Design of diaphragm walls according to EN 1997-1:2004 Eurocode 7

Le calcul de 'parois and moulées' sur la base EN 1997-1:2004 Eurocode 7

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ABSTRACT

In 2007, Polish new standard *PN - EN 1997-1 Geotechnical design. Part 1. General Rules* will be issued. Currently in Poland there are discussions concerning the introduction of the Eurocode 7 and the choice of Design Approach (DA) for the National Annex, for example to deep excavation walls. Due to the above, analysis of three standard design problems were performed. Analysis were made in order to make the comparison between currently used design methods and new ones, which will be soon used together with the introduction of EC7. In the conclusions, recommendations for the purpose of evaluation of the Polish National Annex are presented.

RÉSUMÉ

En 2007, paraîtra en Pologne la nouvelle norme *PN - EN 1997-1Calcul géotechnique. Patrie 1. Règles générales*. La disscusion conçernant le choix des Approches de Calcul en Annexe Nationale pour le dimensionnement de paroi moulée est en cours. Calcul des trois examples, conduit suivant la Norme Polonaise et les deux Approches de Calcul de EC7, par la méthode du module de réactions et méthode des éléments finis sont comparés. L'examen des résultats montre, que pour le calcul de parois moulée sur la base EC7 l'Approche de Calcul 2 peut être récommandée dans Annexe Nationale.

1 INTRODUCTION

In Poland, since 2004 and before, when Poland was only an associated member in CEN, the works on implementation of European codes, including Eurocode 7 Geotechnical design, have been carried out. Last year was dedicated for engineers to learn new rules, recommendations, design approaches and requirements brought by the Eurocode. Translated into Polish, identical to the original, *PN - EN 1997-1 Geotechnical Design. Part 1. General Rules* will be issued in Poland in 2007, which means that Poland adopts Eurocode 7 for geotechnical design. In this code thirty points has been listed, which must be specified in National Annexes. These are e.g. the choice of Design Approaches (DA), the choice of soil behavioural models and the choice of values of partial safety factors, defined in the Appendix A of the Eurocode 7. Currently, in Poland, discussions are held concerning the introduction of the Eurocode 7 for example to the design of deep excavation walls and the choice of DA for the National Annex. The last issue is now of a great importance, because a significant raise in construction of underground structures in Poland is expected. A great number of deep excavations for underground car parks, metro stations or road tunnels will be built. These excavations are usually executed in a very complex geotechnical conditions with high water table using as a support diaphragm walls. These requires a special care to be taken while choosing Design Approach and other data for Polish National Annex of Eurocode 7. Analysis were made in order to make the comparison between currently used design methods and new ones, which will be soon used together with the introduction of Eurocodes.

2 CALCULATIONS ASSUMPTIONS

Calculations of three standard design problems were performed. These cases were: cantilever diaphragm wall embedded in sands, anchored and strutted diaphragm walls. First two cases are modified examples N° 6 and 7 proposed by the committee ERTC-10 "Evaluation of Eurocode 7", in which retaining walls were replaced by 80 cm thick diaphragm walls. Third example concerns an excavation within strutted diaphragm wall - method of support of excavation walls very common in Poland. This case was obtained from the database owned by polish delegate to GeoTechNet.

Calculations were performed using following methods:

- Dependent pressures method, according to Polish Code PN-83/B-03010 Design of retaining walls,
- Dependent pressures method, according to Eurocode 7,
- Finite Elements Method according to Eurocode 7.

Dependent pressures method was chosen because of its simplicity and as it is very common in European and Polish design practice.

According to Eurocode 7 retaining walls should be designed at limit states (GEO). Point 2.4. of Eurocode 7 specifies 3 Design Approaches with combinations of partial safety factors referring to surcharges, material coefficients and soil resistance. Calculations were performed using two combinations of partial safety factors from the first Design Approach (DA1), named DA1A and DA1B as well as the DA2. Third DA (DA3) was ignored, because of the similarity in the values of partial safety factors.

Calculations employing dependent pressure method were performed using software GEO5 Sheeting check. The method of evaluation of subgrade reaction modulus (k_h) based on nomogram of Chaidesson was chosen.

Finite element plain strain analysis were carried out using PLAXIS software. Coulomb-Mohr constitutive soil model was chosen for modelling the soil body, diaphragm walls were modelled as beam elements. Non-associated plastic flow law was considered. For modelling wall frictions Coulomb-Mohr low was used. Water pressures were estimated by calculating groundwater flow. FEM model mesh, generated automatically, was built of 15-nodes triangle elements. Two combinations of partial safety factors DA1A and DA1B were considered in finite element method analysis

Representative values of actions were calculated assuming the value of coefficient $\psi = 1.00$, according to PN EN 1990 Basis of structural design. Design values of actions were calculated applying partial safety factors according to Polish Code (PN) or Eurocode 7.

In total 18 analysis were performed determining minimum penetration of the diaphragm wall below the bottom of the excavation (D) and maximum bending moments (Mmax). In addition, maximum lateral displacements of the wall (Umax) were calculated and compared.

3 DESCRIPTION OF CALCULATIONS

3.1 Cantilever diaphragm wall

The geometry of the case is shown on Figure 1.

In this example following soil parameters were considered:

- $E = 100\,MPa$; $\nu = 0.3$; $\varphi_k' = 37°$; $c_k' = 0\,kPa$;
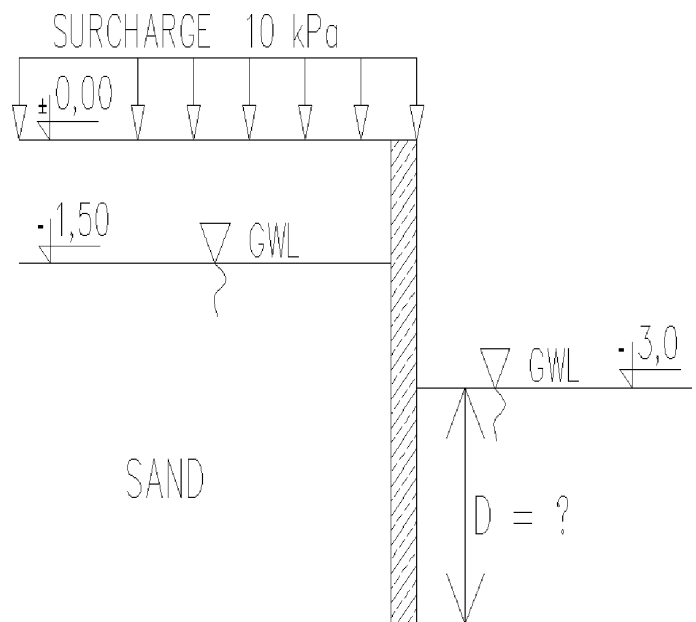- $\gamma_{saturated} = 20\,kN/m^3$; $\gamma_{above\ water\ table} = 19\,kN/m^3$;

Figure 1. First example case - geometry and soil conditions.

- $\delta = 1/2\ \varphi_k'$ (structure-ground interface friction angle for active earth pressures);
- $\delta = 2/3\ \varphi_k'$ (structure-ground interface friction angle for passive earth pressures).

For modelling the diaphragm wall following parameters were taken:

$E = 31\,GPa$; $\nu = 0.18$; $\gamma = 25\,kN/m^3$; $d = 0.80\,m$

In terms of actions: characteristic surcharge behind the wall - 10 kPa was considered as permanent load as well as groundwater level at depth of 1,5 m below ground surface behind the wall and at the ground surface in front of the wall was modelled. One construction stage was modelled – excavation till the depth of 3 m b.g.s. (Fig. 1).

3.1.1 Calculations according to PN - 83/B-03010
Calculations were performed using dependent pressures method. The values of material partial factors, load partial factors, safety factor applied to soil resistance, active and passive pressures coefficients as well as subgrade reaction modulus (k_h) are given below:

- partial factor for weight density of the soil, for active pressures: $\gamma_m = 0{,}91$
- partial factor for weight density of the soil, for passive pressures: $\gamma_m' = 1{,}11$
- partial safety factor for angle internal friction and cohesion of the soil: $\gamma_m'' = 1{,}11$
- partial safety factor for reduction of soil resistance in front of the wall: $n = 1{,}5$
- partial safety factor for characteristic surcharge (permanent and variable) on the surface behind the wall: $\gamma_f = 1{,}2$
- value of subgrade reaction modulus for reduced value of φ_k': $k_h = 39{,}35\,MN/m^3$

3.1.2 Calculations according to Eurocode 7
Calculations according to Eurocode 7 were performed using dependent pressures method as well as finite

element method. Design values of actions, design values of soil parameters and subgrade reaction modulus values are given it Table 1, for each Design Approach respectively. Surface surcharge was activated in the first construction phase.

In the DA2 partial safety factor for reduction of soil resistance in front of the wall $\gamma_R = 1,4$ was considered.

FEM model mesh, consisted of 677, 15-noded triangle elements (number of nodes: 5655). Values of K_0 were calculated for the reduced value of φ'_k, using equation: $K_0 = 1 - \sin \varphi'_k$. In FE calculations initial phase was considered with the input of K_0, in next stage diaphragm wall was activated as well as excavation and dewatering were modelled.

3.2 *Anchored diaphragm wall*

Second design example was anchored diaphragm wall. The geometry of the case is given on Figure 2. Two calculation stages were considered:

- stage 1 - excavation below the anchorage level, till the depth of 2,0 b.g.s., installation of anchors at the depth of 1,5 m b.g.s.,
- stage 2 - excavation to final depth of 8,0 m b.g.s., mobilization of anchors (Fig. 2).

Table 1. Design values of actions and soil parameters

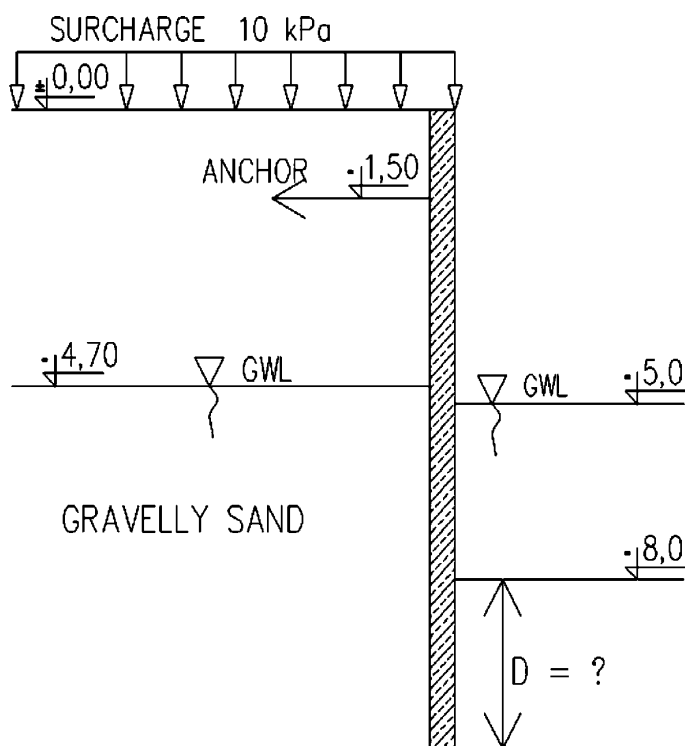| DA	Action kPa	φ'_d °	γ_s kN/m^3	γ_{awt} kN/m^3	k_h MN/m^3
DA1A	15	37	20	19	44,83
DA1B	13	31,1	20	19	36,12
DA2	15	37	20	19	44,83

Figure 2. Second example case – anchored diaphragm wall.

Diaphragm wall is embedded in sands of following properties:

- $E = 80 \, MPa$; $\nu = 0,3$; $\varphi'_k = 35°$;
- $\gamma_{below \, water \, table} = 20 \, kN/m^3$;
  $\gamma_{above \, water \, table} = 18 \, kN/m^3$;
- $\delta = 1/2 \, \varphi'_k$ (structure-ground interface friction angle for active earth pressures);
- $\delta = 2/3 \, \varphi'_k$ (structure-ground interface friction angle for passive earth pressures);

For modelling the diaphragm wall following parameters were taken:

$E = 31 \, GPa; \quad \nu = 0,18; \quad \gamma = 25 \, kN/m^3; \quad d = 0,80 \, m$

In terms of actions following was taken into account:

- characteristic surcharge behind the wall - 10 kPa was considered as permanent load.
- Groundwater conditions were stable in both construction stages. Groundwater level at the depth of 3,3 m below ground level behind the wall and 3,0 m below ground level in front of the wall were modelled.

3.2.1 *Calculations according to PN - 83/B-03010*
Calculations were performed using dependent pressures method. Construction phases were modelled as it was mentioned above, please refer to clause 3.2. Surface surcharge was activated in the first construction phase.

The values of material partial factors, load partial factors, safety factor applied to soil resistance, active and passive pressures coefficients as well as subgrade reaction modulus (k_h) are given below:

- partial factor for weight density of the soil, for active pressures: $\gamma_m = 0,91$
- partial factor for weight density of the soil, for passive pressures: $\gamma'_m = 1,11$
- partial safety factor for angle internal friction and cohesion of the soil: $\gamma''_m = 1,11$
- partial safety factor for reduction of soil resistance in front of the wall: $n = 1,5$
- partial safety factor for characteristic surcharge (permanent and variable) on the surface behind the wall: $\gamma_f = 1,2$
- value of subgrade reaction modulus calculated for reduced value of φ'_k: $k_h = 37,36 \, MN/m^3$

3.2.2 *Calculations according to Eurocode 7*
Calculations according to Eurocode 7 were performed using dependent pressures method as well as finite element method. Construction phases were modelled, clause 3.2. Surface surcharge was activated in the first construction phase.

Design values of actions, design values of soil parameters and subgrade reaction modulus values are given it Table 2, for each DA respectively.

In the DA2 partial safety factor for reduction of soil resistance in front of the wall $\gamma_R = 1,4$ was considered.

Table 2. Design values of actions and soil parameters

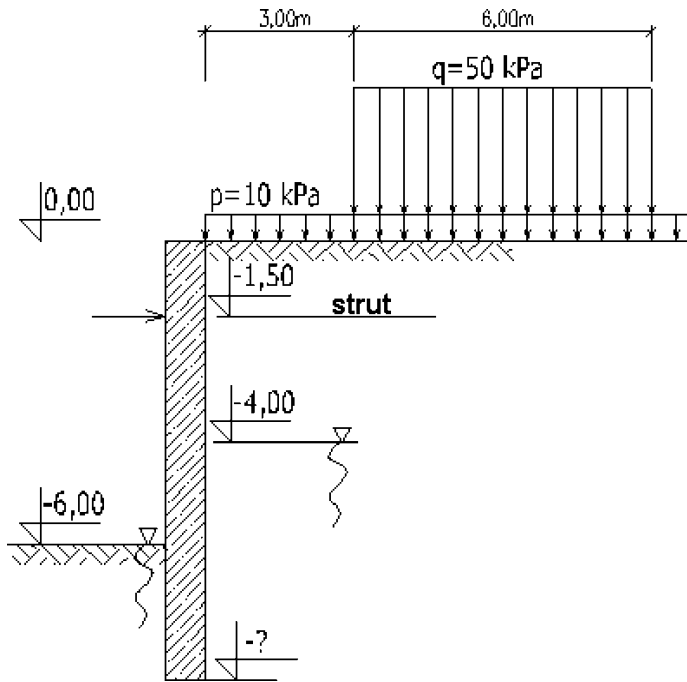| DA	Action kPa	φ'_d °	γ_s kN/m³	γ_{awt} kN/m³	k_h MN/m³
DA1A	15	35	20	18	41,40
DA1B	13	29,25	20	18	34,16
DA2	15	35	20	18	41,40

Figure 3. Third example case – strutted diaphragm wall.

FEM model mesh, consisted of 709, 15-noded triangle elements (number of nodes: 5982). Values of K_0 were calculated for the reduced value of φ'_k, using equation: $K_0 = 1 - \sin \varphi'_d$.

In FE calculations initial phase was considered with the input of K_0, in next stages diaphragm wall was activated and construction steps were introduced.

Following stiffness of anchors was considered: $EA = 150\,\text{MN/m}$.

3.3 Strutted diaphragm wall

Third example was 6 m deep excavation executed within diaphragm walls. The geometry of the case is given on Figure 3.

The stability of the excavation walls was provided by one level of struts.

Following construction stages were considered:

- stage 1 – excavation to level – 2,0 m b.g.s.,
- stage 2 – installation of struts at level – 1,5 m b.g.s.
- stage 3 – dewatering inside the excavation to level – 6,0 m b.g.s.
- stage 4 – excavation to level – 6,0 m b.g.s.

Diaphragm wall is embedded in cohesive soil of following properties:

- $E = 30\,\text{MPa}$; $\nu = 0,3$; $\varphi'_k = 27,5°$; $c = 10\,\text{kPa}$;

- $\gamma_{saturated} = 20\,\text{kN/m}^3$; $\gamma_{above\ water\ table} = 19\,\text{kN/m}^3$;
- $\delta = 1/2\ \varphi'_k$ (structure-ground interface friction angle for active earth pressures);
- $\delta = 2/3\ \varphi'_k$ (structure-ground interface friction angle for passive earth pressures);

For modelling the diaphragm wall following parameters were taken:

$E = 31\,\text{GPa}; \quad \nu = 0,18; \quad \gamma = 25\,\text{kN/m}^3; \quad d = 0,80\,\text{m}$

In terms of actions: characteristic surcharge behind the wall - 10 kPa was considered as permanent load and the surcharge of 50 kPa as variable load. The groundwater level was at depth of 4,0 m below ground surface behind the wall and 6,0 below ground surface in front of the wall.

3.3.1 Calculations according to PN - 83/B-03010

Calculations were performed using dependent pressures method. Construction phases were modelled as it was mentioned above, please refer to clause 3.3. Surface surcharges – permanent and variable - were activated in the first construction phase.

The values of material partial factors, load partial factors, safety factor applied to soil resistance, active and passive pressures coefficients as well as subgrade reaction modulus (k_h) are given below:

- partial factor for weight density of the soil, for active pressures: $\gamma_m = 0,91$
- partial factor for weight density of the soil, for passive pressures: $\gamma'_m = 1,11$
- partial safety factor for angle internal friction and cohesion of the soil: $\gamma''_m = 1,11$
- partial safety factor for reduction of soil resistance in front of the wall: $n = 1,5$
- partial safety factor for characteristic surcharge (permanent and variable) on the surface behind the wall: $\gamma_f = 1,2$
- value of subgrade reaction modulus for reduced value of φ'_k: $k_h = 39,26\,\text{MN/m}^3$

3.3.2 Calculations according to Eurocode 7

Calculations according to Eurocode 7 were performed using dependent pressures method as well as finite element method. Construction phases were modelled, clause 3.3. Surface surcharges – permanent and variable - were activated in the first construction phase.

Design values of actions, design values of soil parameters and subgrade reaction modulus values are given it Table 3, for each DA respectively.

Table 3. Design values of actions and soil parameters

DA	Action kPa		φ_d' °	c kPa	γ_s kN/m³	γ_{awt} kN/m³	k_h kN/m³
	permanent	variable					
DA1A	13,5	75	27,5	10	20	19	41,49
DA1B	10	65	22,59	8	20	19	37,95
DA2	13,5	75	27,5	10	20	19	41,49

In the DA2 partial safety factor for reduction of soil resistance in front of the wall $\gamma_R = 1,4$ was considered.

FEM model mesh, consisted of 581, 15-noded triangle elements (number of nodes: 4943).

In FE calculations initial phase was considered with the input of $K_0 = 0,5$, in next stages diaphragm wall was activated and construction steps were introduced.

Following stiffness of struts was considered: $EA = 1500\,MN/m$.

4 RESULTS

In total 18 analysis were performed determining minimum length of the diaphragm wall below the bottom of the excavation (D) for the critical construction stage as well as maximum bending moments (Mmax) and maximum lateral displacements of the wall (Umax). The results of the analysis of example cases are presented below, in the tables: 4, 5 and 6 respectively.

Table 4. Results of calculations. First example case.

| | Dependent Pressures Method (Geo5) | | | | FEM (Plaxis) | |
| | Results of calculations according to PN-83/B-03010 | Results of calculations according to EN1997-1:2004 EUROCODE 7 | | | Results of calculations according to EN1997-1:2004 EUROCODE 7 | |
		DA 1A	DA 1B	DA 2	DA 1A	DA 1B
D, m	4,0	3,3	4,6	3,5	3,3[*]	4,6[*]
Umax, mm	22,2	18,7	20,6	23,6	7,5	7,0
Mmax, kNm/m	97,6	84,4	131,7	87,6	53,0	83,6

[*] embedment resulting from dependent pressures calculations.

5 CONCLUSIONS

The example cases proposed by the committee ERTC-10 are very simple in terms of structure and geotechnical conditions. That gave authors an opportunity to compare properly different design approaches – up-to-date (Polish Code) and new, now

Table 5. Results of calculations. Second example case.

| | Dependent Pressures Method (Geo5) | | | | FEM (Plaxis) | |
| | Results of calculations according to PN-83/B-03010 | Results of calculations according to EN1997-1:2004 EUROCODE 7 | | | Results of calculations according to EN1997-1:2004 EUROCODE 7 | |
		DA 1A	DA 1B	DA 2	DA 1A	DA 1B
D, m	3,1	2,8	3,9	2,8	2,8[*]	3,9[*]
Umax, mm	24,8	23,2	31	23,7	9,2	12,9
Mmax, kNm/m	209,6	183,1	276,8	192,2	265,0	389,8

[*] embedment resulting from dependent pressures calculations.

Table 6. Results of calculations. Third example case.

| | Dependent Pressures Method (Geo5) | | | | FEM (Plaxis) | |
| | Results of calculations according to PN-83/B-03010 | Results of calculations according to EN1997-1:2004 EUROCODE 7 | | | Results of calculations according to EN1997-1:2004 EUROCODE 7 | |
		DA 1A	DA 1B	DA 2	DA 1A	DA 1B
D, m	3,2	2,6	4,0	2,8	2,6[*]	4,0[*]
Umax, mm	2,4	2,9	4,8	2,6	7,4	8,0
Mmax, kNm/m	193,5	181,2	285,1	186,8	180,5	263,7

[*] embedment resulting from dependent pressures calculations.

being introduced (Eurocode 7). The analysis of the results have been performed considering the results of all calculation series taking into account both: Polish Code and Eurocode 7 (DA1A, DA1B and DA2) differing dependent pressures and finite elements methods.

Taking into consideration results of analysis following was observed:

- in all cases, greatest values of embedment of the wall below the bottom of the excavation, biggest bending moments and horizontal displacements were obtained when applying Eurocode 7, the second combination of partial safety factors from Design Approach 1 (DA1B) - using both: dependent pressures method and finite elements method,
- considerable differences between the results (values of bending moments and horizontal displacements) of dependent pressures method and finite elements method calculations were observed in all discussed cases. Lateral diaphragm wall displacements calculated using FEM were always smaller and differences were significant (up to 150%).
- similar values of embedment of the wall, bending moments and horizontal displacements were obtained applying DA1A (partial safety factor $\gamma_G = 1,5$ – for surcharges) and DA2 (partial safety factor $\gamma_R = 1,4$ for reduction of soil resistance) – differences do not exceed 10 % in all cases analyzed using dependent pressures method,
- when using dependent pressures method the results of calculations according to Polish Code and Eurocode 7 - DA2 are comparable both in terms of bending moments and lateral wall displacements. Differences do not exceed 15 %,
- in finite elements method calculations the choice of the modulus of elasticity of the soil body is of great importance.

Basing on the above, the following can be concluded:

- For the purpose of evaluation of Polish National Annex for the design of diaphragm walls serving as a support of deep excavations (using dependent pressures method) the use of Eurocode 7 Design Approach N° 2 should be recommended. This is an economical solution, which gives as a result the level of safety comparable to the one, which could be obtained following old Polish Code.
- Special attention should be paid when using FEM, for calculation of lateral displacements of diaphragm walls. The results may be unfavorable in terms of construction safety. Especially if the value of modulus of elasticity of the soil body is overestimated.

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