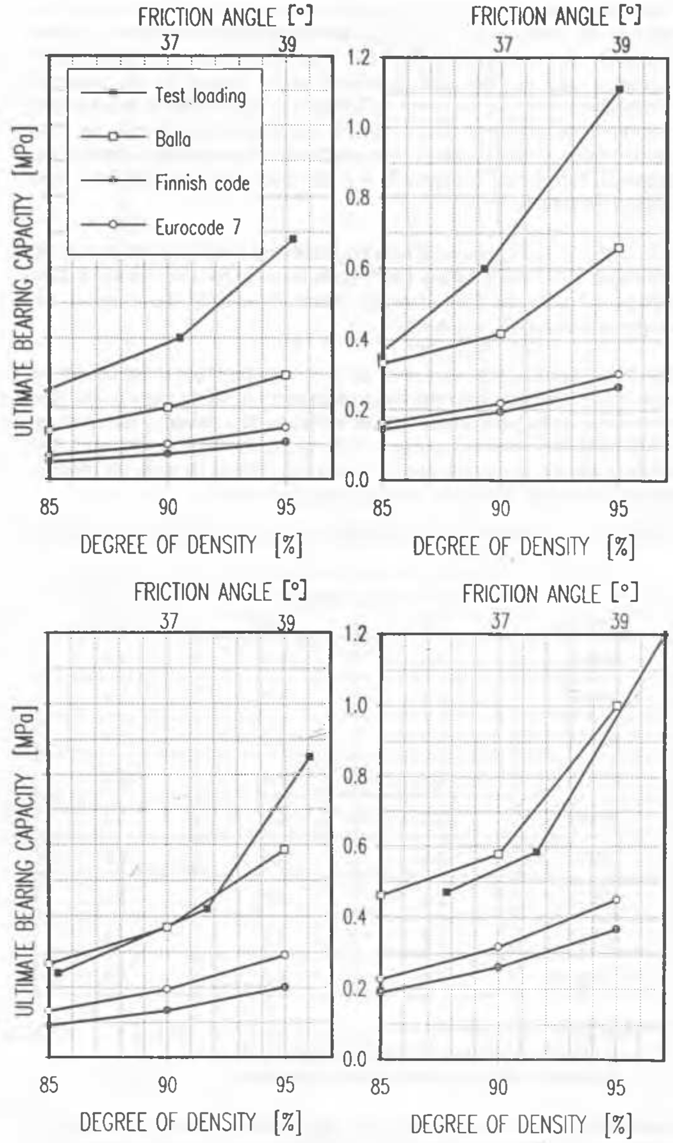

Figure 8. Comparison of test loading results of strip foundations on till a) size 150 x 1500 and depth 0, b) size 150 x 1500 and depth 150, c) size 300 x 1500 and depth 0, and d) size 300 x 1500 and depth 150.

CONCLUSIONS

The calculation methods for ultimate bearing capacity of strip foundations given in most common standards are based on the 70-year-old theory of Prandtl (1920), as also is the proposed calculation method of Eurocode 7. Since the system of plastification zones in this theory is not kinematically possible, it leaves internal hidden safety in the calculation method. This is about m ~ 2 in the proposed Eurocode 7, for example. Although the kinematically more accurate calculation method of Balla (1962), which gives good results in comparision of test loadings without any hidden internal safety, has been available for more than 30 years, we may still have to wait a few years to see this method incorporated into common dimensioning standards. A newer calculation method which gives good agreement with test results, such as Lewandowska's & Dembicki's (1991) variational method may have to wait even longer to enter the Eurocode.

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