Tunnel design – state of the art design examples

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Szerkezetépítési és Geotechnikai tanszék
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Tartalom

- Introduction - K. Glatz
- Basics
- Bergen light rail tram
- Three celled tunnel in a city
- Numerical modelling - T. Megyery
- Further examples
16,500 employee
Offices in 50 countries, working in 140 countries

35 employee

Mott MacDonald Limited

Mott MacDonald Hungary

Civil Engineering team

Environmental team
Civil engineering key services

- Engineering Design (from feasibility studies to detailed design)
- Geotechnics and Rock Mechanics
- Cut and Cover Structures, Reinforced Concrete and Steel Structures
- Tunnel Design in Soft Ground and Hard Rock
- Numerical Modelling (in 2D and 3D)
- Soil Settlement Analysis, Stability Analysis
- Instrumentation and Monitoring
- Retaining Structure Design
- Foundation Design, Deep Foundation Design, Foundation Strengthening
- Earthquake engineering
- CAD 3D
- Visualisation
- BIM
- Design Supervision
- Construction Supervision
- Technical audit and compliance test (due diligence)
International Expertise

- **our project**
- **our engineers**
State of the art tunnelling?

- Common sense
- Using tunnelling experts experience
- Literature
- Hand calculation
- Empirical, analytical methods
- Numerical Modelling
- Sanity checks, project reviews
- BIM
Tunnel design

• Influencing factors in Tunnel design
  – Client expectations
  – Requested geometry
  – Soil parameters

• Design basis
  – Stand up time
  – Arching, Stress changes
  – Soil – lining interaction
  – Four dimensions
The alignment must be set up to minimise the risks and cost
- In the most beneficial soil layer
- Above ground water level, if possible
- At least one diameter cover everywhere
Geotechnical parameters

Has affect:

• On design
  – Horizontal and vertical alignment
  – Loads on lining

• Construction technology
  – Excavation method
  – Lining, excavation support
  – Building cost and time
3D arching

Original direction of soil stresses

“Arching” of the stresses around tunnel
New equilibrium forms

New equilibrium

Stress release on face

\(\delta u\)
Design methods

- Empirical methods
  - For example: Q-method

- Analytical methods
  - For example: anchor design
  - Soil response curve calculations

- Numerical methods
  - Discrete element method
  - Finite different method
  - Finite element method
Challenges – Improving techniques

- There is no established code for SCL
- Still young and improving science
  - New type of materials
    - New excavating techniques
- Quicker advance rates
- Compact sites, denser built-in areas
Challenges - Modelling

- Empirical methods are not sufficient anymore
- Clients require Numerical modelling proof for designs
- Complex situations, excavation sequences, shapes and loads
- MM is committed to using Best Practice
Choosing the design method

1. Identify soil/rock behaviour
2. Choose an excavation method
3. Choose a design method for all elements of the tunnel
Design basics

- Complex soil – lining interactions
- Complex geometry
- Soil/rock behaviour
- Material behaviour (Soil/rock & lining)
- Time dependent behaviour (soil/rock & lining)
- Other design criteria – as: endurance, water tightness, etc.

3 D problem
Tunnel Quality Index (Q), Barton et al 1974

- Rock characteristics and the support systems requirements
- It is based on huge amount of case studies, experience on underground work
- Probably the most frequently used rock classification method these days
Definition of Quotients

- $RQD/J_n$  Block size
- $J_r/J_a$  Shear strength between blocks
- $J_w/SRF$  Active stress
Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}

Where:
RQD  Rock Quality Designation
J_n  number of cracks
J_r  crack surface grain
J_a  orientation of cracks
J_w  water infill of cracks
SRF  stress relief factor
Q method

- All parameters shall be defined
- The notes to be considered in the table as well
- The Q has to be defined for all structural parts
- The crack arrangement which influence the whole stability shall be checked

<table>
<thead>
<tr>
<th>JOINT SET</th>
<th>SPACING (mm)</th>
<th>TYPE</th>
<th>DIP/DIRECTION</th>
<th>PLANARITY</th>
<th>ROUGHNESS</th>
<th>APERTURE</th>
<th>INFILLING</th>
<th>WEATHERING</th>
<th>COMMENTS</th>
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<td>EH</td>
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<td>T</td>
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<td>50/00/100</td>
<td>J</td>
<td>CV/ST/NC-02-04</td>
<td>P</td>
<td>S</td>
<td>O</td>
<td>T</td>
<td></td>
<td>up to 15mm</td>
</tr>
<tr>
<td>3</td>
<td>40/0-100</td>
<td>J</td>
<td>CV/ST/NC</td>
<td>P</td>
<td>S</td>
<td>O</td>
<td>T</td>
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<td>up to 15mm</td>
</tr>
<tr>
<td>4</td>
<td>30-70/100-120</td>
<td>J</td>
<td>CV/ST/NC</td>
<td>P</td>
<td>S</td>
<td>O</td>
<td>T</td>
<td></td>
<td>up to 10mm</td>
</tr>
</tbody>
</table>

- STRESS REDUCTION FACTOR
  (for treatment of intersecting excavation, which may cause loosening of rock mass when formed by excavation)

- JOINT WATER REDUCTION FACTOR

- ROCK QUALITY INDEX, $Q = \frac{RQD}{Jn \times Ja \times SRF}$
  $RQD = 30$, $Jn = 15$, $Ja = 4$, $SRF = 5$, $Q = 0.1$
Bergen – The gate of fjords

- Bergen: Norwegian city next to the Atlantic ocean
- The largest city of the western part of the country
- It was the most important city of Scandinavia for hundreds of years
- Important port, industrial centre
- „Gateway to the fjords” – dynamically developing tourist centre
- World heritage: remaining buildings of the Hansaeatic city
- International airport: around 50 destinations
video
Bergen – Climate, surroundings

- Bergen: harbour surrounded by high mountains
- The city itself is on a lower but very variable surface
  - The alignment of the roads and trains usually devious, leads through bridges and tunnels
- Large amount of rainwater 2250 mm
- More than 200 days are rainy
- Mild winter: January average 2,8 °C
Bergen – LRT project

- Local government initiative: 2000
- Investor – Bergen Bybanen (transportation operator)
- Light Rapid Transit (LRT) between the city centre and the airport
- Connects the city centre, suburbs and important institutes
  - 50% growth in real estate fees after second phase is finished
- 7 km, 7 stations, 6 tunnels, 3 bridges, 8 portal structures, 6 culverts
Tunnels, portals

- 40% of the 7.1 km length is below ground
- 6 tunnels (lengths: 120-700 m)
- Cross section heights 7.5 m, width: 9.5 m
- 5 tunnels are excavated with drill and blast method (excluded the portals), one is Cut & Cover
- Risks: School, private buildings nearby, shallow tunnels
Collaborating offices

- Dublin (IE): Project lead, 3D & CAD, alignment, drainage, railway, environment, costing
- Cork (IE): Structures, roads
- Bristol (UK): Geology
- Croydon (London, UK): Tunnels, ventilation and fire design
- Prague: (CZ): Bridges, C&C tunnel
- Budapest (HU): Tunnels
- Bergen (NO): site support, meetings
3D modelling and BIM

- First biggest transportation project done in BIM
- Every discipline is responsible for its own 3D model
- Designer meetings, clash detections
- Every 3D object has a Tag which corresponds the costing program’s (G-Prog) elements
- G-Prog: is a client requirement, frequently used in Norway
- Usually used in road projects, lacking code for other disciplines work
Common BIM data environment

- **Common Data Environment (CDE)**
- **ProjectWise based system**
  - Connected servers in the interfacing offices
- **Created by second largest software company: Bentley**
  - MicroStation (DGN), MX (road design), gINT, Staad
- **Capable to handle every types of documents**
  - Native (without conversation) DWG handling
  - Big 3D files are processed quickly
  - Visualisation in the same software
• File based central data storage system

• Versions
  – WIP – Work In Progress
  – Shared: shared with other disciplines, Clash Detection
  – Other disciplines see the latest version but the previous ones remain as well
  – Issued: issued to the client
  – Final: at the end of the project the client owns the file
Bergen – soil surface and alignment
Tunnel Design- Analytical methods

• Loads
  – Soil interaction curve
  – “closed formulas”
  – Wedge stability
  – Lining design – simple structural calculations
Soil Interaction curve

The displacements happen in a finite period of time.
Timing & Support stiffness

Soil response curve

Support stiffness

Load on the support

$\frac{p}{u} = E$ stiffness

$P_i = P_0$ (in situ stress)

Inward radial displacement $u_i$

du or t

displacement
Hole in the elastic continuum

STRESS COMPONENTS AT POINT $(r, \theta)$

Radial $\sigma_r = \frac{1}{2} p_z \left( (1 + k) \left( 1 - a^2/r^2 \right) + (1 - k) \left( 1 - 4a^2/r^2 + 3a^4/r^4 \right) \cos 2\theta \right)$

Tangential $\sigma_\theta = \frac{1}{2} p_z \left( (1 + k) \left( 1 + a^2/r^2 \right) - (1 - k) \left( 1 + 3a^4/r^4 \right) \cos 2\theta \right)$

Shear $\tau_{r\theta} = \frac{1}{2} p_z \left( - (1 - k) \left( 1 + 2a^2/r^2 - 3a^4/r^4 \right) \sin 2\theta \right)$

$\sigma_t = \text{tangential}$

$\sigma_r = \text{radial}$

$p_i$
Analytical methods

• Face or wedge stability

Input data:
• Strength
• Stiffness
• In situ stress
• Crack orientation, density
Analytical methods

- Barrett & McCreaeth (1995) calculation (small block rock)
Numerical analysis

- 2D Numerical analysis
- 3D Numerical analysis
- Discrete element method
- Finite different method
- Finite element method
- Usage of several design methods
<table>
<thead>
<tr>
<th>Formation</th>
<th>Strata</th>
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<td>Fill</td>
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<tr>
<td>Kallang Formation</td>
<td>Estuarine Clay</td>
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<tr>
<td></td>
<td>Fluvial Sand</td>
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<tr>
<td></td>
<td>Fluvial Clay</td>
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<tr>
<td>Bukit Timah Granite</td>
<td>Residual Soil</td>
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<tr>
<td></td>
<td>Completely Weathered Granite</td>
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<tr>
<td></td>
<td>Highly Weathered Granite</td>
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<tr>
<td></td>
<td>Moderately Weathered Granite</td>
</tr>
<tr>
<td></td>
<td>Slightly Weathered Granite</td>
</tr>
<tr>
<td></td>
<td>Fresh Granite</td>
</tr>
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</table>
Geological profile along the NB Track

Geological profile along the SB Track

Mined tunnels

Head of G-III rock

Head of G-IV rock

Head of G-III rock

Head of G-IV rock

Mined tunnels
### Input data

#### Parametres (too conservative)

<table>
<thead>
<tr>
<th>Stratum</th>
<th>SPT value, N (-)</th>
<th>Unit weight, γ (kg/m³)</th>
<th>Undrained shear strength, c_u (kPa)</th>
<th>Effective cohesion, c' (kPa)</th>
<th>Effective friction angle, Φ' (°)</th>
<th>Undrained elastic modulus, E_u (MPa)</th>
<th>Drained elastic modulus, E' (MPa)</th>
<th>Coefficient of earth pressure at rest, K₀ (-)</th>
<th>Coefficient of permeability, k (m/s)</th>
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<tr>
<td>Fill</td>
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<td>19</td>
<td>30</td>
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<td>30</td>
<td>10</td>
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<tr>
<td>E</td>
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<td>1.0 × 10⁻⁶</td>
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<td>5</td>
<td>25</td>
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<td>G-V</td>
<td>N≤50</td>
<td>50 × N</td>
<td>5.0 × N</td>
<td>5</td>
<td>32</td>
<td>2.5 × N</td>
<td>2.0 × N</td>
<td>0.8</td>
<td>2.0 × 10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>50&lt;N≤100</td>
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<td>250</td>
<td>20</td>
<td>32</td>
<td>2.5 × N</td>
<td>2.0 × N</td>
<td>0.8</td>
<td>2.0 × 10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>N&gt;100</td>
<td>20</td>
<td>250</td>
<td>25</td>
<td>32</td>
<td>2.5 × N</td>
<td>2.0 × N</td>
<td>0.8</td>
<td>2.0 × 10⁻⁷</td>
</tr>
<tr>
<td>G-IV</td>
<td>-</td>
<td>24</td>
<td>500</td>
<td>40</td>
<td>40</td>
<td>500</td>
<td>500</td>
<td>0.8</td>
<td>1.0 × 10⁻⁶</td>
</tr>
<tr>
<td>G-III</td>
<td>-</td>
<td>25</td>
<td>1000</td>
<td>90</td>
<td>45</td>
<td>2000</td>
<td>2000</td>
<td>0.8</td>
<td>3.0 × 10⁻⁷</td>
</tr>
<tr>
<td>G-II</td>
<td>-</td>
<td>26</td>
<td>1000</td>
<td>250</td>
<td>45</td>
<td>5000</td>
<td>5000</td>
<td>0.8</td>
<td>5.0 × 10⁻⁸</td>
</tr>
<tr>
<td>G-I</td>
<td>-</td>
<td>26</td>
<td>1000</td>
<td>250</td>
<td>45</td>
<td>5000</td>
<td>5000</td>
<td>0.8</td>
<td>5.0 × 10⁻⁸</td>
</tr>
</tbody>
</table>

#### Failure criteria (Mohr-Coulomb instead of Hoek-Brown)
## Strata – excavation support

### Proposed stratification for Type A analysis

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-III</td>
<td>+91.9 m</td>
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</tr>
<tr>
<td>G-IV</td>
<td>+103.9 m</td>
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</tr>
<tr>
<td>G-VI</td>
<td>+111.0 m</td>
<td></td>
</tr>
<tr>
<td>FILL</td>
<td>+121.0 m</td>
<td>GWT</td>
</tr>
</tbody>
</table>

### Proposed stratification for Type B analysis

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-III</td>
<td>+81.3 m</td>
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</tr>
<tr>
<td>G-IV</td>
<td>+83.5 m</td>
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</tr>
<tr>
<td>G-V</td>
<td>+87.5 m</td>
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</tr>
<tr>
<td>G-VI</td>
<td>+113.3 m</td>
<td></td>
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<tr>
<td>FILL</td>
<td>+119.0 m</td>
<td>GWT</td>
</tr>
</tbody>
</table>
### Soil parameters – Type A and B

#### Table 3.3: Geotechnical properties for the analysis of section Type A (Model 01)

Source: GIBR for Contract T213 [R15]

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Average SPT value, N (-)</th>
<th>Unit weight, γ (kg/m³)</th>
<th>Undrained shear strength, c_u (kPa)</th>
<th>Effective cohesion, c’ (kPa)</th>
<th>Effective friction angle, Φ’ (°)</th>
<th>Undrained elastic modulus, E_u (MPa)</th>
<th>Drained elastic modulus, E’ (MPa)</th>
<th>Coefficient of earth pressure at rest, K₀ (-)</th>
<th>Coefficient of permeability, k (m/s)</th>
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<tbody>
<tr>
<td>Fill</td>
<td>-</td>
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<td>30</td>
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<td>30</td>
<td>10</td>
<td>10</td>
<td>0.5</td>
<td>1.0 × 10⁻⁶</td>
</tr>
<tr>
<td>G-VI</td>
<td>26</td>
<td>19</td>
<td>130</td>
<td>10</td>
<td>32</td>
<td>65</td>
<td>52</td>
<td>0.8</td>
<td>2.0 × 10⁻⁷</td>
</tr>
<tr>
<td>G-V</td>
<td>26</td>
<td>20</td>
<td>130</td>
<td>12</td>
<td>32</td>
<td>65</td>
<td>52</td>
<td>0.8</td>
<td>2.0 × 10⁻⁷</td>
</tr>
<tr>
<td>G-IV</td>
<td>-</td>
<td>24</td>
<td>500</td>
<td>40</td>
<td>40</td>
<td>500</td>
<td>500</td>
<td>0.8</td>
<td>1.0 × 10⁻⁶</td>
</tr>
<tr>
<td>G-III</td>
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<td>25</td>
<td>1000</td>
<td>90</td>
<td>45</td>
<td>2000</td>
<td>2000</td>
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<td>3.0 × 10⁻⁷</td>
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</tbody>
</table>

#### Table 3.4: Geotechnical properties for the analysis section Type B (Model 02)

Source: GIBR for Contract T213 [R15]

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Average SPT value, N (-)</th>
<th>Unit weight, γ (kg/m³)</th>
<th>Undrained shear strength, c_u (kPa)</th>
<th>Effective cohesion, c’ (kPa)</th>
<th>Effective friction angle, Φ’ (°)</th>
<th>Undrained elastic modulus, E_u (MPa)</th>
<th>Drained elastic modulus, E’ (MPa)</th>
<th>Coefficient of earth pressure at rest, K₀ (-)</th>
<th>Coefficient of permeability, k (m/s)</th>
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<tbody>
<tr>
<td>Fill</td>
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<td>0</td>
<td>30</td>
<td>10</td>
<td>10</td>
<td>0.5</td>
<td>1.0 × 10⁻⁶</td>
</tr>
<tr>
<td>G-VI</td>
<td>26</td>
<td>19</td>
<td>130</td>
<td>10</td>
<td>32</td>
<td>65</td>
<td>52</td>
<td>0.8</td>
<td>2.0 × 10⁻⁷</td>
</tr>
<tr>
<td>G-IV</td>
<td>-</td>
<td>24</td>
<td>500</td>
<td>40</td>
<td>40</td>
<td>500</td>
<td>500</td>
<td>0.8</td>
<td>1.0 × 10⁻⁶</td>
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<tr>
<td>G-III</td>
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<td>1000</td>
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<td>45</td>
<td>2000</td>
<td>2000</td>
<td>0.8</td>
<td>3.0 × 10⁻⁷</td>
</tr>
</tbody>
</table>
Groundwater conditions

- Groundwater table is at ground level
- Groundwater table is 5m below ground level
Designed structure

- Three celled tunnel
Soil strengthening around the tunnels

Layout of grouting and forepoles around tunnels (type B)
Empirical methods

- Rock classification methods:
  - Q,
  - RMR,
  - GSI

- The benefits of Q methods
  - More detailed method applicable for tunnel design, supports standardised design
  - Very effective in preliminary design
Analitical methods

- UnWedge software /large blocked rock/
- Barrett&McCreath (1995) calculation
- 3D location, direction of cracks, continuity, distance
Example for input data

- In situ stresses
- + Estimated excavation support elements
- +Estimated excavation sequence
- Relaxation (support effect of the face)
Steps of excavation

An example on the excavation sequence for section type A

Excavation sequence for section type B

<table>
<thead>
<tr>
<th>2</th>
<th>3</th>
<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>12 m</td>
<td>3 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 m</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m</td>
</tr>
<tr>
<td>4 m</td>
</tr>
</tbody>
</table>
Steps of excavation (type A)
Steps of excavation (type A)
Temporary support design
Numerical modelling

2D models for different excavation systems
<table>
<thead>
<tr>
<th>Model</th>
<th>Temporary lining thickness (mm)</th>
<th>Rockbolt length (m)</th>
<th>Longitudinal rockbolt spacing (m)</th>
<th>Lateral rockbolt spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 (section Type A)</td>
<td>150</td>
<td>3.0</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>02 (section Type B)</td>
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<td>3.0</td>
<td>1.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Capacity check of the support system

### Calculations for: Bending moment - Axial force capacity check

<table>
<thead>
<tr>
<th>Divn/Dept:</th>
<th>EDE</th>
<th>Job No./File No.:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated by:</td>
<td>VJ</td>
<td>Date: 2014.04.29</td>
</tr>
<tr>
<td>Checked by:</td>
<td>CG</td>
<td>Date: 2014.05.05</td>
</tr>
</tbody>
</table>

#### Concrete grade

- Concrete Grade: C30/37.5
- D2.5 S 0 after BS EN 14487-1

#### Material factors

- $K_D = 0.97$
- $f_{y,k1} = 1.26$ MPa
- $f_{y,k4} = 0.98$ MPa

#### Design Flexural Tensile Strength ($f_{ctd}$, $f_{fl}$)

- $f_{ctd} = 0.00$ MPa
- $f_{fl} = 0.00$ kPa

#### Effective Tensile Strain Limit if Unreinforced

- $\varepsilon_{tu} = 0.50\%$

#### Section Data

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Diameter</th>
<th>Spacing</th>
<th>Cover to bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension Bar 1</td>
<td>74 mm</td>
<td>150 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>Compression Bar 1</td>
<td>78 mm</td>
<td>150 mm</td>
<td>76 mm</td>
</tr>
<tr>
<td>Compression Bar 2</td>
<td>76 mm</td>
<td>150 mm</td>
<td>76 mm</td>
</tr>
</tbody>
</table>

#### Section Effective Depth

- $d = 150$ mm

#### Tension Steel Ratios

- $0.0\%$ (Section classed as unreinforced, capacity calculated to Section 12.6)

#### MN Capacity Check

![Capacity Curve](image-url)

- MB Tunnel (Stage 07)
- NB Tunnel (Stage 12)
- SB Tunnel (Stage 12)
- CS Tunnel (Stage 18)

### Project

- T213 Construction Singapore

### Sheet No.

- Sheet 1

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N.B. Cover-to-bar is to the tension or compression bar itself, not just the specified minimum cover to rebar generally.
Standardised drawings – excavation support
Monitoring design
Designer support on site