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ANNA BOROWIEC*

SOME ECONOMIC ASPECTS OF EUROCODE 7 INTRODUCTION IN GEOTECHNICAL DESIGN ON THE EXAMPLE OF SPREAD FOUNDATION

ASPEKTY EKONOMICZNE WPROWADZENIA EUROKODU 7 W PROJEKTOWANIU GEOTECHNICZNYM NA PRZYKŁADZIE FUNDAMENTU BEZPOŚREDNIEGO

A b s t r a c t

This paper discusses how new or alternative methods of design influences the cost of foundations and thus the investment. The paper also looks at the introduction of a new standard in geotechnical design – Eurocode 7, which took place in 2010. In order to illustrate problems associated with foundation spread, calculations are carried out for old polish and new European standards. To give some quantitative measurements of cost-effectiveness, the index of load-capacity (LCU) is used to help define the economical index.

Keywords: Eurocode 7, foundation design, subsoil investigation and testing, establishing soil parameters

S t r e s z c z e n i e

Artykuł włącza się do dyskusji na temat o tym, czy i w jaki sposób nowe normy geotechniczne generują dodatkowe koszty lub podwyższają całkowity koszt inwestycji, poprzez na przykład przewymiarowanie fundamentów. Miarą opłacalności nie są wskaźniki ekonomiczne, lecz Wskaźnik Wykorzystania Nośności. W celu zilustrowania problemu przedstawiono porównawcze obliczenia dla fundamentu bezpośredniego.

Słowa kluczowe: Eurokod 7, projektowanie fundamentów, badania podłoża budowlanego, ustalanie parametrów gruntu

* Ph.D. Anna Borowiec, Department of Geomechanics, Civil Engineering and Geotechnics, Faculty of Mining and Geoengineering, AGH University of Science and Technology.

1. Introduction

Eurocode 7 is titled *Geotechnical Design* and is composed of two parts: *Part 1 – General rules* and *Part 2 – Ground investigation and testing*. The first part is divided into 12 sections devoted to different types of geotechnical problems, such as spread and pile foundation, embankments and retaining structures, fill, de watering or ground improvement, as well as hydraulic failure. Eurocode 7 is now the national standard in all Member States of the European Union, and has been since March 2010. Eurocode 7 is implemented via the Polish standards: PN-EN 1997-1:2008/NA:2011P and PN-EN 1997-2:2009P which are translated versions followed by a national annex (NA) and five corrections (AC and Ap).

For the purposes of this article the index of Load-Capacity Use (*LCU*) is defined in the form of resistance ratio, expressed in percentages:

$$LCU = \frac{E_d}{R_d} 100\% \tag{1}$$

where

E_d – design value of effects of actions,
R_d – design resistance.

1.1. Main dissimilarities

Design approaches (DA) and use of the partial factor are two major dissimilarities between Polish and European standards.

For the STR and GEO limit state types, used in persistent and transient situations, three Design Approaches are outlined. They differ in the way they distribute partial factors between actions, the effects of actions, material properties and resistances. In Design Approaches 2 (DA2) and 3 (DA3). A single calculation is required for each part of the design, and the way in which these factors varies according to the calculation considered.

It was verified that the limit state of a rupture or excessive deformation will not occur with the following combination of sets of partial factors: A1 '+' M1 '+' R2 in DA2 and A1 (on structural actions) or A2 (on geotechnical actions) '+' M2 '+' R3 for DA3. Tables with specific values of adequate partial factors can be found in *Annex A* of Eurocode 7. Technical Committee 254, Geotechnics regulated additionally that set A1 should only be used when calculating the effects of actions. The summary of all factors in DA2 is gathered in Table 1.

The second important distinction lies in the different use of partial factors listed in Table 1, formerly known as material, load and correction factors, i.e. γ_m, γ_f and *m*. According to Polish standards, these coefficients varied upwards or downwards in relation to the unity, depending on the need to increase or decrease multiplied characteristic values respectively. In Eurocode 7, partial factors are always (except in one case) greater than one – and in order to diminish the characteristic value, division by a partial factor is required. When the partial factor $\gamma_{R;v}$ = 1.4 is used for calculating a design value of bearing resistance, it reduces the characteristic value by almost 29%. A reduction of such a magnitude never occurs in polish standards dedicated to spread foundations.

Table 1

Partial factors in DA2

Actions – set A1	Materials – set M1	Resistance – set R2*
γ_G = 1.35 for Permanent Unfavourable	γ_M = 1.0 for all soil parameters	$\gamma_{R;v}$ = 1.4 for bearing of the spread foundation
γ_G = 1.0 for Permanent Favourable		$\gamma_{R;h}$ = 1.1 for sliding of the spread foundation
γ_Q = 1.5 for Variable Unfavourable		$\gamma_{b/s/t}$ = 1.1 for base, shaft and total of the pile in compression
γ_Q = 0.0 for Variable Favourable		$\gamma_{s;t}$ = 1.15 for base, shaft and total of the pile in tension

* Set R2 does not provide any diversification for pile technology.

2. Spread foundations

The provisions of *Section 6* of the first part of Eurocode 7 apply to spread foundations including pads, strips and rafts. The calculation method for this type of foundations may consist of any of the following: analytical, semi-empirical, numerical and prescriptive.

The analytical method is described in *Annex D* and is based on Meyerhof's formula for soil resistance. A similar approach is presented in the Polish standard PN-B-03020:1981P.

A sample prescriptive method for deriving presumed bearing resistance for spread foundations on rock is given in *Annex G*. When such a method is applied, design result should be evaluated on the basis of comparable experience.

The semi-empirical method for bearing resistance estimation should be based for example on pressure meter test results and is described in *Annex E*. The pressure meter is not commonly used in Poland – the lack of experience in testing and interpreting the results may lead to substantial inaccuracy in the design of the foundation and hence increase of its costs. A significant majority of geotechnical reports are prepared on the basis of drilling and one or two tests carried out *in situ* – mostly using a wide range of dynamic probing methods. Therefore, the semi-empirical and prescriptive methods raised will gain attention in polish geotechnical circles.

2.1. Ultimate Limit State

To establish bearing resistance under Drain Conditions (DC), the use of Meyerhof's formula is recommended:

$$R = A'[c' N_c i_c s_c b_c + q' N_q i_q s_q b_q + 0.5\gamma' N_\gamma i_\gamma s_\gamma b_\gamma] \tag{2}$$

When calculating soil resistance according to PN-81/B-03020 equation (2) had a form of:

$$Q_{fNB} = \overline{A}\,[(1+0.3\overline{B}/\overline{L})\; c_u^{(r)} N_c i_c + (1+1.5\overline{B}/\overline{L})\; D_{\min}\gamma_D^{(r)} N_D i_D + \\ + (1-0.25\overline{B}/\overline{L})\;\overline{B}\;\gamma_B^{(r)} N_B i_B\,] \qquad (3)$$

All symbols for equations (2) and (3) are explained and compare in the Table 2.

Table 2

Comparison of the symbol used in EC7 (in DA2) and PN for Meyerhof's formula

	PN-EN 1997-1:2008	PN-B-03020:1981P
Effective cohesion	$c' = c'_k$	$c_u^{(r)}$
Effective friction angle	$\varphi' = \varphi'_k$	$\varphi^{(r)}$
Effective weight densities	$\gamma' = \gamma'_k$ – below foundation	$\gamma_D^{(r)}$, $\gamma_B^{(r)}$ – mean values
Effective overburden pressure	q'_k	$D_{\min}\gamma_D^{(r)}$
Factor for bearing resistance	N_c, N_q, N_γ	N_C, N_D, N_B
Factor for shape of foundation	s_c, s_q, s_γ	1 + 0.3 (B/L) 1 + 1.5 (B/L) 1 – 0.25 (B/L)
Factor for inclination of the load	i_c, i_q, i_γ	i_C, i_D, i_B
Factor for inclination of foundation base	b_c, b_q, b_γ	not present*
Area of the foundation (reduced after consideration of eccentricity of loads)	$A' = B' \times L'$	$\overline{A} = \overline{B} \times \overline{L}$
Bearing resistance	R	Q_{fNB}

* Present in PN-B-03010:1983P instead.

It is obvious that even for the same soil parameters (i.e. friction angle) both formulas (2) and (3) give different values of bearing resistance. In addition, according to DA2*, only characteristic values of material parameters should be used, which leads to even greater discrepancies.

Ultimate Limit State (ULS) is written as:

$$E_d \le R_d\ , \qquad (4)$$

where:

E_d – design effects of actions,

R_d – design bearing resistance.

Considering a square footing for instance, for which in EC7 the Ultimate Limit State (ULS) is satisfied for the dimensions of 2.2 m by 2.2 m and the design bearing resistance R_d equals 1614 kN. With effects of actions E_d = 1455 kN providing 9.85% of the reserve in load capacity (LCU = 90.15%). But calculating a square footing of identical dimensions according to PN-B03020 for the same loading and geotechnical conditions, the value of 2029 kN is obtained. This is a corrected value of Q_{fNB} with the correction factor of 0.9 as *Method A* is used to establish soil parameters. The ULS is also fulfilled, but the index of Load-Capacity use is equal to 76.98% – the footing is therefore over designed and the LCU value is unacceptable from an economical point of view. A summary of procedural use in these calculations, with more detailed values is given in the Table 3.

Table 3

Comparison of the calculations of the bearing resistance according to EC7 and PN

	PN-EN 1997-1:2008	PN-B-03020:1981P
Cohesion	c'_k = 22 kPa	$c_u^{(r)}$ = 19.8 kPa
Friction angle	φ'_k = 16.6°	$\varphi^{(r)}$ = 14.94° ≈ 15°
Factor for bearing resistance	N_c = 12.05 N_q = 4.59 N_γ = 2.14	N_C = 10.98 N_D = 3.94 N_B = 0.59
Factor for shape of foundation	s_c = 1.32 s_q = 1.25 s_γ = 0.73	1 + 0.3(*B/L*) = 1.27 1 + 1.5 (*B/L*) = 2.33 1 – 0.25 (*B/L*) = 0.78
Factor for inclination of the load	i_c = 0.95 i_q = 0.96 i_γ = 0.94	i_C = 0.95 i_D = 0.96 i_B = 0.93
Characteristic bearing resistance	R_k = 2260 kN	Q_{fNB} = 2254 kN
Partial/correction factor	$1/\gamma_R$ = 1/1.4 = 0.71	*m* = 0.9
Design bearing resistance	R_d = 1614 kN	$0.9Q_{fNB}$ = 2029 kN
Design effects of actions	E_d = 1455 kN	Q_r = 1562 kN
LCU	**90.15%**	**76.98%**

2.2. Problem with eccentricity

It is well known in polish standards that eccentricity of resultant actions can't protrude beyond the core of the section that is *B*/6, where *B* is the width of the foundation. The lack of satisfaction provided by these conditions can therefore lead to an enlargement of the foundation width to avoid lifting. For foundations with a width smaller than 1.0 meter it is quite possible to deal with this condition.

In EC7 the problem is treated less seriously if not ignored. Firstly the boundary of eccentric load is place only at *B/*3 which is twice the value pointed out by polish standards. Secondly where the eccentricity of loading exceeds the *B/*3 the situation is called *Load with large eccentricity,* therefore special precautions should be taken. The recommendations given here boil down to: A careful review of the design values of actions and designing the location of the foundation edge by taking the magnitude of construction tolerances into account. The natural conclusion is that **Eurocde 7 removes the lower limit on the foundation width** which existed in PN-B-03020:1981P, although not expressed directly.

2.3. Undrained Conditions

The distinction between drained and undrained conditions is well known in Geomechanics. Eurocode 7 also introduces (rather unknown in polish design) bearing resistance calculations for undrained Conditions:

$$R = A'([\pi + 2]c_u i_c s_c b_c + q) \tag{5}$$

where:

- c_u – undrained shear strength,
- i_c, s_c, b_c – factors for: bearing resistance, shape and base inclination respectively,
- q – overburden or surcharge pressure at the level of the foundation base.

In the equation (5) undrained shear strength c_u plays the most important part. It can be derived from laboratory testing such as fall cone and triaxial testing or *in situ* investigations such as the Field Vane Test (FVT) and Cone Penetration Test (CPT).

Whether the Undrained Conditions (UC) can be unfavorable and therefore decisive is highly questionable. They are even omitted in PN-B-03020:1981P.

For a circular footing of 1.6 m in diameter and for the following soil parameters: φ'_k = 15.7°, c'_k = 35.9 kPa and c_u = 68 kPa, where φ'_k, c'_k are characteristic effective cohesion and friction angle – bearing resistance in UC R_{kUC} = 602 kN while in DCR_{kDC} = 911 kN. It is noticeable that for the design effects of actions of E_d = 618 kN and design resistances equal R_{dUC} = 430 kN and R_{dDC} = 650 kN under UC and DC respectively – the first case the ULS is not satisfied. All values are more clearly presented in Table 4.

Table 4

Comparison of the calculations of the bearing resistance under Drained and Undrained Conditions

	UC	DC
Effective cohesion	–	c'_k = 35.9 kPa
Effective friction angle	–	φ'_k = 15.7°
Shear strength	c_u = 68 kPa	–
Formula use to calculated R_k	(5)	(2)
Overburden pressure	q = 29.88 kPa	q' = 22.88 kPa
Characteristic bearing resistance	R_{kUC} = 602 kN	R_{kDC} = 911 kN

cd. tab. 4

	UC	DC
Design bearing resistance	R_{dUC} = 430 kN	R_{dDC} = 650 kN
Design effects of actions	E_d = 618 kN	
LCU	**ULS not satisfied**	**95%**
'Proper' shear strength	c_u = 100 kPa	–
Characteristic bearing resistance	R_{kUC} = 909 kN	R_{kDC} = 911 kN
Design bearing resistance	R_{dUC} = 649 kN	R_{dDC} = 650 kN
LCU	**95%**	**95%**

This situation should not take place due to the fact that soil having the strength parameters mentioned in the Table 4, shear strength should be larger than 100 kPa. Design bearing resistance in UC for c_u = 100 kPa rises to 649 kN and the Ultimate Limit State is fulfilled. But this observation is derived from geotechnical experience only as there is no relationship between cohesion, friction angle and shear strength in practise.

From an economical point of view it may be wise to check the ULS in undrained Conditions for such sub soils (rather made ground than natural deposit) which show an unnatural disproportion between cohesion, friction angle and shear strength. In this case calculations should then be carried very carefully, every possible reaction should be considered and no phenomena ignored even if that means a complete change in design philosophy.

2.4. Serviceability Limit State

It is worth mentioning that Eurocode 7 takes three components of settlement into account: immediate, caused by consolidation and creep, while in polish standards only the first two are considered. The Serviceability Limit State (SLS) is written as:

$$E_d \leq C_d \tag{6}$$

where:

E_d – design value of the effect of actions,
C_d – limiting design value of the relevant serviceability criterion.

Eurocode 7 also states that calculations of settlements should not be regarded as accurate as they merely provide an approximate indication. A National Annex of specific values of the relevant serviceability criterions are given. They seem to be very general and chosen in the manner that most of the SLS could be fulfilled. In that context SLS does not influences the cost-effectiveness of a foundation and thus is not a point of interest of this paper.

3. Soil parameter derived from field testing

Aside from the alternative methods of calculations mentioned in PN-EN 1997-1:2008P (see Section 2), the second part of the Eurocode 7 standard recommends numerous way of establishing bearing resistance and/or settlements by means of field testing. Table 5 shows which soil parameters and from which *in situ* tests, can be derived and used directly or indirectly to check Limit States.

Table 5

Different values derived from field testing and used directly or indirectly in Limit States according to PN-EN 1997-2:2009P

Field testing type	Soil parameter	Limit State	Letter of the Annex
CPT – Cone Penetration Test	effective friction angle, oedometer modulus, modulus of elasticity	ULS, SLS	D1÷D5
PMT – Pressure Meter Test	bearing resistance, settlement	ULS, SLS	E1÷E3
SPT – Standard Penetration Test	density index, effective friction angle, settlement	ULS, SLS	F1÷F3
DP – Dynamic Probing	density index, effective friction angle, oedometer modulus	ULS, SLS	G1÷G3
WST – Weight Sounding Test	effective friction angle, modulus of elasticity	ULS, SLS	H
FVT – Field Vane Test	undrained shear strength	ULS	I
DMT – Flat Dilatometer Test	oedometer modulus	SLS	J
PLT – Plate Loading Test	undrained shear strength, settlement	ULS, SLS	K1, K2

4. Conclusions

All methods of design mentioned in the previous chapters are often not applicable to the situations where: the subsoil presents a definite structural pattern of layering and discontinuities, the properties of layered deposits vary greatly between one another or a strong formation underlies a weak formation. Numerical procedures should then be applied to determine the most unfavourable failure mechanism.

Although not commented on in EC7, the use of numerical methods is known to be cost-effective for large and extra large projects only. Modelling other problems, by means of numerical methods will lead to an overestimation in dimensions and stiffness, thus increasing investment costs.

On the other hand numerical methods can be appropriate if the compatibility of strains or the interaction between the structure and the soil at a limit state are considered. Detailed analysis, allowing for the relative stiffness of a structure and the ground, may be required in cases where a combined failure of structural members and the ground could occur. Examples include raft foundations, laterally loaded piles and flexible retaining walls. Particular attention should be paid to the strain compatibility for materials that are brittle or that have strain-softening properties. In that context numerical methods are highly profitable and should be recommended, not only for large projects, but also for modelling the behaviour of complex structures and materials.

After the introduction of Eurocode 7, design projects became more sensitive to ground investigation than ever. Thus more resources call for the allocation of laboratory and field testing of the subsoil. This will definitely raise the cost of preparing geotechnical reports.

It is also possible that existing spread foundations recalculated according to Eurocode 7 will not satisfy the Ultimate Limit State, proving the EC7 tendency to over design this type of foundation.

Although the design procedures in EC7 and PN are different and lead to different dimensions of the foundation, they should not entail changes on the level of technology. Therefore, from the financial point all these changes will reflect more on construction material and labor than construction equipment.

The paper presents an engineering rather than economic perspective of cost-effectiveness of the investment. In this context the introduction of new standards may increase the cost of investment which doesn't necessarily mean a drop of cost-effectiveness. For example detailed and wide soil testing are always profitable and insures against unexpected subsoil failure. EC7 is a standard which emphasizes the role of *in situ* tests and the soil parameters obtained that way can be seen in table 5.

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