Comparison of European bearing capacity calculation methods for shallow foundations

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The aim of this paper is to compare the methods used by the European countries to evaluate the bearing capacity of shallow foundations. Comparisons of several formulations of bearing capacity factors, depth and shape factors, load inclination and eccentricity factors, as well as values of these factors, are presented. This study has deliberately been restricted to methods using the bearing capacity factors N_c, N_q and N_γ: other methods exist and are used, but few of them are in common use in all European countries (for example, the pressiometric method is used almost exclusively in France), and consequently the comparison would be awkward. The most important conclusion is that the evaluated bearing capacity depends highly on the country. Therefore, bearing capacity needs to be better understood using new parametric and numerical analyses.

Keywords: codes of practice and standards; European Union (EU); foundations

Notation

A	foundation surface area
a	base adhesion of the footing
B	foundation width
B'	reduced width
c	soil cohesion
c_u	undrained soil cohesion
e	load eccentricity
i_γ, i_c, i_q	load inclination factors
L	foundation length
N_γ, N_c, N_q	bearing capacity factors
$\bar{q}$	surcharge per unit area
q_u	ultimate bearing capacity
s_γ, s_c, s_q	shape factors
V_u	ultimate vertical load
w	foundation vertical displacement
γ	unit weight
δ	load inclination
θ	load inclination including adhesion between soil and foundation
ϕ	angle of internal friction

Introduction

This work was carried out with the support of members of the European Action COST C7 'Soil–Structure Interaction in Urban Civil Engineering'. Countries which are not directly mentioned in the current paper have not sent information concerning the standards used. The information transmitted by Belgium could not easily be integrated into this analysis. At the end, we have information concerning 17 countries, some countries using foreign regulations or standards. The 12 countries directly concerned with this comparative analysis are listed in Table 1: we note that only four countries have a standard and two have regulations.

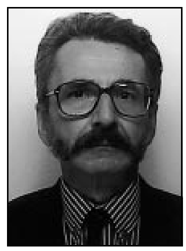
Generalities

2. The basic formulation concerns strip footings loaded vertically in the plane of

Table 1. Standard, regulation or practice

Countries	Standard, regulation or practice
Austria (A)	ÖNORM B 4432[1]
Czech Republic (CZ)	Czech Standard 731001
Germany (D)	DIN V 4017-100[2]
France (F)	DTU 13.12[3]
Finland (FIN)	Design practice
Greece (G)	German standard or US regulation
Ireland (IRL)	(UK) design practice[4]
Norway (N)	Design practice: Danish Brinch Hansen values or Janbu's procedure (only Hansen's method will be considered here for Norway)
Portugal (P)	Design practice: Terzaghi, Meyerhof, Hansen, or Vesic's values
United Kingdom (UK)*	Standard for Foundations BS 8004
Sweden (S)	Design practice
Slovenia (SLO)†	Serbian regulation, UL SFRJ 15/90[5]

* Many British designers also use Eurocode 7 and the associated British NAD.
† Slovenia uses the regulation established before the splitting of ex-Yugoslavia.



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symmetry (Fig. 1). One of the first formulations of this problem was given by Terzaghi[6] as

$$q_u = 0{\cdot}5B\gamma N_\gamma + \bar{q}N_q + cN_c \qquad (1)$$

in which q_u is the ultimate bearing pressure, γ is the unit weight of the soil under the foundation, B is the foundation width, N_γ is the bearing capacity factor concerning a cohesionless soil (internal friction angle ϕ), N_q is the bearing capacity factor concerning the embedment D, and N_γ is the bearing capacity factor concerning the cohesion c.

3. Three countries use another form for equation (1). Germany and Austria incorporate the coefficient 0·5 in N_b:

$$q_u = B\gamma N_b + \bar{q}N_q + cN_c \qquad (2)$$

Slovenia uses explicitly only two bearing capacity factors:

$$q_u = 0{\cdot}5B\gamma N_\gamma + \bar{q} + (c + \bar{q}\tan\phi)N_c \qquad (3)$$

4. For more complicated cases (rectangular footing, eccentric load, etc.), each bearing capacity factor is multiplied by correction factors

(*a*) the shape factor for a rectangular footing
(*b*) the eccentricity correction factor for an eccentric load
(*c*) the inclination factor for an inclined load.

Bearing capacity factors

5. Only the case of a strip footing loaded by a vertically centred force will be considered in this section.

Classical formulae

6. Most of the presented formulations are summarized by Bowles[7] (Table 2).

Methods used by each country

7. The methods used by each country are listed in Table 3. Some countries provide information on the bearing capacity factors using analytical formulae, and others with curves or tables.

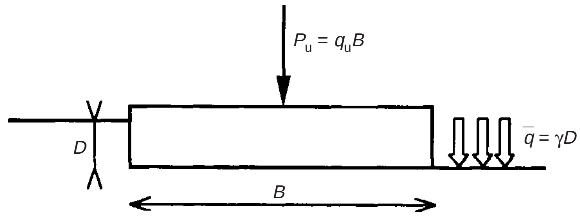


Fig. 1. Basic diagram

Specific formulations

8. A few countries use specific values.

9. *Germany and Austria*. Germany and Austria include the coefficient 0·5 in the factor N_b and use specific formulations as indicated above. To allow a comparison between the full values, the factor N_γ—which has the same formulation as in the German edition of Eurocode 7—will be used instead of factor N_b, as follows.

10. For both countries

$$N_\gamma = 2N_b \qquad (4)$$

with

$$N_b = (N_q - 1)\tan\phi \qquad (5)$$

in Germany and N_b given in tables and curves in Austria.

11. *France*. France uses Giroud's values for N_γ (given in a table).

12. *Sweden*. The formulation used by Sweden is similar to Hansen's:

$$N_\gamma = F(\phi)\left[\tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right)\exp(1{\cdot}5\pi\tan\phi) - 1\right] \qquad (6)$$

in which

$$F(\phi) = 0{\cdot}08705 + 0{\cdot}3231\sin 2\phi - 0{\cdot}04836\sin^2 2\phi$$

13. *Slovenia*. It was explained previously

Table 2. Classical formulae of bearing capacity factors

Author	N_γ	N_c	N_q
Terzaghi[6]	$\frac{\tan\phi}{2}\left(\frac{K_{p\gamma}}{\cos^2\phi} - 1\right)$ $K_{p\gamma}$ is given in tables	$(N_q - 1)\cot\phi$	$\frac{a^2}{2\cos^2[(\pi/4) + (\phi/2)]}$ with $a = \exp\left[\left(\frac{3\pi}{4} - \frac{\phi}{2}\right)\tan\phi\right]$
Meyerhof[8]	$(N_q - 1)\tan(1{\cdot}4\phi)$	$(N_q - 1)\cot\phi$	$\tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right)\exp(\pi\tan\phi)$
Hansen[9]	$1{\cdot}5(N_q - 1)\tan\phi$	$(N_q - 1)\cot\phi$	$\tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right)\exp(\pi\tan\phi)$
Vesic[10,11]	$2(N_q + 1)\tan\phi$	$(N_q - 1)\cot\phi$	$\tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right)\exp(\pi\tan\phi)$
Eurocode 7[12]	$2(N_q - 1)\tan\phi$	$(N_q - 1)\cot\phi$	$\tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right)\exp(\pi\tan\phi)$

Table 3. Methods used to estimate the bearing capacity factors

Countries	N_q	N_c	N_γ	Formulae	Curves	Tables
Austria (A)	Specific	Specific	Specific	No	Yes	Yes
Czech Republic (CZ)	Meyerhof	Meyerhof	Hansen	Yes	Yes	No
Germany (D)	Meyerhof	Meyerhof	E7	Yes	Yes	Yes
France (F)	Meyerhof	Meyerhof	Giroud[13]	No	No	Yes
Finland (FIN)	Meyerhof	Meyerhof	Hansen	Yes	–	–
Ireland (IRL)	Meyerhof	Meyerhof	Hansen	No	Yes	No
Norway (N)	Meyerhof	Meyerhof	Hansen	No	No	No
Portugal (P)	Terzaghi Meyerhof	Terzaghi Meyerhof	Terzaghi Meyerhof Hansen Vesic	Yes	Yes	Yes
Sweden (S)	Meyerhof	Meyerhof	Specific	Yes	No	No
Slovenia (SLO)	–	Meyerhof	E7	No	N_c–N_γ	No
Eurocode 7	Meyerhof	Meyerhof	Specific	Yes	No	No

that Slovenia uses explicitly only two bearing capacity factors. After transformation of equation (3) into the classical form, we obtain

$$N_q = 1 + N_c \tan\phi \qquad (7)$$

or also

$$N_c = (N_q - 1)\cot\phi \qquad (8)$$

which is clearly Terzaghi's formulation.

Comparison of results

14. N_q and N_c values are shown in Fig. 2(a). Note that Austria uses bearing capacity factors which are systematically lower than the ones used by the other countries. The largest values are given by Terzaghi.

15. Concerning N_γ (Fig. 2(b)), the values given by the Eurocode are near those used by France. Values issued from the Eurocode are located between Hansen's and the Austrian values, which are the highest.

Eccentricity correction

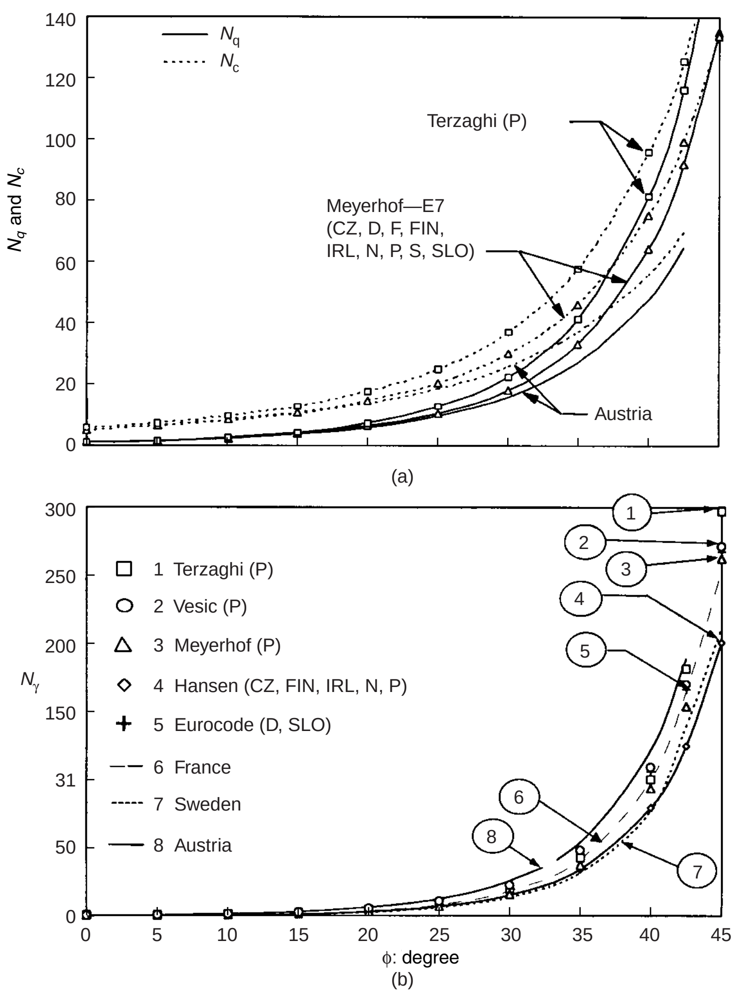
16. All countries use the method proposed by Meyerhof, which consists of replacing the footing by an effective footing with width B' centred on the external load (Fig. 3), where B' is given by

$$B' = B - 2e \qquad (9)$$

where e is the eccentricity of the load measured from the symmetry plane of the footing.

17. For a rectangular footing, a double eccentricity in the direction of the width and in the direction of the length can exist: in this case, the footing is replaced by a footing with a

Fig. 2. Bearing capacity factors plotted against ϕ: (a) N_q and N_c; (b) N_γ



double reduced dimension according to equation (9), taking into account the eccentricity in both directions.

Shape factors

18. The bearing capacity factors presented above are defined in the case of a strip footing. To take into account the non-infinite length of a rectangular footing, a shape factor s_i is introduced for each bearing capacity factor:

$$q_u = 0{\cdot}5B\gamma N_\gamma s_\gamma + \bar{q}N_q s_q + cN_c s_c \qquad (10)$$

The footing has width B and length L, and we assume that $B \leq L$.

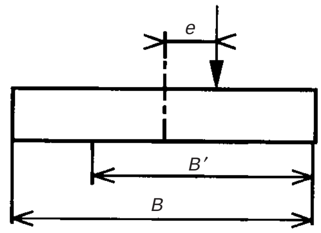


Fig. 3. Effective width

Shape factors according to the authors

19. The shape factors used by the mentioned authors are listed in Table 4. Terzaghi's results given for a square footing can be extended to a rectangular footing by a linear function of B/L. We can also see that $s_\gamma \leq 1$ for

Table 4. Shape factors according to the authors

Authors	s_q	s_c	s_γ
Terzaghi (square)	1	1·2	0·8
Meyerhof $K_p = \tan^2\left[\frac{\pi}{4}+\frac{\phi}{2}\right]$	$1+0{\cdot}1K_p\frac{B}{L}$ $\phi > 10°$ 1 $\phi = 0$	$1+0{\cdot}2K_p\frac{B}{L}$	$1+0{\cdot}1K_p\frac{B}{L}$ $\phi > 10°$ 1 $\phi = 0$
Hansen	$1+\frac{B}{L}\sin\phi$	$1+\frac{N_q}{N_c}\frac{B}{L}$ $\phi \neq 0$ $1+0{\cdot}2\frac{B}{L}$ $\phi = 0$	$1-0{\cdot}4\frac{B}{L} \geq 0{\cdot}6$
Vesic	$1+\frac{B}{L}\tan\phi$	$1+\frac{N_q}{N_c}\frac{B}{L}$	$1-0{\cdot}4\frac{B}{L} \geq 0{\cdot}6$

Table 5. Shape factors according to the countries

Countries	s_q	s_c ($\phi \neq 0$)	s_c ($\phi = 0$)	s_γ
Austria (A)	$1+\frac{B}{L}\sin\phi$	$\frac{s_qN_q-1}{N_q-1}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}3\frac{B}{L}$
Czech Republic (CZ)	$1+\frac{B}{L}\sin\phi$	$1+0{\cdot}2\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}3\frac{B}{L}$
Germany (D)	$1+\frac{B}{L}\sin\phi$	$\frac{s_qN_q-1}{N_q-1}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}3\frac{B}{L}$
France (F)	1	$1+0{\cdot}2\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}2\frac{B}{L}$
Finland (FIN)	$1+0{\cdot}2\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}4\frac{B}{L}$
Ireland (IRL)	$1+0{\cdot}2\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}4\frac{B}{L}$
Norway (N)	$1+\frac{B}{L}\sin\phi$	$1+\frac{N_q}{N_c}\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}4\frac{B}{L}$
Sweden (S)	$1+\frac{B}{L}\tan\phi$	$1+\frac{N_q}{N_c}\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}4\frac{B}{L}$
Slovenia (SLO)	$\frac{1+s_cN_c\tan\phi}{1+N_c\tan\phi}$	$1+0{\cdot}2\frac{B}{L}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}4\frac{B}{L}$
Eurocode 7	$1+\frac{B}{L}\sin\phi$	$\frac{s_qN_q-1}{N_q-1}$	$1+0{\cdot}2\frac{B}{L}$	$1-0{\cdot}3\frac{B}{L}$

all authors except Meyerhof. On the other hand, other forms are usual for the factor s_c. If we introduce into the formulation given in Table 4 equation (7) between N_c and N_q and Vesic's factor s_q, we obtain

$$s_c = 1 + \frac{N_q B}{N_c L} = 1 + \frac{N_q(s_q - 1)}{N_q - 1} = \frac{N_q s_q - 1}{N_q - 1} \qquad (11)$$

Shape factors according to the countries

20. The shape factors used by the mentioned countries are listed in Table 5. A comparison of the Tables 4 and 5 shows which author's formulations are effectively used by each country.

21. Only the shape factor s_c corresponding to a soil without internal friction is used by all countries. For some countries, the other factors depend only on the size of the footing, and for other countries, also on the internal friction.

22. Slovenia uses a specific equation (equation (12)) according to the specific bearing equation (equation (3)), so only two factors (S_c and S_γ) appear explicitly:

$$q_{\mathrm{u}} = 0{\cdot}5B\gamma N_\gamma S_\gamma + \bar{q} + (c + \bar{q}\tan\phi)N_c S_c \qquad (12)$$

After comparison with equation (11) and the introduction of equation (7), one obtains

$$s_\gamma = S_\gamma \qquad (13)$$

$$s_q = \frac{1 + s_c N_c \tan\phi}{1 + N_c \tan\phi}$$

$$s_c = S_c$$

The numerical results are given in Fig. 4. These results show great variation from one country to another. Germany and Austria use the same formulation to evaluate the shape factor s_c ($\phi \neq 0$), but the values of the bearing capacity N_q are different. Nevertheless, the numerical values obtained for s_c by both countries remain very close.

23. Meyerhof's method is the least used. We see also that a lot of countries use a different method for each factor: for example, the Czech Republic calculates s_q with Hansen, and s_c with Terzaghi, and has a specific method for determining s_γ.

Inclination factors

24. The bearing capacity factors presented above are defined for a vertical load. To take into account the inclination of the load, an inclination factor i_{i} is introduced in each bearing capacity factor:

$$q_{\mathrm{u}} = 0{\cdot}5B\gamma N_\gamma i_\gamma + \bar{q}N_q i_q + cN_c i_c \qquad (14)$$

Parameters

25. Two parameters can be defined to characterize the inclination of the load. The external force has a vertical component V and a horizontal component H (Fig. 6). Therefore, the inclination is naturally introduced as a parameter using the angle δ defined as follows:

$$\tan\delta = \frac{H}{V} \qquad (15)$$

26. Another possibility consists of introducing the adhesion a between the soil and the base of the footing. However, this adhesion must be smaller than (or equal to) the cohesion c of the soil, and depends on the roughness of

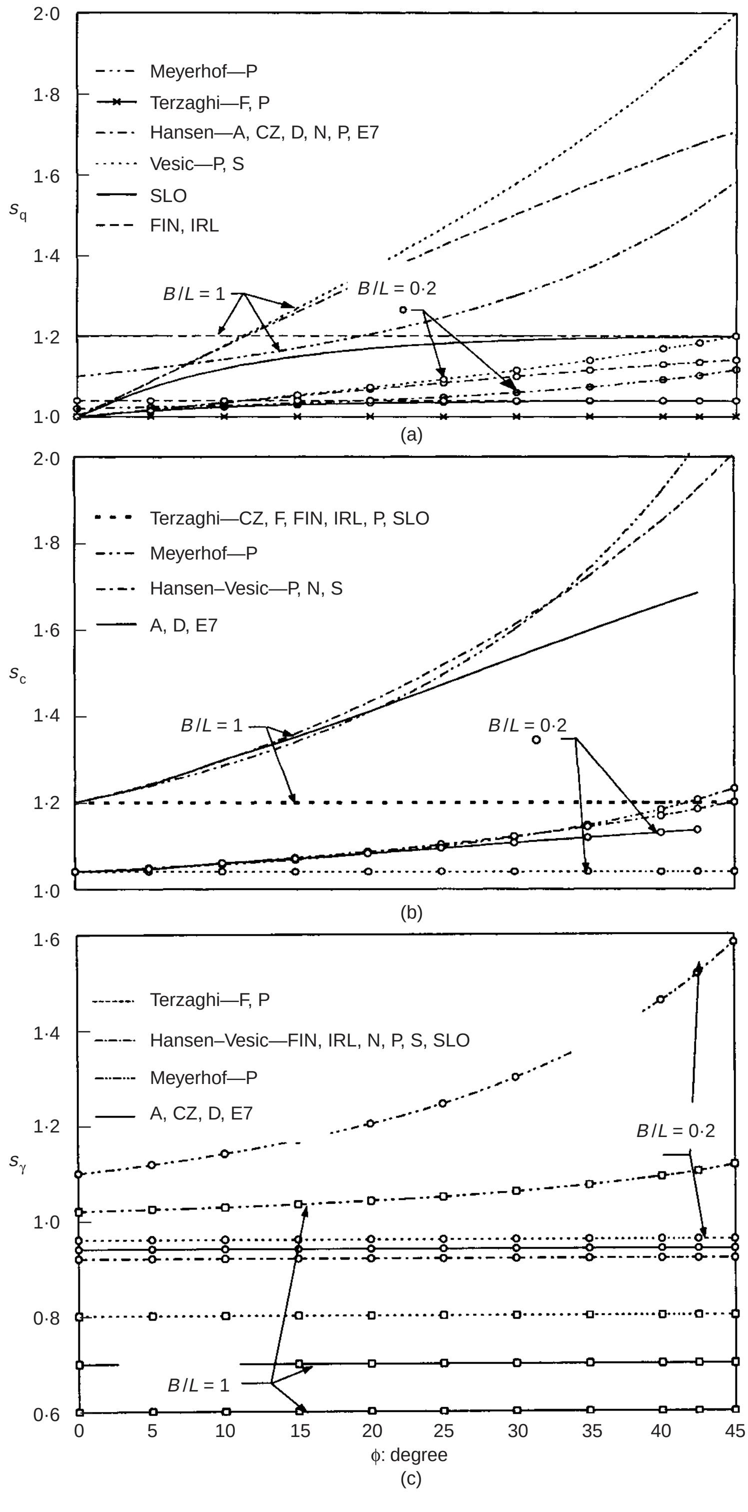


Fig. 4. Shape factor plotted against ϕ and B/L: (a) s_q; (b) s_c; (c) s_γ

the footing. Consequently, a second form to describe the inclination of the load consists of introducing an angle θ defined by

$$\tan\theta = \frac{H}{V + Aa\cot\phi} \qquad (16)$$

in which A is the effective soil–footing contact area.

27. δ and θ are equal for a cohesionless soil ($c = 0$) or for a perfectly smooth footing. This last case is not realistic in practice.

28. The classical formulations are listed in Table 6.

29. The Eurocode assumes that the adhesion a is equal to the cohesion c of the soil.

30. It can be seen that Vesic also introduces the shape of the footing into the inclination factor.

31. Hansen published at the same time tables and curves, but he did not specify the values of α_1 and α_2 corresponding to these curves. After analysis of his curves, one obtains the following values:

$$\alpha_1 \approx 4{\cdot}8 \qquad (17a)$$

$$\alpha_2 \approx 5{\cdot}5 \qquad (17b)$$

We will use these values later, although the second one is out of the range given by Hansen himself.

Formulations

32. The formulations used by the mentioned countries are listed in Table 7. Some countries directly use Meyerhof's, Hansen's or Vesic's formulations, and others introduce different coefficients or exponents.

33. Results given by Austria include directly the inclination factors in the bearing capacity factors: these can be calculated by division by the values obtained without inclination.

34. Slovenia also proposes a specific formulation according to the bearing capacity equation (equation (3)) and explicitly uses only two factors (I_c and I_γ):

$$q_u = 0{\cdot}5\gamma B N_\gamma I_\gamma + \bar{q} + (c + \bar{q}\tan\phi)N_c I_c \qquad (18)$$

After comparison with equation (10) and introduction of equation (7), one obtains

$$i_\gamma = I_\gamma \qquad (19a)$$

$$i_q = \frac{1 + (N_q - 1)i_c}{N_q} \qquad (19b)$$

$$i_c = I_c = \frac{N_q i_q - 1}{N_q - 1} \qquad (19c)$$

Comparison of results

35. We will have to separate comparisons for the methods using δ and those using θ. It does not make sense to compare both methods within a general case. But in order to simplify the presentation of the results, the curves in Fig. 5 show the values obtained with both methods (for Vesic's analysis, the presented results concern only a strip footing).

36. *Comparison of results for methods using* δ. The calculated results of the three factors concerning Austria are not significantly depen-

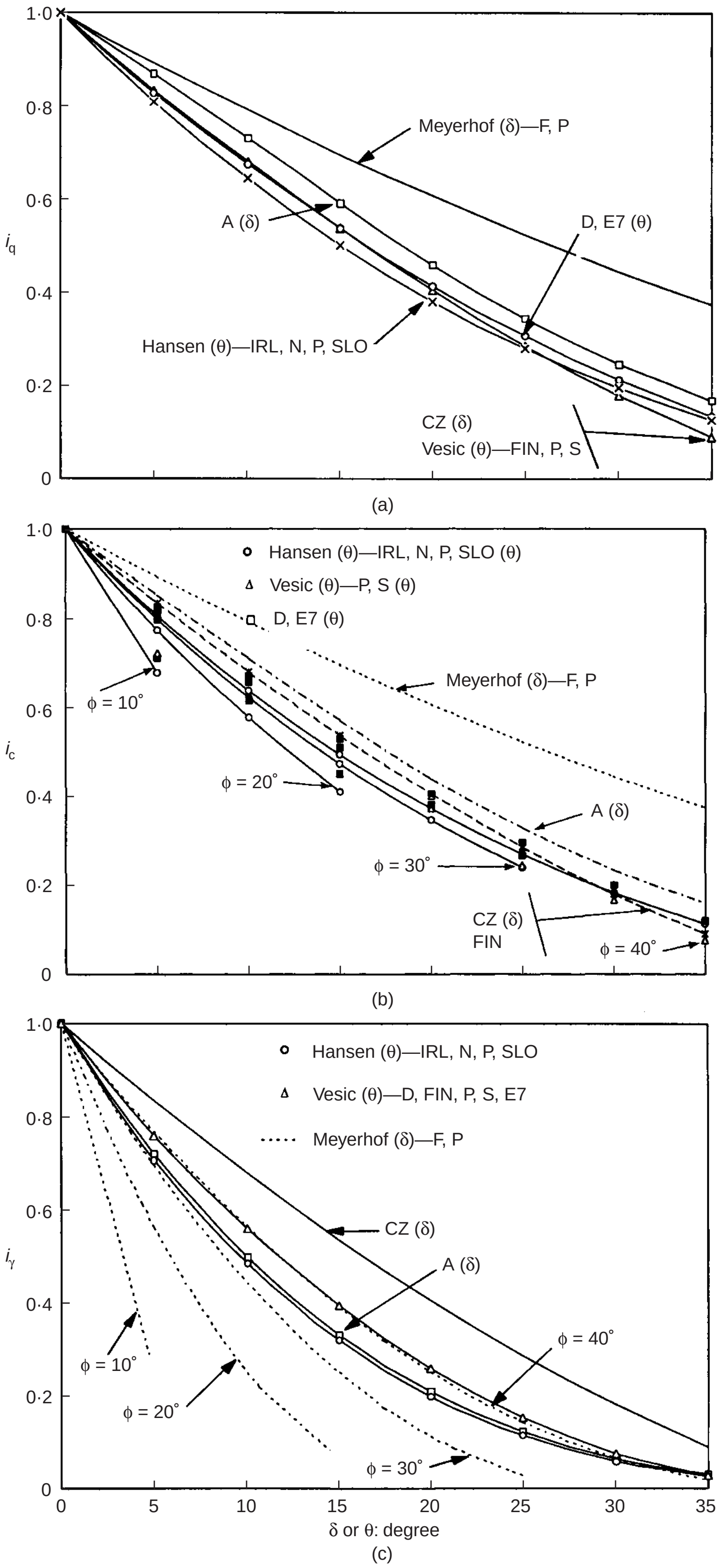


Fig. 5. Inclination factor plotted against δ, θ and ϕ: (a) i_q against δ and θ; (b) i_c against δ, θ and ϕ; (c) i_γ against δ, θ and ϕ

Table 6. Classical formulations for inclination factors

Authors	i_q	$i_c\ (\phi \neq 0)$	$i_c\ (\phi = 0)$	i_γ	Comments
Meyerhof	$\left(1-\frac{2\delta}{\pi}\right)^2$	$\left(1-\frac{2\delta}{\pi}\right)^2$	$\left(1-\frac{2\delta}{\pi}\right)^2$	$\left(1-\frac{\delta}{\phi}\right)^2$	–
Hansen	$(1-0{\cdot}5\tan\theta)^{\alpha_1}$	$\frac{i_qN_q-1}{N_q-1}$	$0{\cdot}5-\sqrt{\left(1-\frac{H}{Aa}\right)}$	$(1-0{\cdot}7\tan\theta)^{\alpha_2}$	$2\leq\alpha_1\leq5$ $2\leq\alpha_2\leq5$
Vesic	$(1-\tan\theta)^m$	$\frac{i_qN_q-1}{N_q-1}$	$1-\frac{mH}{AaN_c}$	$(1-\tan\theta)^{m+1}$	$m=\frac{2+B/L}{1+B/L}$
Eurocode 7	$1-\frac{H}{V+Ac'\cot\phi'}$	$\frac{i_qN_q-1}{N_q-1}$	$0{\cdot}5\left[1+\sqrt{\left(1-\frac{H}{Ac_u}\right)}\right]$	$1-\frac{H}{V+Ac'\cot\phi'}$	–

Table 7. Inclination factors

Countries	i_q	$i_c\ (\phi \neq 0)$	$i_c\ (\phi = 0)$	i_γ
Austria (δ)	Integrated into N_q	Integrated into N_c	Integrated into N_c	Integrated into N_γ
Czech Republic (δ)	$(1-\tan\delta)^2$	$(1-\tan\delta)^2$	$(1-\tan\delta)^2$	$(1-\tan\delta)^2$
Germany (θ)	$(1-0{\cdot}7\tan\theta)^3$	Hansen and Vesic	$0{\cdot}5+0{\cdot}5\sqrt{\left(1-\frac{H}{Aa}\right)}$	Vesic $m=2$
France (δ)	Meyerhof	Meyerhof	Meyerhof	Meyerhof
Finland (θ)	Vesic $m=2$	$(1-\tan\theta)^2$	Vesic $m=2$	Vesic $m=2$
Ireland (θ)	Hansen	Hansen	Hansen	Hansen
Norway (θ)	Hansen	Hansen	Hansen	Hansen
Sweden (θ)	Vesic	Vesic	Vesic	Vesic
Slovenia (θ)	–	Hansen	Hansen	Hansen
Eurocode 7 (θ)	$(1-0{\cdot}7\tan\theta)^3$	Hansen	$0{\cdot}5+0{\cdot}5\sqrt{\left(1-\frac{H}{Aa}\right)}$	$(1-\tan\theta)^3$

dent on the value of ϕ, so it seems reasonable to consider these factors as being non-dependent on the internal friction angle of the soil.

37. It appears also that the differences between the results obtained by Austria and the Czech Republic are not very important for i_q and i_c. In general, the results given by Meyerhof and used by France are significantly different from those used by Austria and the Czech Republic, except for i_γ with $\phi = 40°$, which is near to the values used by Austria.

38. *Comparison of results for methods using* θ. It can be seen that the results used by the mentioned countries are very close, and that the differences between the methods using θ are more limited than those obtained with the methods using δ.

39. *General comparison*. For all authors and countries, i_q is non-dependent on ϕ. At the same time, Hansen, Vesic and Eurocode 7 consider that i_c is dependent on ϕ, and Meyerhof considers that this factor is not dependent on ϕ. In contrast, all authors and countries except Meyerhof use a factor i_γ not dependent on ϕ.

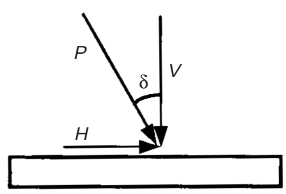


Fig. 6. Inclined load

40. In the particular case of a cohesionless soil, δ and θ are equal. The comparison is limited to i_q and i_γ, because the factor i_c is not directly relevant to cohesionless soil. Concerning i_q, the results obtained by all countries except France using Meyerhof's formulation are similar. Concerning i_γ, all countries obtain similar results (but only for $\phi = 40°$ for France), except for the Czech Republic, which uses larger coefficients than the other countries.

Examples

41. To clarify the differences obtained with all these methods, two examples will illustrate the application of the bearing capacity factors and correction factors discussed previously.

Example 1

42. The first example concerns a shallow foundation for which bearing capacity tests were performed on the centrifuge of the University of Bochum. The characteristics of soil and footing (prototype) are listed in Table 8.

43. *Numerical bearing capacity.* Values of the more important factors are listed in Table 9. This example illustrates the large difference between the results. Only Meyerhof considers a shape factor s_γ larger than 1, so his result can be considered as a specific case. Concerning the other authors and countries, the bearing capacity varies from 160 to 321 kN (ratio 1:2). Using the smallest bearing capacity factors, it is easy to see that Sweden obtains the smallest bearing capacity load.

44. *Comparison with experimental bearing capacity.* Load tests were performed on the centrifuge of the University of Bochum. The load–displacement curve presented in Fig. 7 could be analysed in terms of failure criterion with three different methods: (*a*) load corresponding to a ratio displacement $d \leq 10\%$; (*b*) load determined using Hansen's failure criterion; and (*c*) load obtained by linear regression of the end of the load–displacement curve.

45. In the first method, $d = w/B$, where w is the vertical displacement of the footing. In the second method, the loading is considered as the failure loading when the load corresponding to half the displacement is very close to this loading (difference less than 10%), as shown in Fig. 8. With the third method, we obtain an initial value and the slope of the end of the load–displacement curve. The initial value found is used as the ultimate load in the initial experimental conditions of the tests.

46. Table 10 shows the results obtained for four tests. For each method, the error does not exceed 6%: this attests to the quality of the tests. This example also proves that the bearing capacity value depends on the method used: the mean value for each method fluctuates from 307 to 423 kN (ratio 1:1·4).

47. In comparison with the numerical bearing capacity values which are in the range 160–443 kN (321 kN when excluding the Meyerhof results), it is clear that the experimental values are systematically larger than the numerical values. The third method gives results which are closer to the numerical analysis, because the calculation takes into account only the initial conditions, as the third analysis does. From this point of view, the

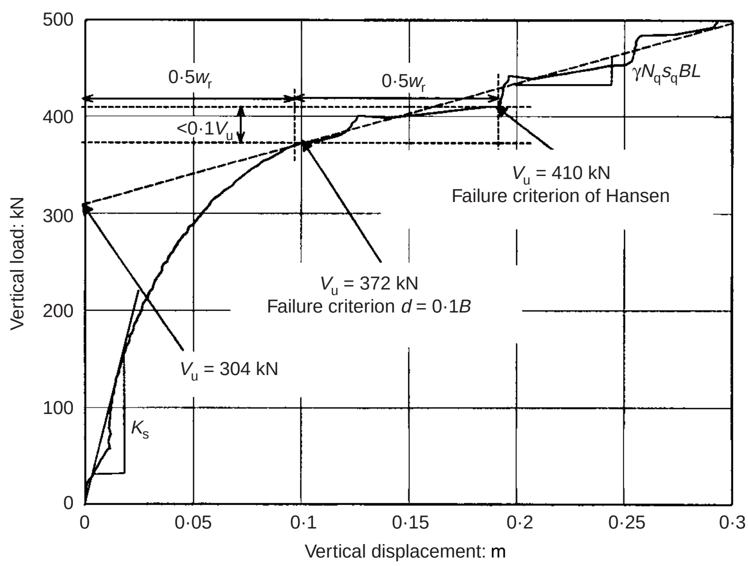
Table 8. Soil and footing characteristics

Soil	ϕ: degree	c: kPa	γ: kN/m^3	Footing	B: m	Embedment, D/B
Dry sand	35	0	17·0	Square	1	0

Table 9. Factors and bearing capacity

Authors and countries	N_γ	s_γ	V_u: kN
Terzaghi	42·4	0·8	288
Meyerhof	37·2	1·4	443
Hansen	33·9	0·6	173
Vesic	48·0	0·6	245
Sweden	31·4	0·6	160
Finland	33·9	0·6	173
Ireland	33·9	0·6	173
Norway	33·9	0·6	173
Czech Republic	33·9	0·7	202
Slovenia	45·2	0·6	245
Germany	45·2	0·7	269
France	41·1	0·8	279
Austria	54·0	0·7	321
Eurocode 7	45·2	0·7	269

Fig. 7. Load–displacement curve



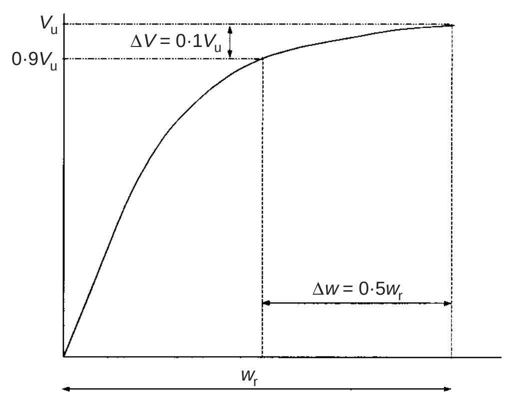


Fig. 8. Hansen's failure criterion

Table 10. Experimental ultimate load with several interpretation methods for the failure criterion

Test	Ultimate vertical loading: kN		
	$d \leqslant 10\%$	Hansen failure criterion	Linear regression
2	384	440	302
19	372	410	304
25	384	428	310
31	384	414	314

Table 11. Soil and footing characteristics

Soil	ϕ: degree	c: kPa	γ: kN/m^3	Footing	B: m	Embedment, D/B	Load inclination: degree
Unsaturated sand	35	10	19·0	Square	1	0·6	$\delta = 10$

Table 12. Values of bearing capacity factors

Authors and countries	N_γ	s_γ	i_γ	N_q	s_q	i_q	N_c	s_c	i_c
Meyerhof	37·2	1·4	0·51	33·3	1·37	0·79	46·1	1·74	0·79
Hansen	33·9	0·6	0·48	33·3	1·57	0·64	46·1	1·73	0·63
Vesic	48	0·6	0·56	33·3	1·7	0·68	46·1	1·72	0·67
Ireland	33·9	0·6	0·48	33·3	1·2	0·64	46·1	1·2	0·63
Slovenia	45·2	0·6	0·48	33·3	1·19	0·64	46·1	1·2	0·63
Finland	33·9	0·6	0·56	33·3	1·2	0·68	46·1	1·2	0·68
Austria	27·8	0·7	–	19·5	1·57	–	26·5	1·6	–
France	41·1	0·8	0·51	33·3	1	0·79	46·1	1·2	0·79
Czech Republic	33·9	0·7	0·68	33·3	1·57	0·68	46·1	1·2	0·68
Norway	33·9	0·6	0·48	33·3	1·57	0·64	46·1	1·72	0·63
Germany	45·2	0·7	0·56	33·3	1·57	0·67	46·1	1·59	0·66
Sweden	31·4	0·6	0·62	33·3	1·7	0·68	46·1	1·72	0·67
Eurocode 7	45·2	0·7	0·56	33·3	1·57	0·67	46·1	1·59	0·66

Austrian method provides results closer to the experimental values.

Example 2

48. The second example concerns the same shallow foundation but embedded in a frictional soil with cohesion and loaded by an inclined load. The characteristics of soil and footing and load are listed in Table 11. It is assumed that $\tan\delta$ and $\tan\theta$ are not significantly different.

49. Values of the more important factors are shown in Table 12, and the bearing capacities in Fig. 9.

50. This example shows the large differences between the results: the bearing capacity fluctuates from 734 to 1297 kN (ratio 1:1·8). Concerning the mentioned countries, we conclude that the largest values for the ultimate load are obtained by Sweden and Germany

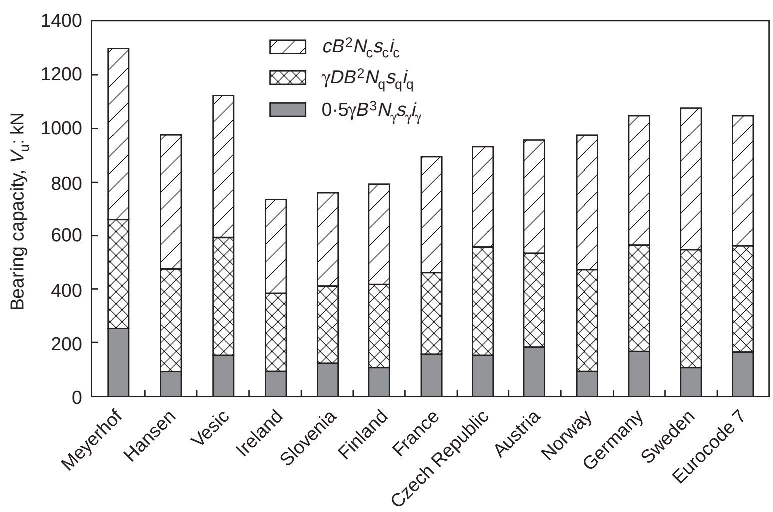


Fig. 9. Bearing capacities

(Eurocode 7), and the smallest by Ireland, Slovenia and Finland.

Conclusion

51. The most important conclusion is that the evaluated bearing capacity depends highly on the method used, and therefore on the country. Only the eccentricity correction is accepted unanimously: however, this does not mean that this correction is more accurate. The previous illustrations show that the results obtained by a country are not systematically the smallest or the largest. Sweden obtains the smallest bearing capacity value in example 1 (Table 8) and the largest in example 2 (Fig. 9). Although Meyerhof largely overestimates bearing capacity values in both examples, we can conclude that the results calculated with Eurocode 7 stay in the high mean of results found from the European methods used here.

52. Thus, bearing capacity needs to be better understood using new parametric and numerical analyses. Another question is the definition and the experimental or numerical determination of the bearing capacity of a shallow foundation in relation to its displacement.

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