Slope Stabilisation for the Thirlmere Aqueduct at Nab Scar
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Introduction

- History of Thirlmere Reservoir and Aqueduct
- Original construction of conduit at Nab Scar
- Aqueduct issues at Nab Scar
- Requirements & restrictions
- Selected solution
- Design of spaced piles
- Effectiveness of works
History of Thirlmere Reservoir and Aqueduct

- Man made reservoir
- Water to support industrial revolution in Manchester
History of Thirlmere Reservoir and Aqueduct

- Connection established in 1894
- Mass unreinforced concrete
- 95 miles in length
- 180m @Thirlmere to 110m @Manchester
- Gradient 450mm to 1km (1 in 2200)
- 220 million litres of water per day
- Water speed 3 to 5 kph
Original construction of conduit at Nab Scar
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Original construction of conduit at Nab Scar
Original construction of conduit at Nab Scar
Aqueduct issues at Nab Scar

- Inspections & investigations since 2005
- Series of spiral crack observed within the conduit & around arch barrel
- Opening of joint between slab and walls
- Torsional movement considered due to the movement of ground over top of conduit
Requirements & Restrictions

• No direct loading of the conduit
• Minimal vibration techniques
• No slope loading
• Monitoring of conduit and slope throughout works:
  • Hillside surface & ground at depth
  • Conduit position
  • Conduit internal cracks
Selected Solution

• All about construct-ability
Design of spaced piles

- Determination of required stabilising force
- Determination of pile loads to provide required stabilising resistance force
- Layout of stabilisation works
- Development of load on A-frames
- Analysis results considering different models
- Micropile & cap dimensions
Design of spaced piles: determination of stabilising resistance force

- Slope stability analysis
- Circular slip and infinite slope analysis
- Back calculate soil and ground water parameters
- Establish required restoring force to provide increase stability FoS = 1.3

FoS = 1.0; Slip depth: 2.5m, φ’ = 45°, ground water: 1m b.e.g.l
FoS = 1.3; restoring force = 250kN per m run of slope
Design of spaced piles: determination of stabilising resistance force

- Infinite slope & finite slope eqns
- FoS = 1.0 for existing case
- FoS = 1.3 with 250kN/m restoring force

\[
F = \frac{c}{\gamma_{\text{sat}} l \sin \beta \cos \beta} + \frac{(\gamma_{\text{sat}} - \gamma_{\omega} l \cos^2 \beta - \gamma_{\omega} m z \sin \beta \cos \beta \tan \phi + H) \tan \phi}{\gamma_{\text{sat}} l \sin \beta \cos \beta}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma_{\text{sat}})</td>
<td>20 kN/m³</td>
</tr>
<tr>
<td>(\gamma_{\omega})</td>
<td>10 kN/m³</td>
</tr>
<tr>
<td>(\phi)</td>
<td>45°</td>
</tr>
<tr>
<td>(\beta)</td>
<td>34°</td>
</tr>
<tr>
<td>(c)</td>
<td>0 kPa</td>
</tr>
<tr>
<td>depth to slip surface, z</td>
<td>2.5 m</td>
</tr>
<tr>
<td>depth to groundwater surface, z_w</td>
<td>1 m</td>
</tr>
<tr>
<td>slope length, l</td>
<td>38 m</td>
</tr>
<tr>
<td>Restoring force parallel to slope, H</td>
<td>250 kN per m</td>
</tr>
</tbody>
</table>

\(m = \frac{z - z_w}{z}\)  
0.6
Design of spaced piles: Determination of pile loads to provide required stabilising resistance force

- Structural frame model & elastic continuum model using Piglet

Lateral force $H$

Assumed ‘pin’

Tension $T$

Compression $C$

Cross-section sketch of proposed up-slope stabilisation piles

Resolved vertical component: 559 kN

Resolved horizontal component: 829 kN
Design of spaced piles: Layout of stabilisation works

- Pairs of spaced ‘A-frame’ micropiles to provide restoring force
- Targeted permeation grouting
Design of spaced piles: Development of load on A-frames

- Arching check & development of load on spaced A-frames in response to hillside movement

- Function of:
  - Spacing
  - Cap width/pile diameter
  - $\phi'$; $c'$; slip depth $z$

- Output: lateral load on pile cap & piles
## Design of spaced piles: Analysis results considering different models

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Tension pile force</th>
<th>Compression pile force</th>
<th>Individual pile bending moment / shear force</th>
<th>Pile cap moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on providing required restoring force of 250kN per m run:</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Slope restoring force structural frame model</td>
<td>541kN</td>
<td>628kN</td>
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</tr>
<tr>
<td>Slope restoring force elastic continuum model (Piglet)</td>
<td>531kN</td>
<td>635kN</td>
<td>27kNm / 20kN</td>
<td>784kNm</td>
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<tr>
<td>Based on applied slope movement loads according to Ito &amp; Matsui:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope movement induced forces on pile caps: structural frame model</td>
<td>623kN</td>
<td>401kN</td>
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<td>--</td>
</tr>
<tr>
<td>Slope movement induced forces on pile caps: elastic continuum model (Piglet)</td>
<td>623kN</td>
<td>422kN</td>
<td>25kNm / 18kN</td>
<td>663kNm</td>
</tr>
</tbody>
</table>
Design of spaced piles: Micropile & cap dimensions

- 225mm diameter micropiles 6.5m rock socket
- 168.3 x 10mm CHS from cap to 1m into competent rock
- Tension pile: 50mm Gewi bar
- Compression pile: 40mm pre-stressing bar
- 40N/mm² grout
Effectiveness of works: Strain gauge results from inside conduit

![Graph showing strain gauge results over time with specific dates indicating progress in site completion and pile construction.]

- Start on site: 24/09/09
- Completion of downslope piles, caps & perm grouting: 22/01/10
- Completion of upslope piles & caps: 03/03/10

Date range: 24/09/09 to 23/03/10

Microstrain over 126mm
Finished works
Conclusion

• A vital section of water infrastructure has been stabilised
• Early indications show the works to be effective
• Water continues to flow at Queen Victoria Jubilee Fountain in Manchester