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DESIGN OF DEEP EXCAVATIONS ACCORDING TO EUROCODE 7

ANNA SIEMIŃSKA-LEWANDOWSKA, MONIKA MITEW-CZAJEWSKA

Warsaw University of Technology,
al. Armii Ludowej 16, 00-637 Warsaw, Poland. a.lewandowska@il.pw.edu.pl

Abstract: The paper presents the procedure of introducing Eurocode 7 into the design practice in Poland. In the paper, currently used design methods have been compared with new ones, which soon will be used simultaneously with the introduction of Eurocodes. In order to enable the comparison, numerical analysis has been performed on two simple example cases presented by the committee ERTC-10 "Evaluation of Eurocode 7". This gave the authors an opportunity to assess and compare properly different design approaches – up-to-date and new, now being introduced. Final conclusions and issues giving rise to further discussion have been presented at the end of the paper.

1. INTRODUCTION

The paper presents the procedure of introducing EN1997-1:2004 Eurocode 7 into the design practice in Poland. During the past 10 years in Poland a great number of deep excavations for underground car parks, metro stations and tunnels or road tunnels have been built. These excavations are usually conducted under very complex geotechnical conditions with high water table, using as a support the diaphragm walls or retaining walls. The attempts to implement European codes, including Eurocode 7 Geotechnical design, are now in progress. In the year 2007, engineers should have learned new recommendations, design approaches and requirements collected in Eurocode. That was the very reason for the comparison of the methods currently being in use with those which soon will be obligatory due to the introduction of Eurocodes.

In order to make the comparison, numerical analyse have been performed on two example cases presented by the committee ERTC-10 "Evaluation of Eurocode 7". These cases are: cantilever sheet pile retaining the wall embedded in sands and anchored sheet pile retaining the wall serving as a harbour quay. Figures 1 and 2 show detailed data regarding both examples. Calculations have been performed according to the following methods:

• Classical method using Polish software "PAL", BPBKiS "Metroprojekt" 1984, determining the resultants of active and passive pressures according to the Coulomb–Mohr theory.

• Limit states method using software "GEO4 Sheeting design", FINE 2004.

• Dependent pressures method with the consideration of limit states using software "GEO4 Sheeting check", FINE 2004.

• Dependent pressures method – software: "RIDO", Fages 2003.

In total, 24 analyses have been performed to determine a minimum depth of the embedment of the wall below the bottom of the excavation and also bending moments in the wall. In addition, maximum lateral displacements of the wall have been compared. Two independent calculation runs have been carried out:

- The first calculation run – in compliance with currently obligatory Polish Code, PN-83/B-03010.
- The second calculation run – in accordance with the recommendations of EN 1997-1:2004.

2. CALCULATION ASSUMPTIONS

2.1. THE FIRST CALCULATION RUN

The first calculation run has been performed based on the recommendations of PN-83/B-03010. According to Polish Code a retaining wall is treated as a beam with active and passive pressures applied, both calculated using the Coulomb–Mohr theory. The values of material partial factors, load partial factors, safety factor applied to soil resistance, structure–ground interface friction angle for calculating active and passive pressure coefficients as well as subgrade reaction modulus (k_h), estimated based on PN-83/B-03010, are given below and/or in the description of example cases:

- γ_m = 1.1 – partial factor for weight density of the soil at active pressures,
- γ_m = 0.9 – partial factor for weight density of the soil at passive pressures,
- γ_φ = 0.9 – partial factor for the angle of shearing resistance,
- γ_f = 1.2 – partial factor for the surcharge on the surface behind the wall,
- n = 1.5 – reduction of soil resistance below the bottom of excavation,
- n = 1.1 – partial factor for the resultant of active pressures in the PAL program,
- δ = $2/3\phi'$ – structure–ground interface friction angle at active pressures,
- δ = $-2/3\phi'$ – structure–ground interface friction angle at passive pressures.

Designed values of geotechnical parameters (X_d) shall either be assessed directly or shall be derived from representative values (X_k) using the following equation:

$$X_d = X_k \gamma_m.$$

2.2. THE SECOND CALCULATION RUN

The second calculation run has been performed based on recommendations of EN1997-1:2004 Eurocode 7. According to Eurocode 7 retaining walls should be designed at limit states of rupture. In this case, either the resistance of soil during failure or its excessive deformation is critical. Point 2.4.7.3.4. of EN1997-1:2004 Eurocode 7 specifies 3 Design Approaches with the combinations of the sets of partial safety factors referring to: actions, parameters and resistance of soil.

• In the 1st design approach, the following combinations of the sets of partial factors are used for the calculation of limit state:

Combination No. 1: A1 + M1 + R1.

Combination No. 2: A2 + M2 + R1.

• In the 2nd design approach, the following combination of the sets of partial factors is used for the calculation of limit state:

Combination No: A1 + M1 + R2.

• In the 3rd design approach, the following combination of the sets of partial factors is used for the calculation of limit state:

Combination No. 1: A2 + M2 + R3.

For the verification of structural (STR) and geotechnical limit states the set A1 or the set A2 given in table A.3 of EN1997-1:2004 of the partial factors of actions (γ_F) or the effects of actions (γ_E) shall be applied. For the cases analysed in this paper, the following actions are taken into consideration:

- weight of the soil and water,
- stresses in the ground,
- soil pressure and groundwater pressure,
- characteristic (not factored) surcharges and constant loads applied to the structure,
- characteristic (not factored) surface surcharges behind the wall,
- imposed pre-stress in ground anchors or struts.

For the verification of structural (STR) and geotechnical (GEO) limit states the set M1 or the set M2 given in table A4 of EN1997-1:2004 Eurocode 7 of the partial factors on geotechnical parameters of soils (γ_M) shall be applied. Designed values of geotechnical parameters (X_d) shall either be assessed directly or shall be derived from representative values using the following equation:

$$X_d = \frac{X_k}{\gamma_M}.$$

For retaining structures and verifications of limit states (STR, GEO) the sets R1, R2 or R3 included in table A13 of the EN1997-1:2004 Eurocode 7 of partial factors on soil resistance shall be applied. Due to the limitations of the software used for calculations it was not always possible to implement all specific recommendations of this code. After having analysed the possibility of introducing these sets partial factors into the software used for the analysis, the Combination No. 2 from the 1st Design Approach has been chosen for further compilation. Therefore the following partial factors and parameters have been applied in the calculation:

- $\gamma_G = 1$ – from the set A1, for actions,
- γ_M – from the set M2, to soil parameters.
- $\gamma_{R;e} = 1$ – from the set R1, to the resistance of the soil,
- $\delta = 2/3\phi_k$ – structure–ground interface friction angle for active pressures,
- $\delta = -2/3\phi_k$ – structure–ground interface friction angle for passive pressures.

Note: the partial factor γ'_ϕ is applied to $\tan\phi'_k$.

Other parameters used in the calculation are given in the description of example cases.

3. EXAMPLE CASES

3.1. EMBEDDED SHEET PILE RETAINING WALL

Embedded sheet pile retaining wall for a 3 m deep excavation with a 10 kPa characteristic (not factored) surcharge on the surface behind the wall is shown in figure 1.

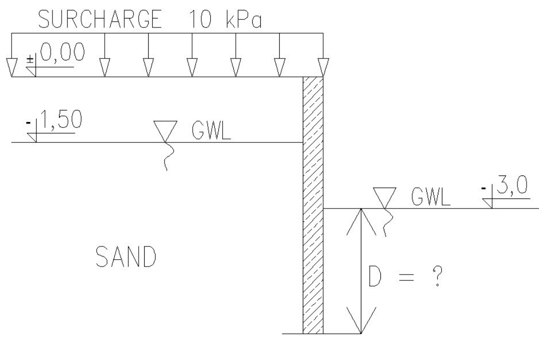

Fig. 1. Embedded, cantilever sheet pile retaining wall, the 1st example case

Soil conditions and parameters:

- Sand: $\phi'_k = 37$, $c'_k = 0$, $\gamma = 18$ kN/m^3, $\gamma_{sr} = 20$ kN/m^3.

Actions:

- Characteristic surcharge on the surface behind the wall, 10 kPa.
- Groundwater level at the depth of 1.5 m below ground surface behind the wall and at the ground surface in front of the wall.

Additional data:

- $\phi'_d = 33.3°$ according to Polish code; $\phi'_d = 31.1°$ according to Eurocode 7.
- Subgrade reaction modulus (from the nomogram of CHADEISSON [1]):

k_h = 36 MN/m^3 (in the calculation run according to Polish code),
k_h = 29.8 MN/m^3 (in the calculation run according to Eurocode 7).

The results of all calculations of the embedded sheet pile retaining wall are presented in table 1.

Table 1

The results of calculations of the cantilever sheet pile retaining wall

	Results of calculations according to PN-83/B-03010				Results of calculations according to EN1997-1:2004 EUROCODE 7			
	Classical method		Pressure--dependent method		Classical method		Pressure--dependent method	
	GEO 4	PAL	GEO 4	RIDO	GEO 4	PAL	GEO 4	RIDO
D [m]	4.24	5.84	4.20	4.20*	3.75	6.08	4.70	4.70*
M_{max}[kNm/m]	114.83	93.86	94.60	92.52	105.10	95.01	121.84	110.71
u_{max} [mm]			48.64	38.49			55.62	53.23

* Calculations based on RIDO program have been carried out taking into account the depth of embedment resulting from the GEO4 calculations in order to compare the obtained values of bending moments and lateral displacements.

D – the depth of wall embedment below the bottom of the excavation, M_{max} [kNm/m] – the maximum design bending moment, u_{max} [mm] – the maximum horizontal displacement of the wall.

3.2. ANCHORED SHEET PILE QUAY WALL

Anchored sheet pile retaining wall for an 8 m high quay using a horizontal tie bar anchor is shown in figure 2.

Soil conditions and parameters:

- Gravelly sand: ϕ'_k = 35°, c'_k = 0, γ = 18 kN/m^3, γ_{sr} = 20 kN/m^3.

Actions:

- Characteristic surcharge behind wall, 10 kPa,
- Groundwater level at the depth of 1.5 m below ground surface behind the wall and at the ground surface in front of the wall.

Additional data:

- ϕ'_d = 31.5° according to Polish code, ϕ'_d = 29.3° according to Eurocode 7.
- Subgrade reaction modulus (from the nomogram of CHADEISSON [1]):
  k_h = 30 MN/m^3 (in the calculation run according to Polish code),
  k_h = 26.5 MN/m^3 (in the calculation run according to Eurocode 7).

In both GEO4 and RIDO programs, anchor has been modelled as an elastic support. The results of all calculations are presented in table 2.

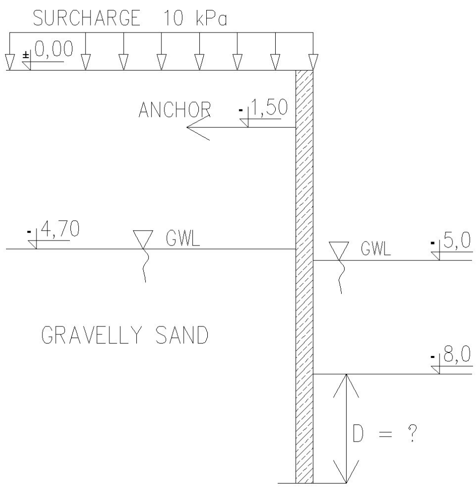

Fig. 2. Anchored sheet pile retaining wall, the 2nd example case

Table 2

The results of calculations of the anchored sheet pile retaining wall

	Results of calculations according to PN-83/B-03010				Results of calculations according to EN1997-1:2004 EUROCODE 7			
	Classical method		Pressure-dependent method		Classical method		Pressure-dependent method	
	GEO 4	PAL	GEO 4	RIDO	GEO 4	PAL	GEO 4	RIDO
D [m]	3.35	3.8	3.90	3.90*	5.23	3.80	5.00	5.00*
M_{max} [kNm/m]	226.24	188.34	160.83	163.93	186.62	172.79	183.35	209.96
u_{max} [mm]			33.10	32.96			68.55	51.96

* Calculations based on RIDO program have been carried out taking into account the depth of embedment resulting from the GEO4 calculations in order to compare the obtained values of bending moments and lateral displacements.

D [m] – the depth of wall embedment below the bottom of the excavation, M_{max} [kNm/m] – the design bending moment in the wall, u_{max} [mm] – the maximum horizontal displacement of the wall.

4. CONCLUSIONS

The example cases proposed by the ERTC-10 committee are very simple in terms of structural and geotechnical conditions. This allowed us to assess and compare properly different design approaches – up-to-date and new, now being introduced. All software used for calculations is widely known and often applied in the engineering practice in Europe. The best software was chosen from the wide variety available on the Polish market. It may be noticed that lately, in the design practice for the analysis of retaining structures, the pressure-dependent method is more often used as it models the soil structure interaction in a better way.

The analysis of the results of all calculation series based on both Polish and Eurocodes differing classical and pressure-dependent methods has been carried out. As a complement, a crude comparison of the results obtained based on Polish Code versus Eurocode has been made without differing calculation methods. The differences in percentages between extreme (maximum EC and minimum PC) values of *D* (the depth of the wall embedment), M_{max} (the design bending moment) and u_{max} (the maximum lateral displacement) have been calculated. These differences are presented in table 3.

Table 3

Comparison of the results of calculations; "+" stands for the increase in the value

	Differences in percentage [%]									
	Classical method				Pressure-dependent method				Overall	
	PAL (PN)-PAL (EU)		GEO 4 (PN)-GEO 4 (EU)		GEO 4 (PN)-GEO 4 (EU)		RIDO (PN)-RIDO (EU)		PN - EU	
	C	A	C	A	C	A	C	A	C	A
D	+ 3.9	0	–11.5	+35.9	+10.6	+ 22	–	–	+ 30	+ 35
M_{max}	+1.4	–8.3	–8.,5	–17.5	+ 22	+12.3	+16.4	+23.4	+ 24	–23.6
u_{max}					+12.5	+51.7	+27.1	+35.4	+ 30	+51.7

C – cantilever sheet pile retaining wall; A – anchored sheet pile retaining wall.

The analysis of the results indicates that the values of *D*, M_{max}, u_{max} calculated based on EN1997-1:2004 EC 7 recommendations are significantly higher than the same values obtained based on Polish Code PN-83/B-03010. The only exception is the result of cantilever wall calculation carried out using classical method. The difference between the results obtained according to EN1997-1:2004 Eurocode 7 and Polish Code concerning the depth of embedment of the wall and the design bending moment ranges between 10 to 35%, depending on the calculation method. Taking into consideration the calculated values of maximum lateral displacements, these differences reach 50%. The authors suppose that this result occurs due to the considerable differences in the reduction of the value of angle of shearing resistance of the soil; according to EN1997-1:2004 Eurocode 7 the partial factor γ'_ϕ equals 1.25 (γ'_ϕ is applied to $\tan\phi'_k$), while in Polish Code $\gamma = 1/0.9 = 1.11$ (applied directly to ϕ'_k). In general, the values of the shearing resistance and the soil cohesion influence greatly the results of calculations in both GEO4 and RIDO programs.

It should be stressed that, as was noticed above, the retaining structures from the examples considered in the paper (proposed by ERTC 10) are very simple. The question arises – what will be the results in the case of more complicated embedded structures under complex geotechnical conditions? When more complex cases are to be modelled, bigger differences may occur. Moreover, one must remember that in such cases simple design methods are usually insufficient. The use of more sophisticated methods, such as, e.g., finite elements method, is required. What differences will be obtained as a result? These problems should be analysed and discussed in the nearest future. We also should accept the necessity of taking a special care of Eurocode 7 after its introduction.

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