Retaining structures I – design of gravity walls

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Director, Geocentrix Ltd
Chairman TC250/SC7
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
Retaining structures I – design of gravity walls

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:

\[ H_d = H_{nom} + \Delta H \]

<table>
<thead>
<tr>
<th>Wall type</th>
<th>For normal site control $\Delta H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cantilever</td>
<td>10% $H$</td>
</tr>
<tr>
<td>Supported</td>
<td>10% height below lowest prop</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.5 m</td>
</tr>
</tbody>
</table>
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)
Retaining structures I – design of gravity walls

BASIS OF DESIGN FOR GRAVITY WALLS
Verification of strength for GEO/STR (Bond & Harris, 2008)
# Design Approaches explained

<table>
<thead>
<tr>
<th>Design Approach</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
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<tbody>
<tr>
<td>Combination 1</td>
<td></td>
<td></td>
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<tr>
<td>Actions</td>
<td>A₁ + M₁ + R₁</td>
<td>A₂ + M₂ + R₁</td>
<td>A₁ + M₁ + R₂</td>
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<tr>
<td>Material properties</td>
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<tr>
<td>Actions/effects &amp; resistances</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural actions/effects &amp; material properties</td>
<td></td>
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</tr>
</tbody>
</table>

(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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Combination 1</th>
<th>Combination 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A1  M1  R1</td>
<td>A2  M2  R1</td>
</tr>
<tr>
<td>Permanent action (G)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Unfavourable</td>
<td>$\gamma_G$</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td>Favourable</td>
<td>$(\gamma_{G,fav})$</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Variable action (Q)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unfavourable</td>
<td>$\gamma_Q$</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Favourable</td>
<td>-</td>
<td>(0)</td>
<td>(0)</td>
</tr>
<tr>
<td>Shearing resistance ($\tan \varphi$)</td>
<td>$\gamma_{\varphi}$</td>
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<td>1.25</td>
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<tr>
<td>Effective cohesion ($c'$)</td>
<td>$\gamma_{c'}$</td>
<td></td>
<td></td>
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<tr>
<td>Undrained shear strength ($c_u$)</td>
<td>$\gamma_{c_u}$</td>
<td>1.0</td>
<td>1.4</td>
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<tr>
<td>Unconfined compressive strength ($q_u$)</td>
<td>$\gamma_{q_u}$</td>
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<tr>
<td>Weight density ($\gamma$)</td>
<td>$\gamma_{\gamma}$</td>
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<td>Bearing resistance ($R_v$)</td>
<td>$\gamma_{R_v}$</td>
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<tr>
<td>Sliding resistance ($R_h$)</td>
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<td>1.0</td>
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<tr>
<td>Earth resistance ($R_e$)</td>
<td>$\gamma_{R_e}$</td>
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<tr>
<td>Factors given for persistent and transient design situations</td>
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</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Design Approach 2</th>
<th>Design Approach 3</th>
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<tr>
<td></td>
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<td>M1</td>
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<td>Permanent action (G)</td>
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<td></td>
<td>Favourable</td>
<td>$\gamma_{G,fav}$ 1.0</td>
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<td>Variable action (Q)</td>
<td>Unfavourable</td>
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<td></td>
<td>Favourable</td>
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<td>Shearing resistance ($\tan \varphi$)</td>
<td>$\gamma_\varphi$</td>
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</tr>
<tr>
<td>Effective cohesion (c')</td>
<td>$\gamma_c$</td>
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<tr>
<td>Undrained shear strength ($c_u$)</td>
<td>$\gamma_{cu}$</td>
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<td>1.4</td>
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<tr>
<td>Unconfined comp. str. ($q_u$)</td>
<td>$\gamma_{qu}$</td>
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<tr>
<td>Weight density ($\gamma$)</td>
<td>$\gamma_v$</td>
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</tr>
<tr>
<td>Bearing resistance ($R_v$)</td>
<td>$\gamma_{RV}$</td>
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<td>1.4</td>
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<td>Sliding resistance ($R_h$)</td>
<td>$\gamma_{Rh}$</td>
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<td>Earth resistance ($R_e$) walls</td>
<td>$\gamma_{Re}$</td>
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<td>1.4</td>
</tr>
<tr>
<td>Earth resistance ($R_e$) slopes</td>
<td>$\gamma_{Re}$</td>
<td></td>
<td>1.1</td>
</tr>
</tbody>
</table>

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)
Retaining structures I – design of gravity walls

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

\(\gamma = \) 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:

\[ K_{a, \beta} = \left( \frac{\cos \beta - \sqrt{\cos^2 \beta - \cos^2 \phi}}{\cos \beta + \sqrt{\cos^2 \beta - \cos^2 \phi}} \right) \cos \beta \]

\( K_{a, \beta} = \) active earth pressure coefficient for inclined thrust (\( = \sigma'_{\beta} / \sigma'_{\nu} \))

\( \phi = \) angle of shearing of soil; \( \beta = \) angle of inclination of ground surface

\( \sigma'_{\beta} = \) inclined effective stress; \( \sigma'_{\nu} = \) vertical effective stress

When \( \beta = 0 \), this reduces to the more familiar:

\[ K_a = \frac{1 - \sin \phi}{1 + \sin \phi} \]
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 \( (\sigma'_h / \sigma'_v) \)
- \( \varphi \) = angle of shearing of soil;
- \( OCR \) = overconsolidation ratio \( (\sigma'_{v,\text{max}} / \sigma'_v) \)
- \( \beta \) = slope angle of ground surface
- \( \sigma'_h \) = horizontal effective stress; \( \sigma'_v \) = 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
Retaining structures I – design of gravity walls

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.

\[
\begin{align*}
K_a &= f\left\{\varphi, \beta, \delta \right\} \\
K_p &= f\left\{\varphi, \frac{\beta}{\varphi} \right\}
\end{align*}
\]
‘New’ formulation for active and passive earth coefficients (Annex C)

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

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

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

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

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

\[
K_{aq} \quad K_{pq} \quad K_{pc}
\]

\[
K_{ay} \quad K_{py}
\]

\[
= K_n \times \cos \beta \times \cos(\beta - \theta)
\]

\[
= K_n \times \cos^2 \beta
\]

\[
= (K_n - 1) \times \cot \varphi
\]
Charts of Brinch Hansen’s earth pressure coefficients (Bond & Harris, 2008)
Retaining structures I –
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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
Retaining structures I – design of gravity walls

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 \( \geq 3.0 \)
Retaining structures I – design of gravity walls

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:

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