Design and Construction of Metro Stations and Underground Structures to Eurocode 7 - with Case Histories

David Beadman
Byrne Looby Partners
Contents

The Eurocodes and Eurocode 7
Jubilee Line, London – North Greenwich Station
Jubilee Line, London – Canary Wharf Station
Copenhagen Metro – Eurocode 2
Copenhagen Metro – Observational Method
The Eurocodes and Eurocode 7

November 2008

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# Eurocode Suite

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 1990</td>
<td>Eurocode: Basis of structural design</td>
</tr>
<tr>
<td>EN 1991</td>
<td>Eurocode 1: Actions on structures</td>
</tr>
<tr>
<td>EN 1992</td>
<td>Eurocode 2: Design of concrete structures</td>
</tr>
<tr>
<td>EN 1993</td>
<td>Eurocode 3: Design of steel structures</td>
</tr>
<tr>
<td>EN 1994</td>
<td>Eurocode 4: Design of composite steel and concrete structures</td>
</tr>
<tr>
<td>EN 1995</td>
<td>Eurocode 5: Design of timber structures</td>
</tr>
<tr>
<td>EN 1996</td>
<td>Eurocode 6: Design of masonry structures</td>
</tr>
<tr>
<td>EN 1997</td>
<td>Eurocode 7: Geotechnical design</td>
</tr>
<tr>
<td>EN 1998</td>
<td>Eurocode 8: Design of structures for earthquake resistance</td>
</tr>
<tr>
<td>EN 1999</td>
<td>Eurocode 9: Design of aluminium structures</td>
</tr>
</tbody>
</table>
Structure of the Eurocodes

EN 1990

EN 1991

EN 1992  EN 1993  EN 1994
EN 1995  EN 1996  EN 1999

Basis of structural design

Actions on structures

Design and detailing

Geotechnical and Seismic design
a  National title page
b  National foreword
c  EN title page
d  EN text
e  EN Annex(es)
f  National annex
National Annex?

- The member states refinement of the CEN released Eurocode to reflect its own national practices
- Values of Nationally Determined Parameters (NDP’s)
- The decisions where main text allows alternatives
- The choice to adopt informative annexes
- Non-contradictory complementary information (NCCI)
Embedded retaining walls – guidance for economic design.
London 2003

CIRIA C580
Approved by CEN on 23 April 2004.
Implementation

1. Release of Eurocode to BSI by CEN
   - Develop National Annex
   - Modify Existing Standards
   - BSI Publish Eurocode with National Annex
     - Coexistence of Eurocode with British Standard
       - Withdrawal of British Standard

2 Years

3 Years
Operation and Application

Principles

- General statements and definitions for which there is no alternative.
- Requirements for analytical models for which no alternative is permitted
- Principle clauses are identified with the letter ‘P’
- The verb ‘shall’ is used (meaning ‘must’)

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Operation and Application

Application rules

• Generally recognised rules which satisfy the Principles, but alternative rules may be used.
• Verbs ‘should’, ‘may’, ‘can’ etc used
Contents

Section 1: General
Section 2: Basis of geotechnical design
Section 3: Geotechnical data
Section 4: Supervision of construction, monitoring and maintenance
Section 5: Fill, dewatering, ground improvement and reinforcement
Contents

Section 6: Spread foundations
Section 7: Pile foundations
Section 8: Anchorages
Section 9: Retaining structures
Section 10: Hydraulic failure
Section 11: Overall stability
Section 12: Embankments
Contents

Annex A: Recommended partial factors

Annex B-J: Supplementary information

EN1997-2 Performance and evaluation of field and laboratory measurements
Eurospeak

Actions (c.f. Loads)
Permanent & Variable (c.f. Dead and Live)

Geotechnical action 1.5.2.1
Action transmitted to the structure by the ground, fill, standing water or ground-water
Eurospeak 1.5.2.7

Norm
- Standard – EN Euro-Norm i.e. European Standard

Resistance
- capacity ……. to withstand actions without mechanical failure e.g. resistance of the ground, bending resistance, buckling resistance, tensile resistance

Characteristic
- The value of a parameter to be used in design; usually the value of an action only likely to occur with a probability of 0.02 per annum or a material property likely to be achieved with a probability of 0.95.
Calculations 2.4

Characteristic Values 2.4.5.2 (2)P

- The characteristic value of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state.
Soil Parameters

Figure 3.2  Types of soil strength parameters

- Most Unfavourable
- Characteristic material property (used in structural engineering)
- Moderately conservative
- Most Probable

No. of Readings

1 in 1000  1 in 20  1 in 2

Soil Strength Parameter Results
Ultimate Limit States 2.4.7

Internal failure or excessive deformation of the structure or structural elements, including e.g. footings, piles or basement walls, in which the strength of structural materials is significant in providing resistance (STR);
Ultimate Limit States 2.4.7 (STR)
Ultimate Limit States 2.4.7

Failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance (GEO);

NOTE Limit state GEO is often critical to the sizing of structural elements involved in foundations or retaining structures and sometimes to the strength of structural elements.
Ultimate Limit States 2.4.7 (GEO)
Design Approach 1  2.4.7.3.4.2

Check for a limit state of rupture or excessive deformation:

– Combination 1: A1 “+” M1 “+” R1
– Combination 2: A2 “+” M2 “+” R1

(Except for the design of axially loaded piles and anchors.)
## Eurocode 7 Table A.3

### Table A.3 - Partial factors on actions ($\gamma_F$) or the effects of actions ($\gamma_E$)

<table>
<thead>
<tr>
<th>Action</th>
<th>Symbol</th>
<th>Set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$A_1$</td>
</tr>
<tr>
<td>Permanent</td>
<td>$\gamma_G$</td>
<td>1,35</td>
</tr>
<tr>
<td>Unfavourable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Favourable</td>
<td></td>
<td>1,0</td>
</tr>
<tr>
<td>Variable</td>
<td>$\gamma_Q$</td>
<td>1,5</td>
</tr>
<tr>
<td>Unfavourable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Favourable</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>
### Table A.4 - Partial factors for soil parameters ($\gamma_{M}$)

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>Symbol</th>
<th>Set</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M1</td>
<td>M2</td>
<td></td>
</tr>
<tr>
<td>Angle of shearing resistance(^{a})</td>
<td>$\gamma'_{\phi}$</td>
<td>1,0</td>
<td>1,25</td>
<td></td>
</tr>
<tr>
<td>Effective cohesion</td>
<td>$\gamma'_{c}$</td>
<td>1,0</td>
<td>1,25</td>
<td></td>
</tr>
<tr>
<td>Undrained shear strength</td>
<td>$\gamma'_{cu}$</td>
<td>1,0</td>
<td>1,4</td>
<td></td>
</tr>
<tr>
<td>Unconfined strength</td>
<td>$\gamma'_{qu}$</td>
<td>1,0</td>
<td>1,4</td>
<td></td>
</tr>
<tr>
<td>Weight density</td>
<td>$\gamma_{i}$</td>
<td>1,0</td>
<td>1,0</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) This factor is applied to tan $\phi'$. 

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## Eurocode 7 Table A.13

<table>
<thead>
<tr>
<th>Resistance</th>
<th>Symbol</th>
<th>Set</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td><strong>R1</strong></td>
</tr>
<tr>
<td>Bearing capacity</td>
<td>$\gamma_{R;v}$</td>
<td>1,0</td>
</tr>
<tr>
<td>Sliding resistance</td>
<td>$\gamma_{R;h}$</td>
<td>1,0</td>
</tr>
<tr>
<td>Earth resistance</td>
<td>$\gamma_{R;e}$</td>
<td>1,0</td>
</tr>
</tbody>
</table>
Ground surfaces 9.3.2.2 (2)

- Ultimate limit state – level of resisting ground lowered by $\Delta a$, where $\Delta a$ is, for normal levels of control:
  - 10% of wall height for a cantilever or 10% of depth below the lowest support, limited to a maximum of 0.5m
  - i.e. “Overdig” allowance
Embedded retaining wall

Combination 2 to determine toe depth (Geo) i.e. BS 8002 design

Soil strength $\div \gamma_M$
   (table A.4)
Soil stiffness $\div 2$
(CIRIA C580)
Include ‘over-dig’
Surcharge $\times \gamma_F$ equiv.
   $=1.3/1.0$ (table A.3)

Resulting section forces
(BM & SF) $\times \gamma_F = 1.0$
(table A.3) – Design values.
Embedded retaining wall

Combination 1 to determine section forces (Str) i.e. BS 8110 design

Soil strength $\div \gamma_M = 1.0$ (table A.4)

Soil stiffness unfactored

Include ‘over-dig’

Surcharge $\times \gamma_F$ equiv. $= 1.5/1.35$ (table A.3)

Resulting section forces $(BM \& SF) \times \gamma_F = 1.35$ (table A.3) – Design values.
Embedded retaining wall

Serviceability loadcase to determine deflections

Soil strength unfactored

Soil stiffness unfactored

No ‘over-dig’

Surcharge unfactored
Execution Standards 7.1(3)p

BS EN 1536:1999, Execution of special geotechnical works - bored piles
BS EN 12063:2000, for sheet pile walls,
BS EN 12699:2000, for displacement piles.
BS EN 14199 for micro-piles.
The Jubilee Line Extension, London
North Greenwich station
North Greenwich Station

- Large internal space
- No internal slabs
- Temporary propping of retaining walls difficult
North Greenwich station

- Box designed independently of any temporary works

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Made Ground

Alluvium

Thames Gravel

London clay
North Greenwich station

- Difficult to build station around temporary props
North Greenwich station
Construction sequence

- Install hard soft secant piles
North Greenwich station

- Excavate outside box to 3m depth
- Excavate inside to 7.5m depth
- Install ground anchors

Made Ground

Alluvium

Thames Gravel

London clay
North Greenwich station

- Excavate to 15.5m depth
- Install prop
North Greenwich station

• Complete excavation

Made Ground

Alluvium

Thames Gravel

London clay
North Greenwich station

Open excavation with ground anchors

Construction of box avoided building around props
North Greenwich station

Excavation Level m

Anchor installed

Prop installed

Prop removed

Movement at top of pile mm

24/06/94
11/07/94
22/07/94
02/08/94
19/08/94
31/08/94
27/09/94
12/10/94
17/10/94
01/11/94
15/11/94
01/12/94
21/02/95
28/03/95

Date

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North Greenwich station

- Analysed with WALLAP (beam-on-springs program)
- Prop load 1500kN/m (unfactored) i.e. 9000kN/prop @ 6m
- Measured typically 6000kN, one prop 15000kN (2500kN/m)
- Note mismatch of stiffnesses - ground anchors and props
North Greenwich station

Analysis now with factored soils, overdig, softening, minimum fluid pressure (i.e. in accordance with Eurocode 7 and CIRIA C580)

Wall is not stable
The Jubilee Line Extension, London
Canary Wharf station
Canary Wharf station

Diaphragm walls installed from the base of an old dock
Diaphragm walls

Dug under bentonite using a Grab or Hydrofraise

Insert reinforcement cage and concrete using tremie pipe
Diaphragm walls

Typical joint detail.

Straight panels, tee panels or corner panels.

Grab length 2.8m typical.
Diaphragm Walls

Reinforcement details:

• Allow for the tremie pipe;
• Allow for the unreinforced area close to the CWS stop end;
• For installation, the cage must be lifted.
Canary Wharf station – slot stability

![Graph showing soil pressure and bentonite pressure against level in mOD and pressure in kPa.](image)
The Copenhagen Metro
Eurocode 2

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Piles require some special attention for buildability
Spreadsheets written and checked

Analysis programs unavailable
## Comparison of BS5400 and the Metro Specification

<table>
<thead>
<tr>
<th>Requirements</th>
<th>BS5400</th>
<th>Metro Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design life</td>
<td>120 years</td>
<td>100 years</td>
</tr>
<tr>
<td>Concrete grade</td>
<td>$f_{cu} = 35\text{N/mm}^2$</td>
<td>$f_{ck} = 30\text{N/mm}^2$</td>
</tr>
<tr>
<td>Minimum cover for durability for retaining wall members, as concrete cast in non-aggressive ground</td>
<td>35mm</td>
<td>50mm</td>
</tr>
<tr>
<td>Minimum cover for structures cast against the ground</td>
<td>75mm</td>
<td>90mm</td>
</tr>
<tr>
<td>Maximum crack width</td>
<td>0.25mm</td>
<td>0.2mm</td>
</tr>
</tbody>
</table>
Top down construction sequence

Stage 1 Install retaining wall
Stage 2 Excavate and construct roof
Stage 3 Excavate and construct waling beam
Stage 4 Excavate to formation level
Station cross-section

Structure hung from roof

Large fixed-end moments
Crack-width for concrete sections

Calculate crack width at cover required for durability
Eurocode 2 - Crack width calculation

1180mm diameter pile 1050mm diameter pile

Crack width check at 50mm cover
Concrete tension zone
Neutral axis
860mm overall diameter links
Eurocode 2 - Lapping of bars

Principle – not permitted to lap bars greater than 32mm diameter. (Not satisfied)
Eurocode 2 - Equivalent diameter of bar bundles

Bundles of equivalent diameter greater than 55mm not permitted (Application Rule)

Bundles to be considered as notional bars for purposes of crack-width calculation (Application Rule)
### Eurocode 2 - Equivalent diameter of bar bundles

<table>
<thead>
<tr>
<th>Description</th>
<th>Calculation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bars in bundle: (Assume 40mm diameter bars)</td>
<td>Two:</td>
<td>40 x (2 + (\pi)) = 206mm</td>
</tr>
<tr>
<td>Equivalent perimeter of bundle</td>
<td>40 x (2 + (\pi)) = 206mm</td>
<td></td>
</tr>
<tr>
<td>Equivalent diameter of a single bar</td>
<td>56mm</td>
<td></td>
</tr>
<tr>
<td>Perimeter of equivalent bar</td>
<td>56.6 x (\pi) = 178mm</td>
<td></td>
</tr>
</tbody>
</table>
### Eurocode 2 - Equivalent diameter of bar bundles

<table>
<thead>
<tr>
<th>Number of bars in bundle: (Assume 40mm diameter bars)</th>
<th>Three:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent perimeter of bundle =</td>
<td>$40 \times (3 + \pi) = 246\text{mm}$</td>
</tr>
<tr>
<td>Equivalent diameter of a single bar =</td>
<td>$69.3\text{mm}$</td>
</tr>
<tr>
<td>Perimeter of equivalent bar =</td>
<td>$69.3 \times \pi = 218\text{mm}$</td>
</tr>
</tbody>
</table>
Circular sections – shear capacity

• Feltham I, The Structural Engineer, June 2004
The Copenhagen Metro
The observational method at Norreport station
The Copenhagen Metro
The observational method at
Norreport station

• Description of the project.
• Construction sequence
  and the observational
  method.
• Application
• Results
The Copenhagen Metro

Route of the Metro

Above ground works, on embankment or viaduct.
Challenges

- 100 year design life - 0.2mm crackwidth limit.
- Design to Eurocodes.
- First significant deep basement construction in Copenhagen.
- Environmental standards.
- Programme constraints.
- Architectural requirements.
Architectural challenges

• Natural light available at platform level.
• No internal columns at platform level.
• Minimal internal propping.
• Danish minimalist design details.
Retaining wall details

Ground Conditions:
- Made ground
- Glacial till
- Limestone
TBM Programme
Christianshavn Station

Bottom up construction sequence with temporary props
TBM Programme

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Medieval Bridge
Norreport Station - Bridge Foundations
Medieval Bridge
Application of the observational technique
Observation method management

Site manager
Comet

Design manager
Comet

Permanent works designer
Maunsell

Settlement control engineer
Comet

Retaining wall designer
Bachy Soletanche

Temporary works designer
Carillion

Client’s representative
Cowi
Excavation down to Waling Beam
Excavation down to Base Slab
Eurocodes

Eurocode 7: Geotechnical design — Part 1: General rules