Design of deep excavations according to Eurocode 7

Siemińska-Lewandowska Anna, Mitew-Czajewska Monika

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. Within the paper, currently used design methods have been compared to new ones, which will be soon used together with the introduction of Eurocodes. In order to make the comparison, numerical analysis has been performed on two simple example cases presented by the committee ERTC-10 „Evaluation of Eurocode 7". That gave authors an opportunity to assess and compare properly different design approaches – up-to-date and new, now being introduced. Final conclusions and issues open for further discussion have been presented in the end of the paper.

Résumé :

La nouvelle norme PN - EN 1997-1 Calcul géotechnique. Patrie 1. Règles générales *viens de paraître en Pologne en juin 2007. On présente les résultats de calcul des deux examples proposées par committée ERTC-10, obtenus par la méthode du module de réaction,s en utilisant deux logiciels (GEO4 et RIDO). Le calcul on a conduit suivant la Norme Polonaise et les deux Approches de Calcul de Eurocode 7. La validité des résultats obtenus est discutée.*

Key-words :

retaining wall ; design approach

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 executed in a very complex geotechnical conditions with high water table using as a support diaphragm walls or retaining walls. The works on implementation of European codes, including Eurocode 7 Geotechnical design, are now in progress. Last year was dedicated for engineers to learn new recommendations, design approaches and requirements brought by Eurocode. That was the reason why it was necessary to compare methods currently being in use with the ones, which will be soon obligatory.

The new design methods will be soon used, due to the introduction of Eurocodes. In order to make the comparison, numerical analysis have been performed on two example cases presented by the committee ERTC-10 „Evaluation of Eurocode 7". These cases are: cantilever sheet pile retaining wall embedded in sands and anchored sheet pile retaining wall serving as a harbour quay. Pictures 1 and 2 show detailed data regarding both examples. Calculations have been performed using the following methods:

- Classical method using Polish software „PAL", BPBKiS „Metroprojekt" 1984, determining resultants of active and passive pressures according to Coulomb-Mohr theory,
- Limit states method using software "GEO4 Sheeting design", FINE 2004,

- Dependent pressures method with consideration of limit states using software "GEO4 Sheeting check", FINE 2004,
- Dependent pressures method – software: "RIDO", Fages 2003.

In total 24 analysis have been performed which have determined minimum depth of 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:

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

2 Calculation assumptions

2.1 First calculation run

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

- $\gamma_m = 1,1$ - partial factor for weight density of the soil, for active pressures,
- $\gamma_m = 0,9$ - partial factor for weight density of the soil, for passive pressures,
- $\gamma_\varphi = 0,9$ - partial factor for the angle of shearing resistance,
- $\gamma_f = 1,2$ - partial factor for the surcharge on the surface behind the wall,
- $n = 1,5$ - reduction of soil resistance below the bottom of the excavation,
- $n = 1,1$ - partial factor for the resultant of active pressures in the program PAL,
- $\delta = 2/3\phi'$ - structure-ground interface friction angle for active pressures,
- $\delta = -2/3\phi'$ - structure-ground interface friction angle for 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 Second calculation run

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

- In the 1st design approach, following combinations of sets of partial factors are used for the calculation of limit state:
  Combination N^o 1: A1 + M1 + R1
  Combination N^o 2: A2 + M2 + R1
- In the 2nd design approach, following combination of sets of partial factors is used for the calculation of limit state:
  Combination N^o 1: A1 + M1 + R2
- In the 3rd design approach, following combination of sets of partial factors is used for the calculation of limit state:
  Combination N^o 1: A2 + M2 + R3

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

- weight of the soil and water,
- stresses in the ground,
- soil pressures and ground-water 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 set M1 or set M2 given in the 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:

$X_d = X_k/\gamma_M$

For retaining structures and verifications of limit states (STR, GEO) sets R1, R2 or R3 included in the 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 partial factors sets into the software used for the analysis, the Combination number 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: partial factor γ_ϕ' is applied to $\tan\phi'_k$.

Other parameters used in the calculation are given below, in the example cases description part.

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. Figure 1 shows detailed data concerning this example.

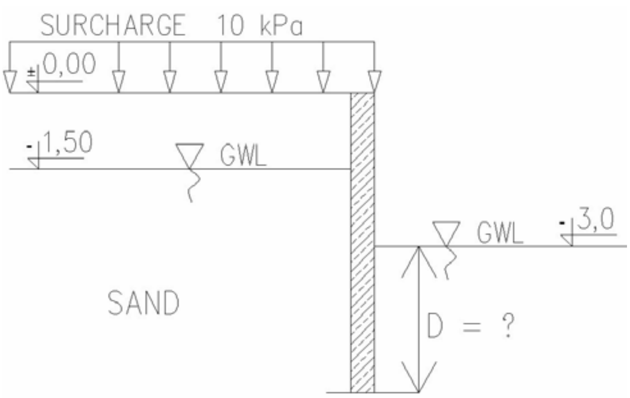

FIG. 1 – Embedded, cantilever sheet pile retaining wall, 1st example case.

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 - 10kPa,
- Groundwater level at depth of 1.5m 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 (1961)):
  $k_h = 36$ 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 the table 1, where: D – depth of wall embedment below the bottom of the excavation, M_{max} [kNm/m] – maximum design bending moment, u_{max} [mm] – maximum horizontal displacement of the wall.

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		dependent pressures method		classical method		dependent pressures 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 using RIDO program has been done taking into account the depth of embedment resulting from the GEO4 calculations in order to compare obtained values of bending moments and lateral displacements.

3.2 Anchored sheet pile quay wall

Anchored sheet pile retaining wall for an 8 m high quay using a horizontal tie bar anchor. Figure 2 shows detailed data concerning this example.

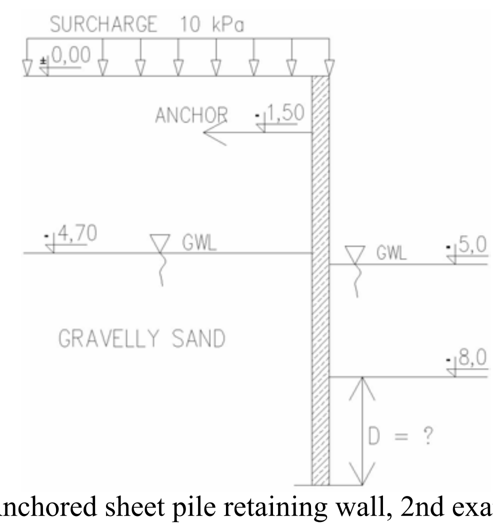

FIG. 1 – Anchored sheet pile retaining wall, 2nd example case.

Soil conditions and parameters:

- Gravelly sand: $\phi'_k = 35°$; $c'_k = 0$; $\gamma = 18$ kN/m^3; $\gamma_{sr} = 20$ kN/m^3,

Actions:

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

Additional data:

- $\phi'_d = 31{,}5°$ according to Polish code; $\phi'_d = 29{,}3°$ according to Eurocode 7,
- Subgrade reaction modulus (from the nomogram of Chadeisson (1961)):
  $k_h = 30$ 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 anchors has been modelled as an elastic support. The results of all calculations are presented in the table 2, where: D [m] – depth of wall embedment below the bottom of the excavation, M_{max} [kNm/m] – design bending moment in the wall, u_{max} [mm] – maximum horizontal displacement of the wall.

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		dependent pressures method		classical method		dependent pressures 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 using RIDO program has been done taking into account the depth of embedment resulting from the GEO4 calculations in order to compare obtained values of bending moments and lateral displacements.

4 Conclusions

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

The analysis of the results have been performed considering the results of all calculation series taking into account both Polish and Euro Codes differing classical and dependent pressures methods. As a complementation general comparison of the results obtained after Polish Code versus Eurocode have been presented without differing calculation methods. Differences in percentages between extreme (maximum EC and minimum PC) values of D (depth of the wall embedment), M_{max} (design bending moment) and u_{max} (maximum lateral displacement) have been calculated. These differences are presented in the table 3, where C – stands for cantilever sheet pile wall, A – anchored sheet pile wall.

Table 3. Comparison of the results of calculations; „+" stands for the increase of the value

	differences in percentage [%]									
	classical method				dependent pressures 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

Analysis of the results indicate that values D, M_{max}, u_{max} calculated basing on EN1997-1:2004 EC 7 recommendations, are significantly higher then same values obtained after Polish Code PN-83/B-03010. The only exception is the result of cantilever wall calculation using classical method. The difference between the results obtained basing on EN1997-1:2004 Eurocode 7 and Polish Code concerning the depth of embedment of the wall and the design bending moment ranges between 10 do 35%, depending on the method of the calculation. Taking into consideration calculated values of maximum lateral displacements these differences reach 50%. 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 partial factor equals to γ_{ϕ}' = 1,25 (γ_{ϕ}' is applied to $\tan\phi'_k$), while in Polish Code it's value amounts to γ=1/0,9=1,11 (applied directly to ϕ_k'). In general, values of shearing resistance and cohesion of the soil influence highly the results of calculations in both programs GEO4 and RIDO.

It should be stressed that, as it was noticed above, the retaining structures from the examples considered in the paper (proposed by ERTC 10), are very simple solutions. The question rises – what are going to be the results in the case of more complicated structures embedded in complex geotechnical conditions? When more complex cases are to be modelled, bigger differences in the results may occur. More over, one must remember that in such cases simple design methods are usually not sufficient. The use of more sophisticated methods, such as e.g. finite elements method, are required. What differences will be obtained in the results then? These are the problems, which should be analysed and discussed in the nearest future. Also that indicates necessity of special care to be taken, when Eurocode 7 will be introduced into practice.

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