European Commission

Retaining structures I – design of gravity walls

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Outline of talk

Scope and contents

Design situations and limit states

Basis of design for gravity walls

Verification of strength

- Reinforced concrete walls
- Mass gravity walls
- Reinforced fill walls

Verification of serviceability

Supervision, monitoring, and maintenance

Summary of key points

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SCOPE AND CONTENTS

Scope of EN 1997-1 Section 9 Retaining structures

Gravity walls

- Walls of stone or plain or reinforced concrete having a base with or without a heel, ledge, or buttress
- The weight of the wall itself … plays a significant role in the support of the retained material
- e.g. concrete gravity walls; spread footing r.c. walls; buttress walls

Embedded walls – to be covered later

Composite retaining structures

- Walls composed of elements of the above two types
- e.g. double sheet pile wall cofferdams; earth structures reinforced by tendons, geotextiles, or grouting; structures with multiple rows of ground anchorages or soil nails

Silos are covered by EN 1991-4

Contents of EN 1997-1 Section 9 Retaining structures

Section 9 applies to retaining structures supporting ground (i.e. soil, rock or backfill) and/or water

§9.1 General (6 paragraphs)
§9.2 Limit states (4)
§9.3 Actions, geometrical data and design situations (26)
§9.4 Design and construction considerations (10)
§9.5 Determination of earth pressures (23)
§9.6 Water pressures (5)
§9.7 Ultimate limit state design (26)
§9.8 Serviceability limit state design (14)

Many provisions from Section 6, 'Spread foundations' also apply to gravity walls

Contents of EN 1997-1's Annexes for retaining structures

Annex C of Eurocode 7 Part 1 provides informative text relevant to retaining structures

Annex C Sample procedures to determine earth pressures (21 paragraphs)

- §C.1 Limit values of earth pressure (3 paragraphs)
- §C.2 Analytical procedure for obtaining limiting active and passive earth pressures (14)
- §C.3 Movements to mobilise earth pressures (4)

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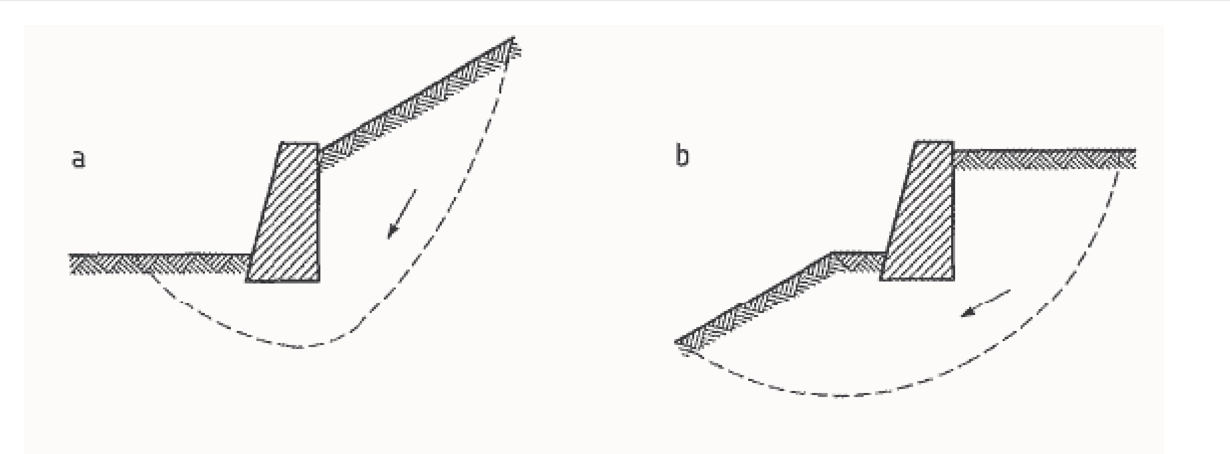
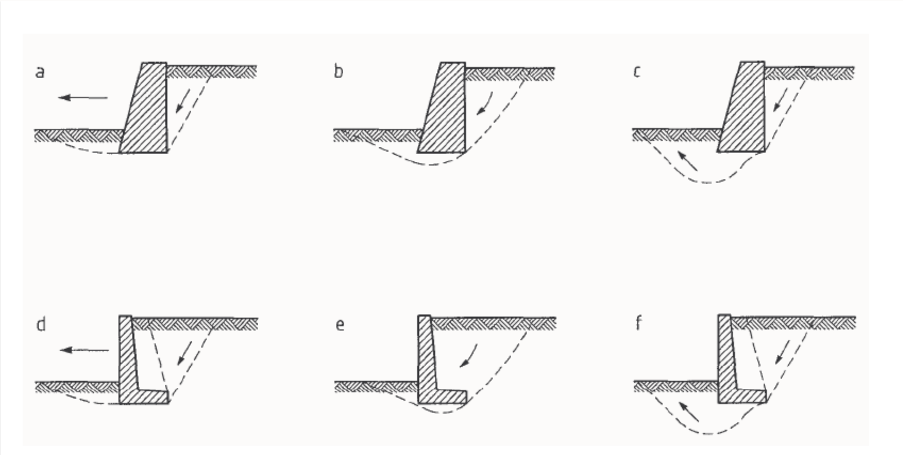
DESIGN SITUATIONS AND LIMIT STATES

Limit modes for overall stability and foundation failures (Figures 9.1 and 9.2)



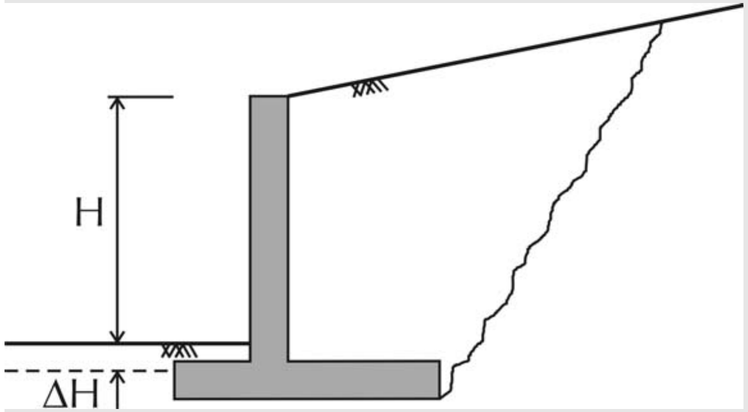


Anticipated and unplanned excavations §9.3.2.2.(2)

Design geometry shall account for anticipated excavation or possible scour in front of the retaining structure

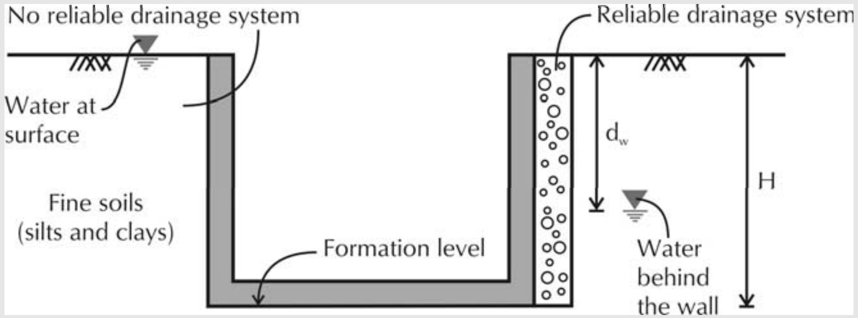
For ULS verifications:

$$H_d = H_{nom} + \Delta H$$



Wall type	For normal site control ΔH
Cantilever	10% H
Supported	10% height below lowest prop
Maximum	0.5 m

Water levels §9.6(3)



When it retains medium or low permeability (mainly fine) soils, the wall should be designed for a water level above formation level

- Without reliable drainage, water level should normally be taken at the surface of the retained material (i.e. $d_w = 0$)
- With reliable drainage, water level may be assumed to be below the top of the wall (i.e. $d_w > 0$) + maintenance requirement

Should water pressures be factored? §2.4.6.1(6)P and (8)

For ultimate limit states (ULSs)…

design values [of groundwater pressures] shall represent the most unfavourable values that could occur during the design lifetime of the structure

For serviceability limit states (SLSs)…

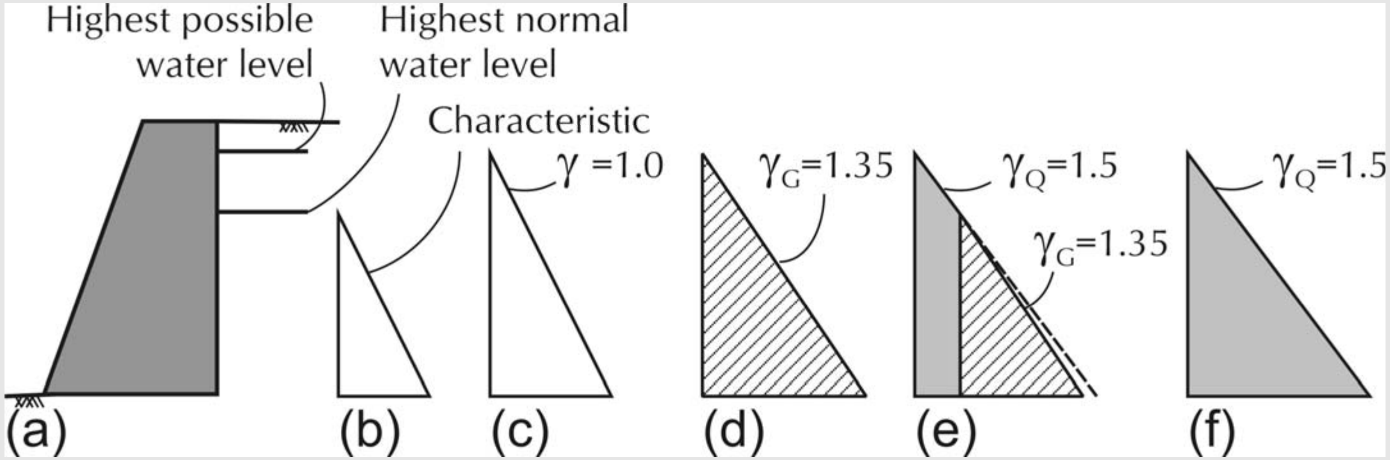
design values shall be the most unfavourable values which could occur in normal circumstances

[EN 1997-1 §2.4.6.1(6)P]

Design values of ground-water pressures may be derived either by applying partial factors to characteristic water pressures or by applying a safety margin to the characteristic water level…

[EN 1997-1 §2.4.6.1(8)]

Possible ways of treating water pressures (Bond & Harris, 2008)



(a) Design water levels for ULS and SLS design situations

(b) Characteristic water pressures for SLS design situation

Design pressures for ULS, with...

(c) no factor applied ($\gamma = 1.0$)

(d) factor on permanent actions ($\gamma_G = 1.35$)

(e) factor on permanent actions ($\gamma_G = 1.35$) applied to normal water level and factor on variable actions ($\gamma_Q = 1.5$) applied to rise in water level

(f) factor on variable actions ($\gamma_Q = 1.5$)

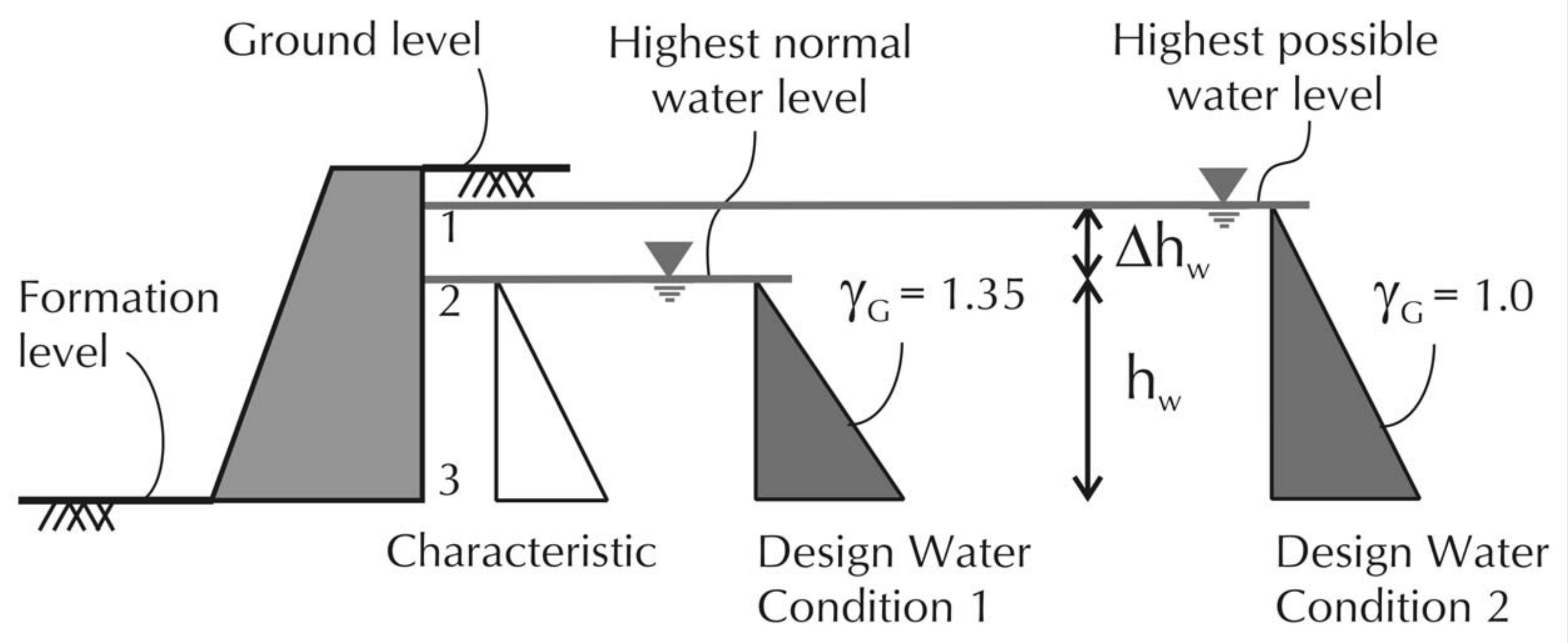
Providing a balance between reliability and realism (Bond & Harris, 2008)

"When partial factors $\gamma_G > 1.0$ are applied to effective earth pressures, then pore water pressures should also be multiplied by $\gamma_G > 1.0$ but calculated from highest normal (i.e. serviceability) water levels – i.e. no safety margin is applied (Design Water Condition 1)

"When partial factors $\gamma_G = 1.0$ are applied [they should be] multiplied by $\gamma_G = 1.0$ but calculated from highest possible (i.e. ultimate) water levels – after an appropriate safety margin has been applied (Design Water Condition 2)"

Bond and Harris (2008)

Recommended treatment of water pressures for design (Bond & Harris, 2008)



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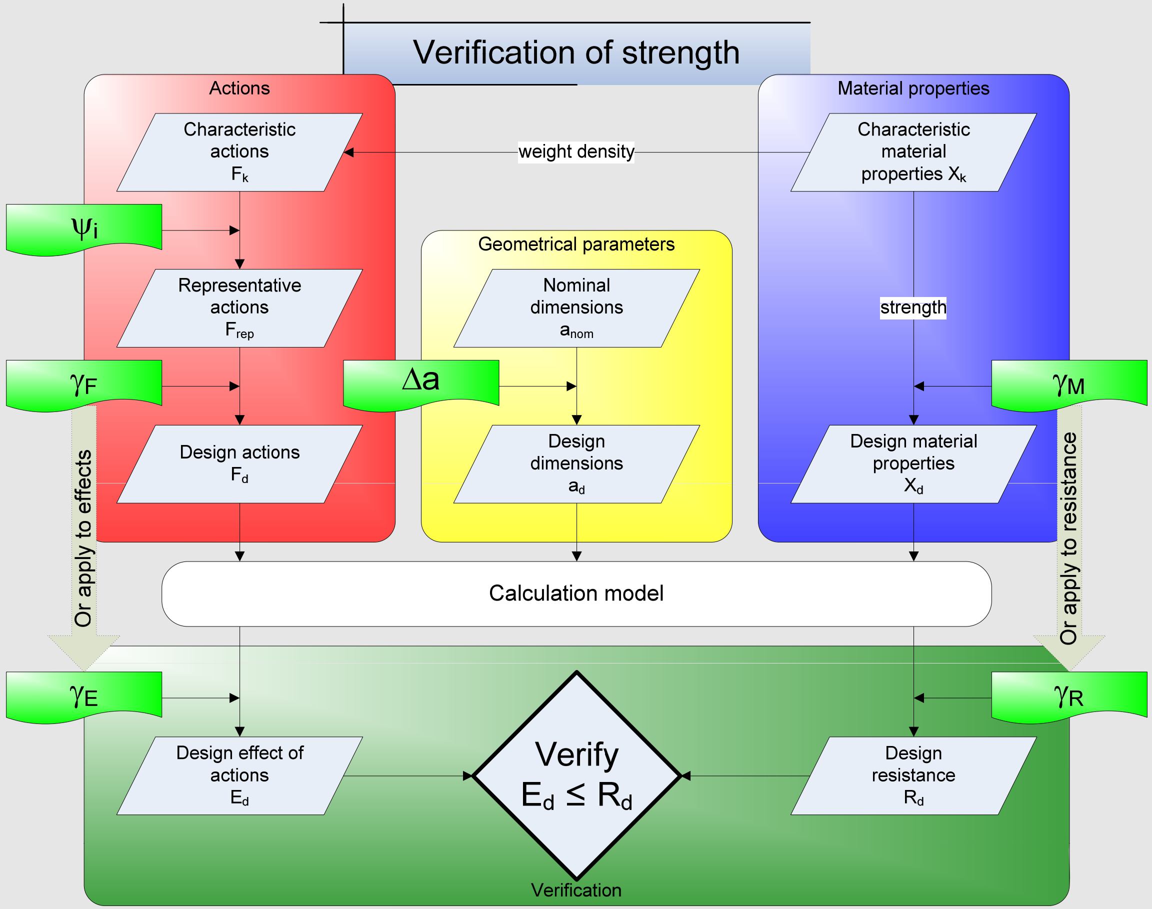
BASIS OF DESIGN FOR GRAVITY WALLS

Verification of strength for GEO/STR (Bond & Harris, 2008)



Design Approaches explained

Design Approach			
1		2	3
Combination 1	Combination 2		
Actions	Material properties	Actions/effects & resistances	Structural actions/effects & material properties
A1 + M1 + R1	A2 + M2 + R1	A1 + M1 + R2	A1/A2 + M2 + R3

(Major) factors >> 1.0; (minor) factors > 1.0
A1-A2 = factors on actions/effects
M1-M2 = factors on material properties
R1-R3 = factors on resistances

Partial factors for GEO/STR (DA1): footings, walls, and slopes

Parameter		Symbol	Combination 1			Combination 2		
			A1	M1	R1	A2	M2	R1
Permanent action (G)	Unfavourable	γ_G	1.35			1.0		
	Favourable	$(\gamma_{G,fav})$	1.0					
Variable action (Q)	Unfavourable	γ_Q	1.5			1.3		
	Favourable	-	(0)			(0)		
Shearing resistance (tan φ)		γ_φ		1.0			1.25	
Effective cohesion (c′)		γ_c						
Undrained shear strength (c_u)		γ_{cu}					1.4	
Unconfined compressive strength (q_u)		γ_{qu}						
Weight density (γ)		γ_γ					1.0	
Bearing resistance (R_v)		γ_{Rv}			1.0			1.0
Sliding resistance (R_h)		γ_{Rh}						
Earth resistance (R_e)		γ_{Re}						
Factors given for persistent and transient design situations								

Partial factors for GEO / STR (DAs 2 / 3): footings, walls, slopes

Parameter		Symbol	Design Approach 2 A1	Design Approach 2 M1	Design Approach 2 R2	Design Approach 3 A1#	Design Approach 3 A2*	Design Approach 3 M2	Design Approach 3 R3
Permanent action (G)	Unfavourable	γ_G	1.35			1.35	1.0		
	Favourable	($\gamma_{G,fav}$)	1.0						
Variable action (Q)	Unfavourable	γ_Q	1.5			1.5	1.3		
	Favourable	-	(0)			(0)			
Shearing resistance (tan φ)		γ_φ		1.0				1.25	
Effective cohesion (c′)		γ_c							
Undrained shear strength (c_u)		γ_{cu}						1.4	
Unconfined comp. str. (q_u)		γ_{qu}							
Weight density (γ)		γ_γ						1.0	
Bearing resistance (R_v)		γ_{Rv}			1.4				1.0
Sliding resistance (R_h)		γ_{Rh}			1.1				
Earth resistance (R_e) walls		γ_{Re}			1.4				
Earth resistance (R_e) slopes					1.1				

Factors given for persistent and transient design situations
#Applied to structural actions; *applied to geotechnical actions

National choice of Design Approach for retaining walls (Bond, 2013)

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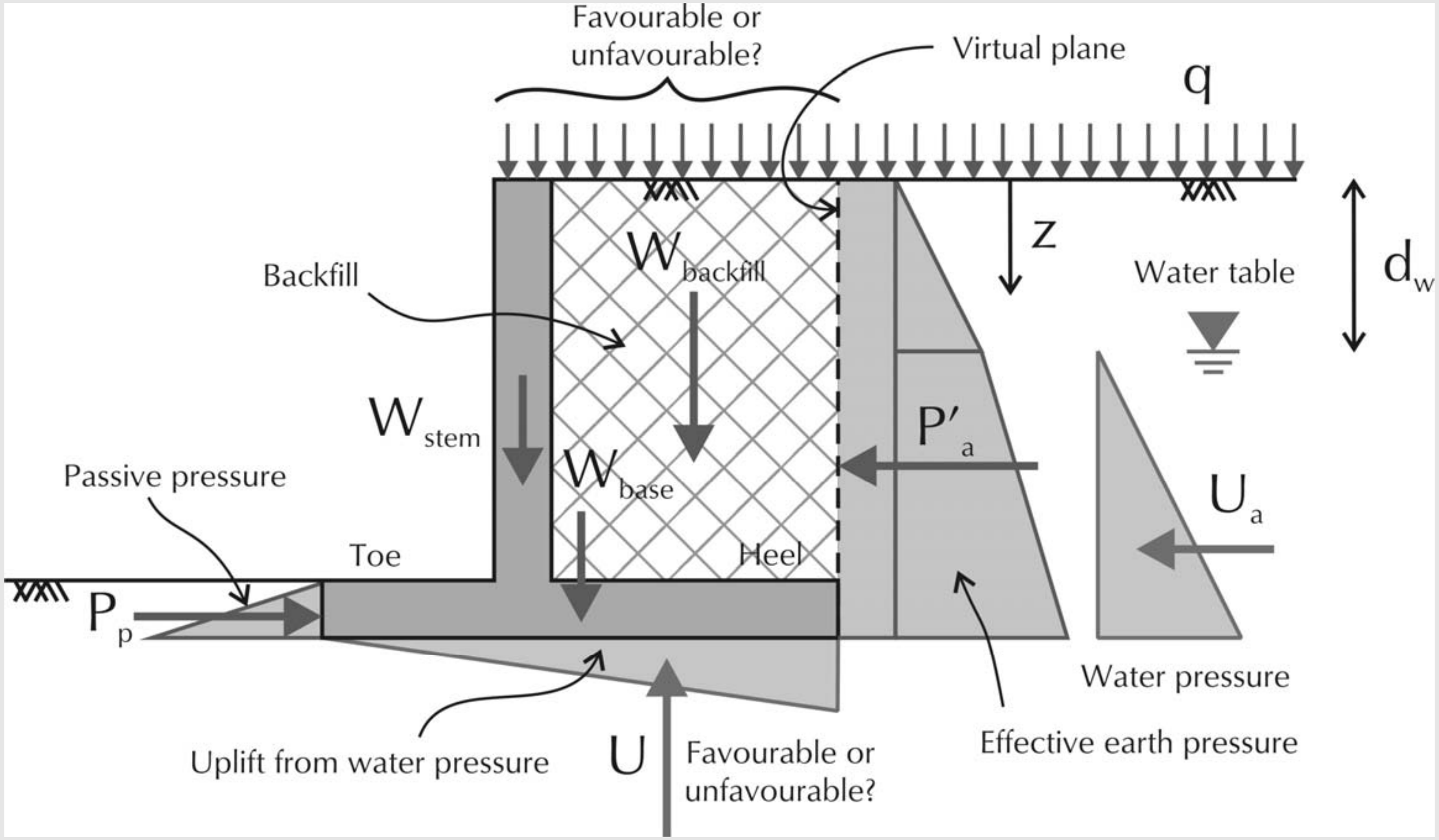
VERIFICATION OF STRENGTH: R.C. WALLS

Earth pressures on a reinforced concrete wall (Bond & Harris, 2008)



Active and passive limit states (Annex C)

Eurocode 7 Part 1 (+Corrigendum 1) gives expressions for active/passive earth pressures:

$$\sigma_a = K_a\left(\int_0^z \gamma dz + q - u\right) - 2c\sqrt{K_a(1+a/c)} + u$$

$$\sigma_p = K_p\left(\int_0^z \gamma dz + q - u\right) + 2c\sqrt{K_p(1+a/c)} + u$$

$\sigma_a(z)$, $\sigma_p(z)$ = active/passive stress normal to wall at depth z

K_a, K_p = horizontal active/passive earth pressure coefficient

γ = weight density of retained ground; c = ground cohesion

q = vertical surface load; z = distance down face of wall

a = wall adhesion

Rankine's earth pressure coefficient

Earth pressure coefficient for active conditions, assuming a Rankine zone forms between the back of the wall and the virtual plane:

$$K_{a,\beta} = \left(\frac{\cos\beta - \sqrt{\cos^2\beta - \cos^2\varphi}}{\cos\beta + \sqrt{\cos^2\beta - \cos^2\varphi}} \right) \cos\beta$$

$K_{a,\beta}$ = active earth pressure coefficient for inclined thrust (= σ'_β / σ'_v)

φ = angle of shearing of soil; β = angle of inclination of ground surface

σ'_β = inclined effective stress; σ'_v = vertical effective stress

When β = 0, this reduces to the more familiar:

$$K_a = \frac{1 - \sin\varphi}{1 + \sin\varphi}$$

At rest earth pressures

Earth pressure coefficient for at-rest conditions:

$$K_0 = (1 - \sin\varphi) \times \sqrt{OCR} \times (1 + \sin\beta)$$

K_0 = at rest earth pressure coefficient (= σ'_h / σ'_v)
φ = angle of shearing of soil;
OCR = overconsolidation ratio (= $\sigma'_{v,max}$ / σ'_v)
β = slope angle of ground surface
σ'_h = horizontal effective stress; σ'_v = vertical effective stress

For normally consolidated soil, assume at rest conditions if movement of structure is less than 0.05% of H

Expression is a combination of Meyerhof's equation for K_0 and Kezdi's modification for sloping ground

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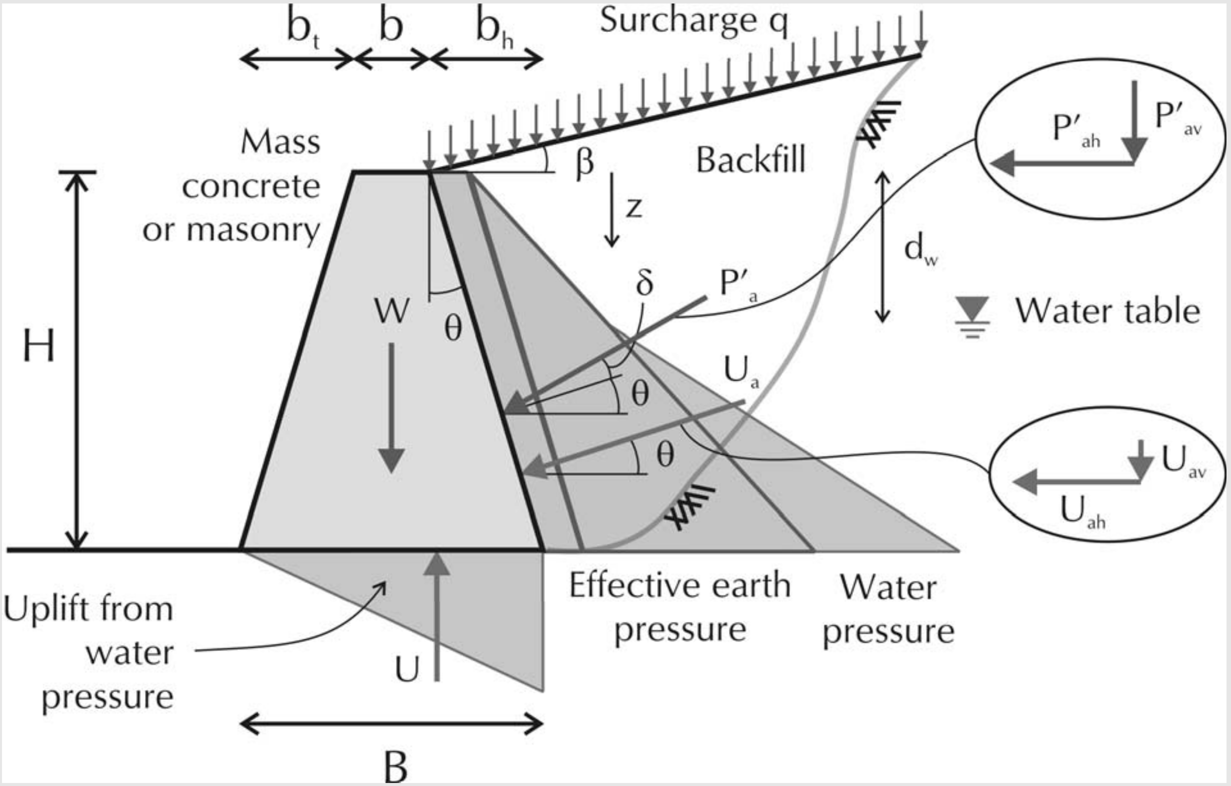
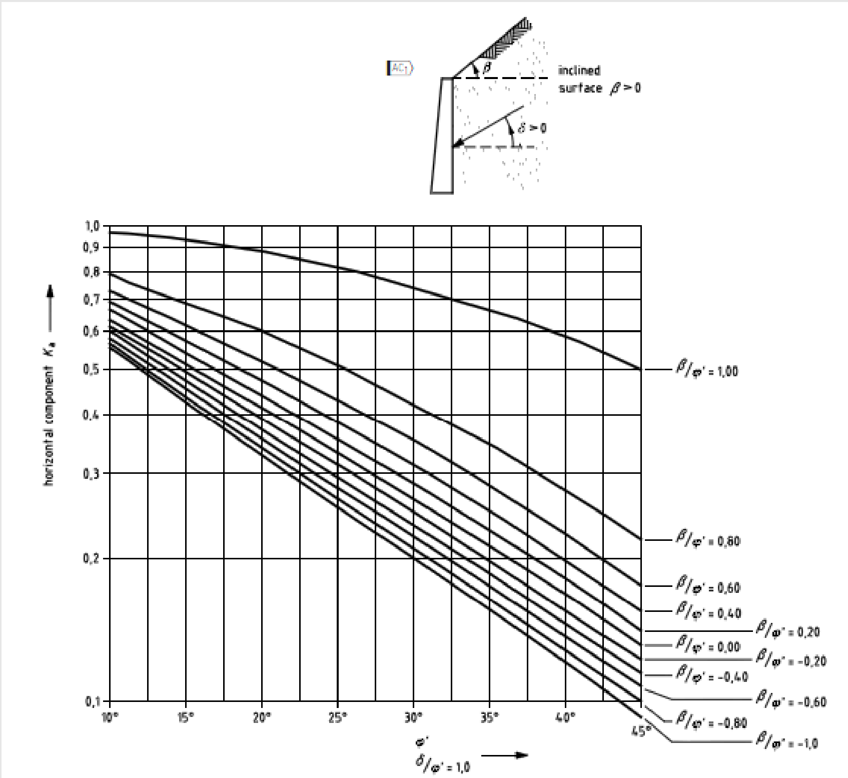
VERIFICATION OF STRENGTH: MASS GRAVITY WALLS

Earth pressures on a mass gravity wall (Bond & Harris, 2008)



Charts of Kerisel and Absi's earth pressure coefficients (Annex C)



Charts are not attributed, but come from Kerisel and Absi's work. They are the same as appear in BS 8002

Kerisel and Absi assumed log-spiral failure surfaces and hence their charts give upper bound values of K_a and K_p

Charts are given for walls with vertical faces only

$$\left.\begin{matrix} K_a \\ K_p \end{matrix}\right\} = f\left\{\varphi, \frac{\beta}{\varphi}, \frac{\delta}{\varphi}\right\}$$

'New' formulation for active and passive earth coefficients (Annex C)

$$\sigma'_a = K_{a\gamma}\left(\int_0^z \gamma dz - u\right) + K_{aq} q - K_{ac} c$$

$$\sigma'_p = K_{p\gamma}\left(\int_0^z \gamma dz - u\right) + K_{pq} q + K_{pc} c$$

$$\left.\begin{matrix} K_{a\gamma} \\ K_{p\gamma} \end{matrix}\right\} = K_n \times \cos\beta \times \cos(\beta - \theta)$$

$$\left.\begin{matrix} K_{aq} \\ K_{pq} \end{matrix}\right\} = K_n \times \cos^2\beta$$

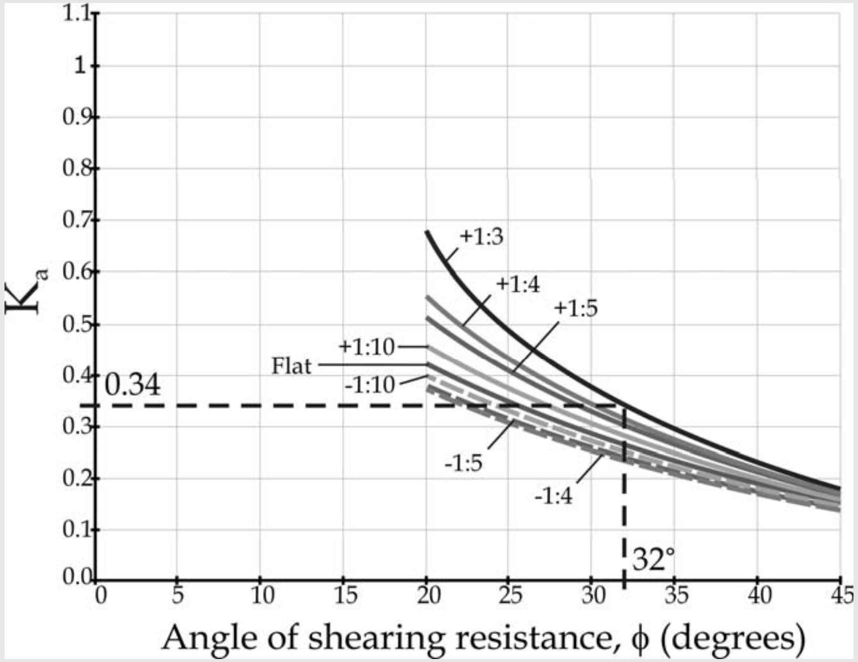
$$\left.\begin{matrix} K_{ac} \\ K_{pc} \end{matrix}\right\} = (K_n - 1) \times \cot\varphi$$

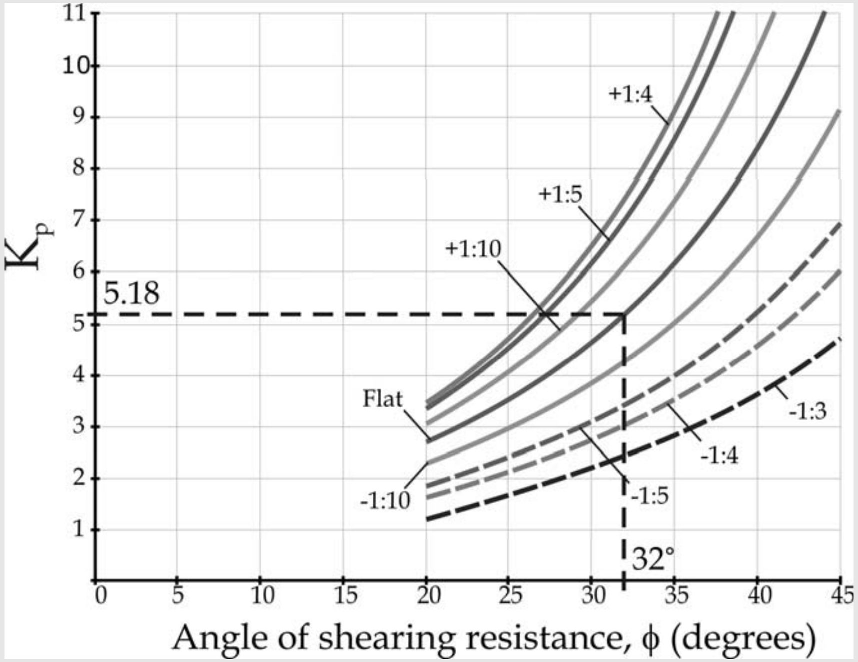
$$2m_t = \cos^{-1}\left(\frac{-\sin\beta}{\pm\sin\varphi}\right) \mp \varphi - \beta$$

$$2m_w = \cos^{-1}\left(\frac{\sin\delta}{\sin\varphi}\right) \mp \varphi \mp \delta$$

$$K_n = \frac{1 \pm \sin\varphi \times \sin(2m_w \pm \varphi)}{1 \mp \sin\varphi \times \sin(2m_t \pm \varphi)} e^{\pm 2(m_t + \beta - m_w - \theta)\tan\varphi}$$

Charts of Brinch Hansen's earth pressure coefficients (Bond & Harris, 2008)





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VERIFICATION OF STRENGTH: REINFORCED FILL WALLS

No single design method accepted throughout Europe

Eurocode 7 … does not cover the detailed design of reinforced fill structures. The values of the partial factors … given in EN 1997-1 have not been calibrated for reinforced fill structures

[Foreword to EN 14475]

Design of reinforced fill structures is currently carried out to national standards (such as BS 8006)

Differences in working practices, geology, and climate, etc. have delayed the development of a single design method accepted throughout Europe

EN 14475 provides guidance on the execution of reinforced fill structures

It is hoped that a future European standard will cover design

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VERIFICATION OF SERVICEABILITY

Verification of serviceability

Verification of serviceability is expressed in Eurocode 7 by:

$$E_d \leq C_d$$

E_d = design effect of actions (e.g. displacement, distortion)
C_d = design constraint (i.e. limiting value of the design effect of actions)

For 'conventional structures founded on clays', Eurocode 7 allows settlement calculations to be avoided if an ultimate limit state calculation for bearing resistance satisfies:

$$E_k \leq \frac{R_k}{\gamma_{R,SLS}}$$

E_k = characteristic effects of actions; E_k = characteristic resistance
$\gamma_{R,SLS}$ = a partial resistance factor ≥ 3.0

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SUPERVISION, MONITORING, AND MAINTENANCE

Supervision of construction (Annex J)

Selected (general) items from checklist in Annex J on supervision of construction:

- Verification of ground conditions and of the location and general lay-out of the structure
- Ground-water flow and pore-water pressure regime; effects of dewatering on ground-water table; effectiveness of measures to control seepage inflow; corrosion potential
- Movements, yielding, stability of excavation walls and base; temporary support systems; effects on nearby buildings and utilities; measurement of soil pressures on retaining structures and of pore-water pressure variations resulting from excavation or loading
- Safety of workmen with due consideration of geotechnical limit state

Supervision water flow and pore-water pressures (Annex J)

Selected items from checklist in Annex J on water flow and pore-water pressures

- Adequacy of systems to control pore-water pressures in aquifers where excess pressure could affect stability of base of excavation, including artesian pressures beneath the excavation; disposal of water from dewatering systems; depression of ground-water table throughout entire excavation to prevent boiling or quick conditions, piping and disturbance of formation by construction equipment; diversion and removal of rainfall or other surface water
- Control of dewatering to avoid disturbance of adjoining structures or areas; observations of piezometric levels; effectiveness, operation and maintenance of water recharge systems
- Settlement of adjoining structures or areas
- Effectiveness of sub-horizontal borehole drains

Monitoring and maintenance (Annex J)

Selected items from checklist in Annex J on performance monitoring:

- Settlement at established time intervals of buildings and other structures including those due to effects of vibrations on metastable soils
- Lateral displacement and distortions, especially those related to fills and stockpiles; soil supported structures, such as buildings or large tanks; deep trenches
- Piezometric levels under buildings or in adjoining areas, especially if deep drainage or permanent dewatering systems are installed or if deep basements are constructed
- Deflection or displacement of retaining structures considering: normal backfill loadings; effects of stockpiles; fills or other surface loadings; water pressures
- Flow measurements from drains
- Water tightness

(No specific guidance given for maintenance)

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SUMMARY OF KEY POINTS

Summary of key points

Design of gravity walls to Eurocode 7 involves checking that the ground beneath the wall has sufficient:

- bearing resistance to withstand inclined, eccentric actions
- sliding resistance to withstand horizontal and inclined actions
- stability to avoid toppling
- stiffness to prevent unacceptable settlement or tilt

Verification of ultimate limit states (ULSs) is demonstrated by satisfying the inequalities:

$$V_d \leq R_d \text{ and } H_d \leq R_d + R_{pd} \text{ and } M_{Ed,dst} \leq M_{Ed,stb}$$

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