Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.78

ANALYSIS OF CANTILEVER RETAINING WALL ACCORDING TO EUROCODES IN DRAINED AND UNDRAINED CONDITIONS

Dejan Ivanovski (1), Julijana Bojadjieva (2), Kemal Edip (3), Vlatko Sheshov (4), Toni Kitanovski (5), Jovana Ristova (6)

(1) *Research assistant, PhD Candidate, Ss. Cyril and Methodius University, Institute of earthquake engineering and engineering seismology-IZIIS, Skopje, North Macedonia, ivanovski@iziis.ukim.edu.mk*
(2) *Associate professor, Ss. Cyril and Methodius University, Institute of earthquake engineering and engineering seismology-IZIIS, Skopje, North Macedonia, jule@iziis.ukim.edu.mk*
(3) *Professor, Ss. Cyril and Methodius University, Institute of earthquake engineering and engineering seismology-IZIIS, Skopje, North Macedonia, kemal@iziis.ukim.edu.mk*
(4) *Professor, Ss. Cyril and Methodius University, Institute of earthquake engineering and engineering seismology-IZIIS, Skopje, North Macedonia, vlatko@iziis.ukim.edu.mk*
(5) *Research assistant, PhD Candidate, Ss. Cyril and Methodius University, Institute of earthquake engineering and engineering seismology-IZIIS, Skopje, North Macedonia, tonik@iziis.ukim.edu.mk*
(6) *M.Sc, Civil Engineering Institute Macedonia, Skopje, North Macedonia, ivanovski@iziis.ukim.edu.mk*

Abstract

Retaining cantilever walls are typically designed under drained conditions, assuming that proper drainage is designed, constructed, and functions throughout the structure's lifespan. Even when appropriate drainage cannot be constructed—such as in walls cutting and retaining a natural slope, where the wall is built adjacent to nearly vertical excavated soil—designers usually use effective soil parameters and effective stresses. This paper analyzes a 6-meter-high cantilever wall, retaining non-cohesive soil (backfill), but founded on different types of soils (non-cohesive and cohesive). Initially, a non-cohesive, granular soil is assumed, with effective soil parameters under drained conditions. The analysis is then repeated under undrained conditions, with a fully saturated backfill and the groundwater table assumed to be at the ground surface behind the wall (for instance, when proper drainage is absent). Both static and seismic conditions are considered. Additionally, a comparison is made between the drained and undrained strength of cohesive material (clay) beneath the wall, using effective and total soil parameters, also under static and seismic conditions. All analyses are conducted according to Eurocode 7 and 8. The differences in the required foundation width of the wall, ensuring stability under static and seismic conditions, are compared by verifying the resistances.

Keywords: cantilever, retaining, wall, drained, undrained, seismic, Eurocode,

1. Introduction

Cantilever retaining walls are important structures widely used in geotechnical engineering to stabilize slopes and prevent soil movement in various civil engineering applications, such as roadways, embankments, and foundations. These walls are typically designed under the assumption that proper drainage is provided, which helps prevent hydrostatic pressures from building up behind the wall. In ideal conditions, effective drainage ensures that the backfill remains dry (in a drained state), allowing for the use of effective soil parameters and stress conditions in the design process. However, there are cases where drainage may not be functional, or may not be included in the structural project, so the retaining wall may experience additional pressure due to the backfill saturation i.e. (undrained state). The analyses are performed using effective soil parameters. The level of groundwater to be considered is specified in Eurocode 7 - Part 1 (EN 1997:1) [1] which states: "Unless the adequacy of the drainage system can be demonstrated and its maintenance ensured, the design ground-water table should be taken as the maximum possible level, which may be the ground surface". According to some authors, the requirements of Eurocode 7 appear more rigorous than what is typically adopted in practice, as it is unusual for the natural water table to rise to the ground surface. Annex E in EC 8-5 (E.5-E.8), addresses

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.78

various water level conditions based on soil permeability and prescribes modifications to the equation for the total design force (static + seismic) acting on the retaining structure.

Additional analyses are conducted with cohesive material (clay) under the foundation, firstly using effective parameters, calculating the drained strength, and then the analysis is repeated with total parameters, calculating the undrained strength. The geomechanical parameters of the soils used are assumed and shown in Table 1. The difference in the required wall's foundation width is assessed as it is the dimension which contributes the most to the stability of a cantilever retaining wall, while all other dimensions shown on Fig. 1 remain the same for all analyses.

The analyses are performed for a 6-meter-high cantilever retaining wall under different conditions (Fig. 1). The procedure prescribed in EC 7-1, design approach 2 – DA-2 is used for the static analyses. Additionally, the analyses are repeated considering the seismic conditions, in accordance with Eurocode 8, part 5 (EN 1998:5) [2], design approach 2 (DA-2) and additionally calculated with design approach 3 (DA-3). According to EC-7, all partial factors for accidental situations, should be taken as 1.0, while partial factors for materials and resistances during accidental (seismic) actions, are not clearly distinguished, neither in EC 7, nor in EC 8. Hence, using DA-2, which applies partial factors to actions and resistances, there is no additional increase in the characteristic value of actions to obtain its design value when performing the seismic analyses. However, DA-3, does not apply partial factors to the actions, but does apply to the materials, so that the seismic analysis is performed with the same partial factors as for the static analysis, resulting in a large increase of the required foundation width. Normally, partial factors for seismic analysis are expected to be lower than those for static analysis.

The pseudo-static approach, according to Mononobe-Okabe theory [4, 5] is used for calculating the seismic forces, applied as horizontal and vertical forces. The ground acceleration is assumed as a_{gR} =0.25g, and the soil type is chosen as type B for the non-cohesive material (corresponding to gravel), and type C for the cohesive material (corresponding to clay), according to Table 3.1 in EN 1998:1 [2]. A reduction coefficient of r=2.0 (EN 1998:5, Table 7.1) [3] is adopted for the performed analyses, so the coefficients k_h and k_v are calculated as:

$$k_h = \alpha * \frac{S}{r} = 0.25 * \frac{1.20}{2} = 0.15 \text{ – non-cohesive material; } k_h = 0.25 * \frac{1.15}{2} = 0.144 \text{ – cohesive material}$$

$$k_v = \pm 0.5\, k_h = \pm 0.075 \text{ – non-cohesive material; } k_v = \pm 0.072 \text{ – cohesive material}$$

The analyses are conducted to satisfy the stability conditions, i.e., the design actions must be less than the resistance to sliding, overturning, and the bearing capacity of the soil i.e.:

$$H_d \leq R_d + R_{pd}; \quad M_{Ed,dst} \leq M_{Ed,st}; \quad V_d \leq R_d$$

The seismic bearing capacity of the ground is given in form of an empirical expression that needs to be satisfied, given in EC 8-5 - annex F.

By comparing the design results under both static and seismic conditions, this study provides a comprehensive understanding of how drainage, soil type, and seismic activity influence the design of cantilever retaining walls according to Eurocodes.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.78

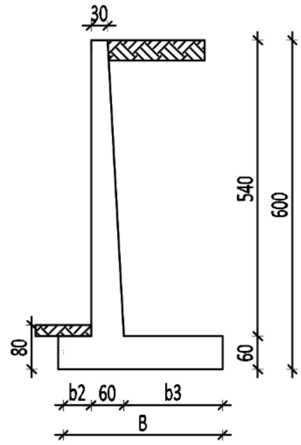

Figure 1: 2D - Scheme of the analyzed wall

Table 1: Assumed geomechanical parameters

Non – cohesive soil (drained analyses)	γ=21 [kN/m3]	φ'=30 [˚]	c'=0 [kPa]
Cohesive soil (effective parameters)	γ=21 [kN/m3]	φ'=19 [˚]	c'=0 [kPa]
Cohesive soil (total parameters)	γ=21 [kN/m3]	/	c_u=50 [kPa]

2. Main differences between drained and undrained conditions in terms of resistance

In the following part, selected main differences in equations for the drained and undrained resistances, important for the aim of this paper are shown:

2.1. Drained conditions

2.1.1. Drained bearing resistance according to EC7-1

The drained bearing resistance of a spread foundation R is given by Eq (1):

$$\frac{R}{A'} = c'N_c b_c s_c i_c + q'N_q b_q s_q i_q + 0.5\gamma' B' N_\gamma b_\gamma s_\gamma i_\gamma \tag{1}$$

where c' is the soil's effective cohesion; q' is the effective overburden pressure at the foundation base; γ' is the effective specific weight of the soil below the foundation; Nc, Nq, and Nγ are bearing capacity factors; b, s and i are factors for base inclination, shape, and inclination, respectively.

2.1.2. Drained sliding resistance according to EC 7-1

The design horizontal resistance Rd for drained conditions (ignoring passive pressure) is given by Eq. (2):

$$\mathrm{R_d} = \frac{(W_{Gd} - U_{Gd})tan\delta_d}{\gamma_{Rh}} \tag{2}$$

where W_{Gd} = the wall's design self-weight, including backfill; U_{Gd} = the design water upthrust beneath the base; δ_d = the design angle of friction between the base and the ground; γ_{Rh} = a partial actor on sliding resistance.

2.2. Undrained conditions

2.2.1. Undrained bearing resistance according to EC 7-1

The undrained bearing resistance of a spread foundation R is given by Eq. (3):

$$\frac{R}{A'} = (\pi + 2)c_u b_c s_c i_c + q \tag{3}$$

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.78

where A' is the footing's effective area, c_u is the soil's undrained shear strength; q the total overburden pressure at the foundation base;

2.2.2. Undrained sliding resistance according to EC 7-1

The characteristic shear resistance τ_{Rk} for undrained conditions (ignoring passive pressure) is given by the expression:

$$R_d = c_{ud} A \quad (4)$$

Where c_{ud} represents the design undrained shear strength of the soil.

3. Results from the performed analyses

3.1. Drained analyses

The 6m wall is analyzed using the software package GEO-5, under different conditions and with different soil types. The minimum required foundation width (100% utilization ratio) is shown for all case-scenarios, allowing for direct comparison. Additionally, the most critical stability verification, which corresponds to the 100% utilization ratio is highlighted. Table 2 presents the results obtained from the drained analysis, using effective parameters. When the wall is analyzed with a dry fill under static conditions, the minimum required foundation width is 2.85m (Fig. 2), with the most critical condition being the bearing resistance. When the backfill is wet, i.e. the ground water table is at the surface behind the wall, the required footing width increases significantly to 7.7m (Fig. 3), to satisfy the sliding resistance which is the most critical stability condition. Of course, sliding resistance can also be increased with introducing a shear key in the foundation, which would reduce the total width required.

Under seismic conditions, the required foundation width is considerably larger than in static conditions. For the dry fill, using design approach 2 (DA-2), the obtained minimum width is 3.8m, while using design approach 3 (DA-3), as mentioned earlier, the required width increases to a minimum of 4.8m. For a wall with a wet fill, achieving the required resistance through foundation width alone is not feasible, even if the width exceeds 10m for both design approaches. However, occurring an earthquake, especially with maximum expected acceleration, during a fully saturated backfill - up to the ground surface, which practically means that there is impermeable soil below the backfill is almost impossible. Therefore, in author's opinion, this case should not be considered a valid load combination for structure design.

In extremely rare cases where designing a retaining structure without drainage is unavoidable, particularly in highly active seismic regions, the groundwater table level behind the wall should be reconsidered. Taking it as the ground surface is overly conservative, even for static conditions. For example, the British practice [6] suggests lowering the water table to approximately H/4 below the surface. Also, other measures could be taken for increasing the sliding resistance, like introducing shear key, pile foundation, etc. The critical resistance (causing utilization ratio of ~100%), is either the bearing or the sliding, while the overturning is not critical in any of the analyzed case-scenarios given the assumed parameters.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.78

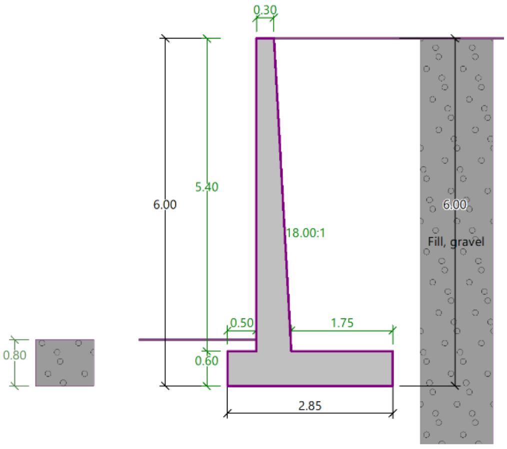

Figure 2. Model geometry - dry fill

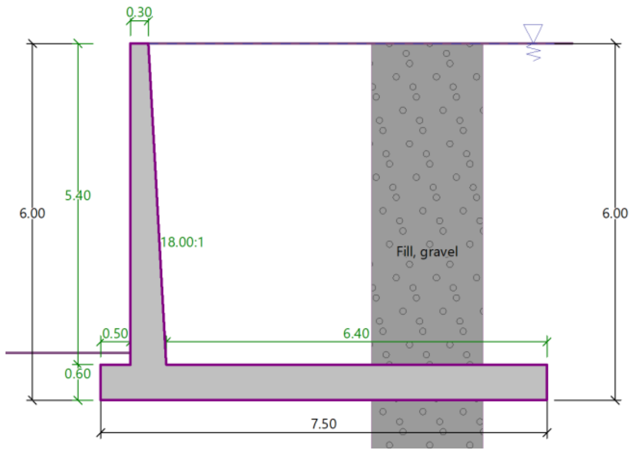

Figure 3. Model geometry - wet fill

Table 2: Results from the drained analysis

Type of analysis	*Foundation width [B]*	*Critical resistance*
Drained - dry fill - static	2.85	Bearing
Drained - wet fill - static	7.7	Sliding
Drained - dry fill - seismic - DA-2	3.8	Bearing
Drained - dry fill - seismic - DA-3	4.8	Sliding
Drained - wet fill - seismic - DA-2	∞	Sliding
Drained - wet fill - seismic - DA-3	∞	Sliding

3.2. Undrained vs. drained strength

Using the same geometry of the wall, several analyses are performed with cohesive soil beneath the wall (Fig. 3) and the same non-cohesive soil as a backfill. The analyses differ only in the input of the geomechanical parameters in the analyses for the cohesive material, shown in Table 1. It is firstly analyzed with total parameters, calculating the undrained strength and then with effective parameters, calculating the drained strength, assuming the parameters are valid for identical soil. Additionally, seismic analyses are carried out, using design approaches 2 and 3 from EC 7, as mentioned earlier.

The results show that there is no significant difference in static conditions, regardless of whether total or effective parameters (undrained or drained strength) are used, although the drained strength is slightly larger than the undrained strength. A larger difference occurs in seismic conditions, so using DA-2, the minimum required foundation width is 5.8m for the undrained strength and 5.0m for the drained strength. Using DA-3, as previously concluded, there is a significantly greater need for foundation width, so the undrained strength requires a width of 10m, while the drained strength requires a narrower width of 7.3m. In other words, the drained strength is larger than the undrained strength for the assumed material. Again, the overturning condition is not critical in any of the performed calculations.

Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.78

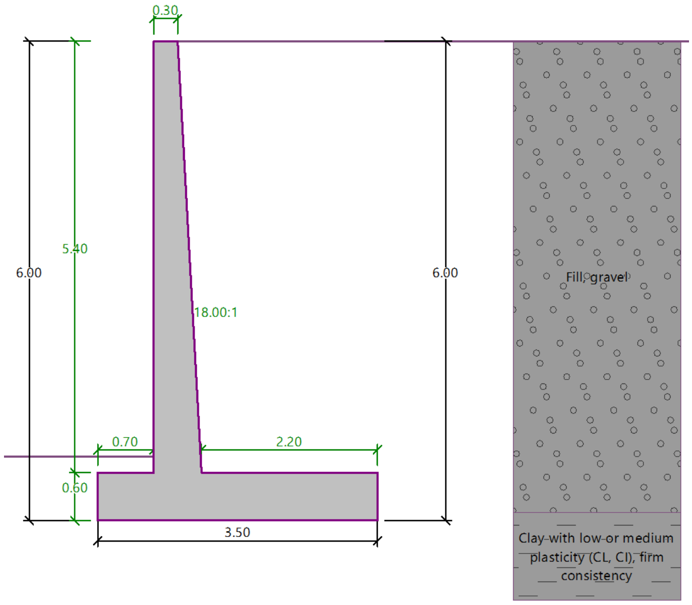

Fig. 3. Model geometry – cohesive soil below foundation

Table 3: Results from the undrained analysis

Type of analysis	*Foundation width [B]*	*Critical resistance*
Undrained strength - static	3.5	Sliding
Drained strength - static	3.4	Bearing
Undrained strength - seismic - DA-2	5.8	Sliding
Undrained strength - seismic - DA-3	10	Sliding
Drained strength - seismic - DA-2	5.0	Sliding
Drained strength - seismic - DA-3	7.3	Sliding

4. Conclusions:

After performing the analyses and making the comparisons, the following conclusions can be drawn:

1. Adding the water table at the surface behind the retaining structure imposes significant additional horizontal pressure, which requires a drastic increase in the foundation width to ensure stability, i.e. resistance of the wall, compared to the width required for a dry fill. This emphasizes the importance of providing appropriate drainage, which should also be regularly maintained
2. The seismic analyses show a significant increase in the required foundation width compared to the static analyses. It is also concluded that design approach 2 (DA-2) results in a smaller required width than design approach 3. However, in author's opinion is that using DA-3 leads to unexpectedly large dimensions of the structure.
3. Seismic analyses with a fully saturated backfill show that it is not possible to meet the required resistance only by increasing the width of the foundation. This scenario is unlikely to happen, and in author's opinion is that it does not have to be considered in the design.
4. Comparing the drained and undrained strength of a cohesive material, it is concluded that generally the drained strength is larger than the undrained one, especially under seismic conditions.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.78

References:

[1] European Committee for Standardization (2004) Eurocode 7: Geotechnical design - Part 1: General rules. CEN, Brussels, EN 1997-1;

[2] European Committee for Standardization (2004) Eurocode 8: Design of Structures for Earthquake Resistance. Part 1: General rules, seismic actions and rules for buildings. CEN, Brussels, EN 1998-1;

[3] European Committee for Standardization (2004) Eurocode 8: Design of Structures for Earthquake Resistance. Part 5: Foundations, retaining structures and geotechnical aspects. CEN, Brussels, EN 1998-5;

[4] Mononobe, N. and Matsuo, H. (1929) On the Determination of Earth Pressure during Earthquakes. Proceedings of the World Engineering Conference, 9, 176;

[5] Okabe S., 1926 General theory of earth pressure. Journal of the Japanese Society of Civil Engineers, Tokyo, Japan 12 (1);

[6] Bond, A., & Harris, A. (2008). Decoding Eurocode 7. CRC Press;

[7] Fardis, M. et al (2005). Designers' guides to the eurocodes, - Designers' guide to EN 1998-1 and EN 1998-5 Eurocode 8: Design of structures for earthquake resistance general rules, seismic actions, design rules for buildings and retaining structures;

[8] Ivanovski D. et. al. (2024): Evaluation of the coefficient "r" in Eurocode 8-5 and choosing a design approach for seismic analysis of retaining structures, *18th World Conference on Earthquake Engineering, WCEE 2024*, Milan, Italy.

[9] Roje-Bonacci T. (2005). Potporne gradzevine i gradzevne jame, Gradzevinsko-Arhitektonski Fakultet Sveucilista u Splitu (in Croatian);

[10] GEO 5, Fine software, Cantilever wall program, Spread Footing program, Czech Republic;

[11] Mircevski J. (2024). Analysis of structures according to Eurocode in undrained conditions, M.Sc thesis, SS. Cyril and Methodius, Skopje.

[12] Ivanovski D. (2022). Comparative analysis and design of retaining structures according to the current practice and Eurocodes, M.Sc thesis, SS. Cyril and Methodius, Skopje.