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Artigo original

Cantilever retaining wall design to Eurocode 7

The influence of characteristic angle of shearing resistance in design

Projecto do muro de arrimo cantilever aplicando o Eurocódigo 7

Influência do ângulo característico de resistência ao cisalhamento

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Abstract: Eurocode 7 is the European Standard for design geotechnical structures and is currently being revised. Firstly, the vision was of encouraging free trade between European member states and the harmonisation of technical specifications. However, this new concept has resulted in several challenges for many designers particularly when and how to introduce the limit states and partial factors in some design approaches to determine a cost-effective design dimension. Nevertheless, a more economical design may lead to potential risks, particularly when factors such as the nature and size of the structure, soil parameters, topography and groundwater situations are not taken into consideration. Hence, an appropriate balance between safety, economy and methodology are relevant to avoid unnecessary risks, financial expenditure and inconvenient errors. This article intends to determine the design of a cantilever retaining wall applying the Eurocode 7 using three different design approaches in overall perspective, analysing the effect of characteristic angle of shearing resistance in the system when submitted to undrained condition. It was accomplished through the creation of a spreadsheet-based design tool focussing mainly on geotechnical failure of Ultimate Limit State (ULS). The results show that the characteristic angle of shearing resistance is intrinsically related to soil properties which the denser soil, the higher is the shear strengthen. Hence, the increase of its angle has increased in the overall Factor of Safety ratios. On the other hand, however, the characteristic angle of shearing resistance for bearing in cohesive soils tends to suffer a more accentuated failure than for sliding when the degree of friction is lower.

Keywords: Eurocode 7, Design Approach, Cantilever Retaining Wall, Characteristic Angle of Shearing Resistance, Undrained Condition.

Resumo: O Eurocode 7 é a norma europeia para estruturas geotécnicas de projecto e está actualmente sendo revisado. Em primeiro lugar, a visão era incentivar o livre comércio entre os estados membros europeus e a harmonização das especificações técnicas. No entanto, esse novo conceito resultou em vários desafios para muitos projectistas, especialmente quando e como introduzir os estados limites e factores parciais em algumas abordagens de design para determinar uma dimensão de design económica. No entanto, um projecto mais económico pode levar a riscos em potencial, principalmente quando factores como natureza e tamanho da estrutura, parâmetros do solo, topografia e situações de águas subterrâneas não são levados em consideração. Portanto, um equilíbrio adequado entre segurança, economia e metodologia é relevante para evitar riscos desnecessários, gastos financeiros e erros inconvenientes. Este artigo pretende determinar o projecto de um muro de arrimo em cantilever aplicando o Eurocode 7 usando três abordagens diferentes de projecto em perspectiva geral, analisando o efeito do ângulo característico de resistência ao cisalhamento no sistema quando submetido a condições não drenadas. Isso foi realizado através da criação de uma ferramenta de projeto baseada em planilha, focada principalmente na falha geotécnica do estado final do limite (ULS). Os resultados mostram que o ângulo característico da resistência ao cisalhamento está intrinsecamente relacionado às propriedades do solo. Quanto mais denso o solo, maior o fortalecimento do cisalhamento. Portanto, o aumento de seu ângulo aumentou nas taxas gerais de factor de segurança. Por outro lado, no entanto, o ângulo característico da resistência ao cisalhamento para suportar solos coesos tende a sofrer uma falha mais acentuada do que para deslizar quando o grau de atrito é menor.

Palabras chave: Eurocode 7, Abordagem de projecto, Muro de arrimo em balanço, Ângulo característico de resistência ao cisalhamento, Condição não drenada.

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INTRODUCTION

Angle of shearing resistance or angle of soil friction is the angle on the graph of Mohr's Circle of the shear stress and normal effective stresses at which shear failure occurs. It is adopted to describe the friction shear resistance of soils together with the normal effective stress. Angle of friction can be determined in the laboratory by the Direct Shear test or the Triaxial Stress Test. Knowing the angle of friction resistance is possible to infer the resistance of the soil and estimate the coefficient of at rest pressure. Additionally, it is possible to predict if the soil is cohesive or not and even the behaviour of the soil under groundwater conditions. This knowledge can be applied in slope, foundations, excavations, to name a few.

This article intends to determine the influence of the characteristic angle of shearing resistance in design of a cantilever retaining wall applying the Eurocode 7 using three different design approaches for the verification of geotechnical ultimate limit states in overall perspective when the walls are submitted to undrained condition.

For achieving this target, it has been developed a spreadsheet-based design tool with reference to the specifications of Eurocode 7.

Overall, the impact of this report may result in a very symbolic contribution for understanding the design analysis of cantilever wall in categories 1 and 2 when applied the characteristic angle of shearing resistance under undrained condition. The target audience of this article is for engineers who are not necessary designers, students whoever subject is related to geotechnical issues and for those interested in this geotechnical design.

GRAVITY CANTILEVER WALL

Gravity walls are defined as walls of stone or plain or reinforced concrete having a base footing with or without a heel, ledge or buttress (BS EN 1997-1 § 9.1.2.1, 2004). They are constructed to retain (hold back) normally masses of earth (soil, rock, or backfill) and water or other loose material where there is an abrupt change in elevation that exceeds the angle of repose of soil. These walls depend on their own weight and setback to retain any of these materials and prevent these from sliding or erosion and are typically shorter.

This condition may occur due to the combination of three natural factors such as climate, topography and type of soil or due to anthropogenic activities namely execution of construction works, the drainage system obstruction, exploration of minerals, agriculture activities just to mention some, giving rise to geological hazards by increasing the risk of damage infrastructures, affecting economic activities as well as loss of human lives.

Examples of such types of structures include cantilever retaining wall having constant or variable thickness, spread footing reinforced concrete walls and buttress walls. Throughout this article, the author is going to focus mainly on cantilever retaining wall.

Ground investigation of cantilever walls

According to Figure 1, the suggested minimum depth of investigation, za, for excavations where the groundwater table is below formation level (excavation base), the larger value of the following conditions should be achieved:

z_a≥0,4h and
z_a≥(t+2,0)m (BS EN 1997-2 § B.3.10, 2007)

Smith (2014) affirms that in general, the maximum excavation for a cantilever wall (H) can reach up to 6 m with a B=0,4H to 0,7H m, base thickness t_b=0,1H m and toe width b_t=0,15H m. This base width includes any projections of the heel or toe of the wall are intended to reduce the bearing pressure between the base of the wall and the supporting soil (see Figure 1).

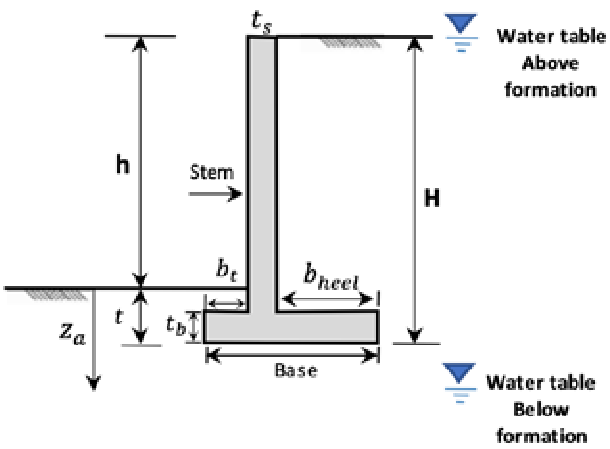

Figure 1: Example of depth of investigation points for a cantilever retaining wall and its elements (adapted from Bond & Harris § Figure 11.1, 2008).

Basis of design

Verification of strength of a retaining wall to Eurocode 7 involves checking that design effects of actions (E_d) do not exceed their corresponding design resistance (R_d) in the ground (GEO) and/or in the structure (STR). Thus, the following inequality must be satisfied:

E_d≤R_d (BS EN 1997-1 § 2.4.7.3.1)

This difference can be considered a measure of over-design factor (ODF) or, conventionally, Factor of Safety (FoS) which is expressed by the following equation:

$$\mathrm{FoS}_{STR} = \mathrm{FoS}_{GEO} = \frac{R_d}{E_d}$$

In which the result must be more than 1 unit otherwise the system will be driven to collapse. However, the safety margin for foundations given by the typical overall safety is from 2,5 to 3,0 commonly applied in traditional designs, especially when the loading design is mostly permanent.

All relevant situations where the strength of the retaining wall is a concern should be considered. Figure 2 illustrates the limit states that can affect L- and T-shaped gravity walls: (top) toppling or overturning, sliding, and bearing failure; and (bottom) structural failure of the wall's stem and toe.

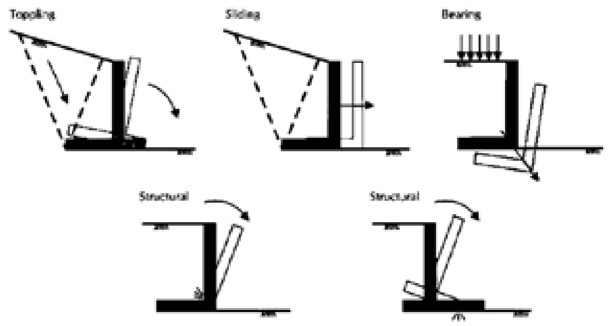

Figure 2: Examples of ultimate limit states for L- and T-shaped gravity walls (based on Bond & Harris § Figure 11.3, 2008)..

In case of gravity retaining wall the most important limit states are bearing and sliding failure of the foundation (GEO ULS) and exceedance of the structural resistance in critical sections of stem walls (STR ULS).

MATERIALS AND METHODS

Overall, the study started with data collection which was applied into computer software system by using the operating system Microsoft Office Excel to create a spreadsheet-based design tool with reference to the specifications of Eurocode 7. Some of the data obtained from the method of finding in literature study from books and articles, particularly the Rankine analysis. The worked example is presented in Figure 3 demonstrating the cantilever retaining wall design situation. To drive the system to collapse was introduced the general method focussing mainly on geotechnical failure (GEO).

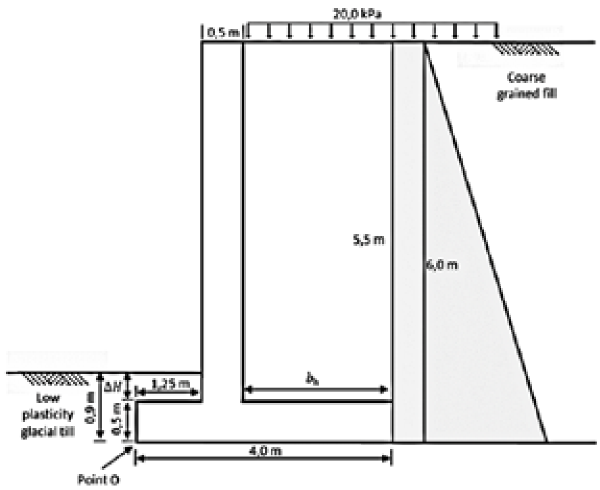

Figure 3: Design example of a cantilever retaining wall under undrained condition

Table 1 shows four (4) relevant inputs required to construct the structural design situation of the cantilever retaining wall. Firstly the design input data of the wall parameters namely its size, weight and other geometrical properties. Secondly, the design input data of the soil properties of the backfill including the characteristic undrained strength (c_u) and the angle of shearing resistance (φ^'). Then the design input data of the underlying soil. Finally the design inputs of the surcharge load conditions (q_k). The designer can adjust the type of retaining wall and its state when appropiate.

Table 1. Input data to construct the cantilever wall design Excel Spreadsheet

Input Data	Symbol	Unit	Value
1. Wall parameters			
Wall stem height	h	m	5,50
Wall stem thickness	t_s	m	0,50
Weight density	γ_{ck}	kNm/m	23,40
Base thickness	t_b	m	0,50
Toe width	b_t	m	1,25
Base width	B	m	4,00
Fill thickness	d	m	0,90
Width wall heel	b_h	m	2,25
Wall height and base thickness	H	m	6,40
Unplanned excavation	ΔH	m	0,55
2. Backfill soil – Coarse grained fill			
Weight density	γ	kNm/m	20,00
Angle of shearing resistance	φ'	°	40
Characteristic drained strength	c_u	kPa	0,00
3. Underlying soil – Low plasticity fine grained glacial till			
Weight density	γ_{fdn}	kNm/m	22
Characteristic undrained strength	$c_{u,fdn}$	kPa	100
4. Surcharge condition			
Surcharge	q_k	kPa	20,00

The output data of the wall design Excel Spreadsheet is comprised of the parameters to determine the overall stability of the wall against sliding, bearing failure and overturning (Table 2).

Table 2. Output data of the wall design Excel Spreadsheet

GEO ULSs Output	Symbol	DA-1 Comb. 1	DA-1 Comb. 2	DA-2	DA-3	unit
Actions						
Characteristic self-weight of wall stem	W_{stem}	69,03	69,03	69,03	69,03	kN/m
Characteristic self-weight of wall base	W_{base}	46,80	46,80	46,80	46,80	kN/m
Total characteristic self-weight of wall	W_{wall}	115,83	115,83	115,83	115,83	kN/m
Characteristic total self-weight of fill	W_{fill}	265,50	265,50	265,50	265,50	kN/m
Moment wall stem	M_{stem}	103,55	103,55	103,55	103,55	kNm/m
Moment Wall base	M_{base}	93,60	93,60	93,60	93,60	kNm/m
Moment Backfill	M_{fill}	763,31	763,31	763,31	763,31	kNm/m
Total characteristic self-weigh	W_{Gk}	381,33	381,33	381,33	381,33	kN/m
Total characteristic stabilizing moment	$M_{Gk,stb}$	960,46	960,46	960,46	960,46	kNm/m
Characteristic surcharge	Q_k	45,00	45,00	45,00	45,00	kPa
Effects of actions						
Design vertical actions	V_d	582,30	439,83	582,30	439,83	kPa
	$V_{d,fav}$	381,33	381,33	381,33	381,33	kPa
Earth pressure						
Design thrust active earth pressure coefficient for fill	$K_{ah,d}$	0,22	0,28	0,22	0,28	
Design thrust from earth pressure on back of virtual						
Backfill	E_{Gd}	120,24	116,42	120,24	116,42	kN/m
Surcharge	E_{Qd}	41,75	47,30	41,75	47,30	kN/m
Total design horizontal thrust	H_{Ed}	161,99	163,72	161,99	163,72	kN/m
Design of destabilizing moments						
From backfill	M_{Gd}	240,47	232,84	240,47	232,84	kNm/m
From surcharge	M_{Qd}	133,60	151,35	133,60	151,35	kNm/m
Total design destabilizing moment	$M_{Ed,dst}$	374,07	384,19	374,07	384,19	kNm/m
Sliding resistance						
Design undrained sliding resistance	H_{Rd}	400,00	285,71	363,64	285,71	kN/m

Bearing resistance						
Design stabilizing moment and surcharge	$M_{Ed,stb+q}$	1490,68	1128,65	1490,68	1128,65	kNm/m
Eccentricity of load	e_d	0,08	0,31	0,08	0,31	m
Verification		OK	OK	OK	OK	
Effective breadth	B'_d	3,84	3,39	3,84	3,39	m
Area	A	3,84	3,4	3,84	3,39	m2
Cohesion	i_c	0,88	0,78	0,88	0,78	
Total overburden at foundation base	$\sigma_{vk,b}$	7,70	7,70	7,70	7,70	kPa
Total resistance	$\sigma_{Rv,d}$	460,20	295,70	460,20	295,70	kPa
Design resistance	N_{Rd}	460,20	295,70	328,72	295,70	kPa
Design bearing force	N_{Ed}	151,83	129,93	151,83	129,93	kPa
Overturning resistance						
Design stabilizing moment due to self-weight alone	$M_{Ed,stb}$	960,46	960,46	960,46	960,46	kNm/m

Once knowing the characteristic angle of shearing resistance is possible to infer the resistance of the soil, its coefficient of earth pressure, cohesiveness and even the behaviour of the soil under groundwater conditions, Table 3 presents a diversity of soils and their geotechnical parameters. Its values are based mainly on USCS, BS and ISO. The characteristic angles of shearing resistances were estimated in terms of effective stresses in the active state for preliminary geotechnical designs between the base of the wall and the ground.

Table 3. Types of soils and their geotechnical parameters

Parameters	CL		ML-CL		SM		GM		GP		GW	Unit
	Clay		Silt and Clay		Silty sand		Clayey gravels, sands		Graded coarse fill		Sandy gravel	
	Compact	Sat	Compact	Sat	Compact	Sat	Compact	Sat	Compact	Sat	Dense	
γ_k	18		18.5		19	21.5	21	23	22	21.5	23	kNm/m
c_u	15	10	30	22	50	12	75	-	100	100	120	kPa
c'	87	-	67	-	20	-	5	-	0	-	0	kPa
φ'	28	-	32	-	34	-	35	-	38	-	40	°
φ_{cv}	0.26	-	0.35	-	0.45	-	0.52	-	0.59	-	0.65	radian

(BS 6349 -1-3 § Table C.1, 2012; ISO 14688-1 § 5.14, 2002; ISO 14688-2 § 5.3, Table 5, 2004)

RESULTS AND DISCUSSION

Graph in Figure 4 (A) & (B) illustrates the variation of the characteristic angle of shearing for different soil types when submitted to sliding and bearing.

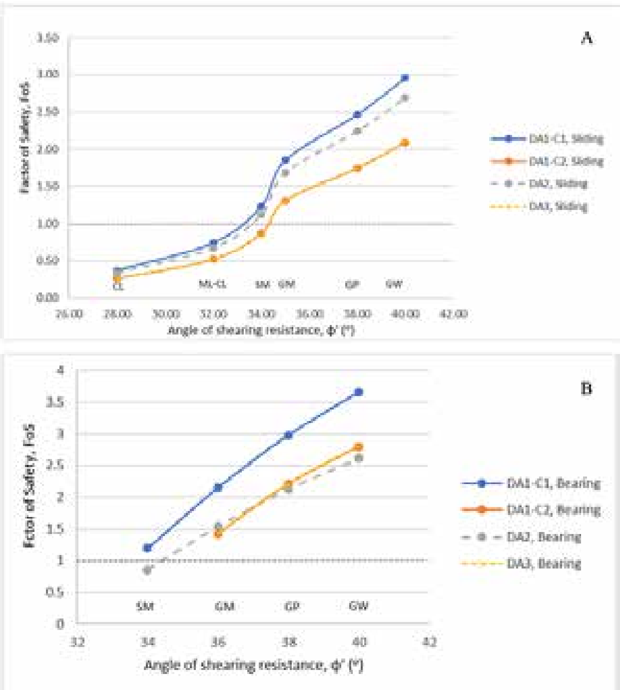

Figure 4: Variation of φ' to sliding (a) & bearing (b)

According to Figure 4 (A) the curves of characteristic angles of shearing resistances against sliding have the same trend, rising from clay (CL) at φ' = 28° to Sandy gravel (GW) at φ' = 40°. This means that when increases the density of soil particles in ground, increases the characteristic angle of shearing resistance, and consequently increases the FoS ratio. Along these curves, the FoS runs from 0,26 in clays to over 2,0 when the soil is constituted of sandy gravel in which are the lowest FoS ratios. Thereafter, the relative conservatism is that DA1-C1 > DA2 > DA1-C2 = DA3.

Figure 4 (B) shows that the curves of characteristic angles of shearing resistances against bearing present two major trends. Those for DA1-C1 & DA2 arising in silty sand material, at φ' = 34°, to reach a peak in Sandy gravel, at φ' = 40°, and those for DA1-C2 & DA3 arising only in gravel soils, at φ' = 36°, then increase gradually to reach a peak in Sandy gravel at φ' = 40°. The curve for DA1-C2 lies only below that for DA2 when φ' ≤ 37 but is entirely coincident with that for DA3.

It means that when increases the characteristic angle of shearing resistance, increases the particles interlock and the internal strength of them, as a result increase also the FoS ratio of the wall. Additionally, this retaining wall does not resist against bearing when the ground is comprised of fine soils, namely CL and ML-CL.

The relative conservatism is as following:

- When φ' ≥ 37: DA1-C1 > DA1-C2 = DA3> DA2; and
- When φ' ≤ 37: DA1-C1 > DA2 > DA1-C2 = DA3.

The coincidence between the ratios for DA1-C2 and DA3 is possibly due to their similarity in terms of partial shearing resistance factors and the same partial load actions.

CONCLUSIONS

It is clear that the characteristic angles of shearing resistances are intrinsically related to soil properties which the denser soil, the higher is the shear strengthen as well as the distance between the design approaches. Accordingly, DA1-C1 by using lower partial coefficient of shearing resistance factors, the friction is lower, as a result, in this design approach the soil presents a strong strength to resist against sliding. For DA1-C2 and DA3 the effect is the opposite.

Therefore, the higher FoS values for DA1-C1 in coarse soils (SM, GM, GP and GW), indicate that this approach controls the ULS design for lateral pressure in undrained conditions. Furthermore, the lower FoS ratios in DA1-C2 and DA3 particularly in fine soils (CL and CL-ML) imply that attention may be necessary when the design resistance due to earth pressure on the side of foundation might be mobilised by external activities. Thus, the model is unacceptable to resist against sliding for fine soils.

It can be reasoned that the characteristic angles of shearing resistances for bearing in cohesive soils tend to suffer a more accentuated failure than for sliding when the degree of friction is lower, possibly because the active earth pressure and internal friction angle are inversely proportional, higher friction angles result in lower active pressure values and thus, less pressure acting on the wall to provoke sliding failure.

BIBLIOGRAPHIC REFERENCE

[1] Bond A. and Harris A. (2008), *Decoding Eurocode 7. Taylor & Francis (1st edition). London and New York.*

[2] BS 6349-1-3: General – *Code of practice for geotechnical design. British Standards Institution, London, 2012.*

[3] ISO 14688-1 (2002) (English): *Geotechnical investigation and testing - Identification and classification of soil - Part 1: Identification and description. International Organization for Standardization, Geneva, 2002.*

[4] ISO 14688-2 (2004) (English): *Geotechnical investigation and testing - Identification and classification of soil - Part 2: Principles for a classification. International Organization for Standardization, Geneva, 2004.*

[5] European Standard EN 1997-1 (2004) (English): *Eurocode 7: Geotechnical design - Part 1: General rules [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC].*

[6] European Standard EN 1997-2 (2007) (English): *Eurocode 7: Geotechnical design - Part 2: Ground investigation and testing [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC].*

[7] Smith, I. (2014), *Smith's Elements of Soil Mechanics (9th edition). Edinburgh Napier University. Wiley Blackwell.*

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