Further Developments with Embankment Dams on the Mercia Mudstone

Saeed Mojabi
Director, Arup
Mercia Mudstone Group UK outcrops

- **BGS RR/01/02**
  Engineering geology of British rocks and soils
  Mudstones of the Mercia Mudstone Group

- **CIRIA C570**

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**Formation Study Areas**

- Gault Formation
- Lias Group
- Mercia Mudstone Group
- Lambeth Group
- Sherwood Sandstone Group
Cribbs Causeway (Bristol)
Mercia Mudstone outcrops
Site Selection

Three phase selection process.

- Long List Assessment
- Short List Assessment
- Cheddar vs Wookey

Considerations

- ground conditions/geology
- proximity to source
- integration with BW network
- absolute constraints
- whole life cost
- environmental
Hydrogeological conceptual model
<table>
<thead>
<tr>
<th>Condition</th>
<th>Flow</th>
<th>Period of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Maximum</td>
<td>250,000 m³/day</td>
<td>Any 24 hour period</td>
</tr>
<tr>
<td>Annual Total</td>
<td>22 million m³/year</td>
<td>1 April to 31 March</td>
</tr>
<tr>
<td>Annual Average</td>
<td>60,300 m³/day</td>
<td>Annual</td>
</tr>
<tr>
<td>No Abstraction Allowed</td>
<td>If minimum flows in Cheddar River Yeo &lt; 11,365 m³/year</td>
<td>15 May to 30 November (inclusive)</td>
</tr>
<tr>
<td>No Abstraction Allowed</td>
<td>If minimum flows in Cheddar River Yeo &lt; 6,819 m³/year</td>
<td>1 December to 14 May (inclusive)</td>
</tr>
<tr>
<td>Abstraction Limited To</td>
<td>⅔ of the annual quantity</td>
<td>15 May to 31 October (inclusive)</td>
</tr>
</tbody>
</table>
Site Selection – Risk

Number of Project Risks by Workstream - Cheddar

<table>
<thead>
<tr>
<th>Workstream</th>
<th>No. risks</th>
<th>Red</th>
<th>Amber</th>
<th>Green</th>
<th>Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>8</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Geotechnical</td>
<td>9</td>
<td>1</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Planning</td>
<td>7</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Construction Logistics</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
<td>2</td>
<td>23</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
Site Selection – constraints
Existing Cheddar Reservoir

- Constructed between 1933 and 1937
- Total Capacity: 6140 Ml
- Top Water Level: 18.288m AOD
- Embankment Height: 1 – 14m
- Cost: £450,000
- Approx. workforce of 270 men
Existing Cheddar Reservoir – Cross section

(Hall, 1937)
Cheddar 2 - Key Reservoir Parameters

- Embankment Length – 3.6 km
- Embankment height – from 9m to 15m
- Top water level – 19.288 mOD (1m above existing reservoir)
- Total capacity (to TWL) – 9,400,000 m³
- Useable capacity – 8,200,000 m³
- Yield – 16,100 m³ per day
- Excavated quantity – 3.25 Mm³
Outline Geology

Existing Cheddar Reservoir

Mercia Mudstone

First terrace or Higher Alluvium

Head

Proposed embankment footprint

Estuarine Alluvium

C04/122-CLCSL British Geological Survey. ©NERC. All rights reserved. ©Crown copyright Licence Number 100039628.
Sequence of Strata

Soft blue/grey clay

Soft blue/grey clay

High chert gravel content. Higher estuarine alluvium?
Sequence of Strata – cores
Sequence of Strata — trial pits

Excavation

Spoil
Key Objectives of the Ground Investigations

• To confirm the ground conditions and ground water conditions.

• To ascertain stratigraphy for cut/fill modelling.

• To obtain high quality samples for lab testing.

• Ascertain strength properties of in-situ and re-worked materials.

• To ascertain permeability of the in-situ and re-worked materials.

• To ascertain workability of the material.

• To inform impact of the proposed works on hydrogeology.

• To inform geo-environmental appraisal of the site.
Potential Geo-Hazards

• Periglacial ice wedges
• Gypsum interbeds
• Solifluction of Head
• Peat bands in Alluvium
• Calcite-filled fractures
• “2ft thick green block marl”
Geotechnical Properties – Moisture Content

**All Soils**

- Mercia Mudstone
- Head Deposits
- Alluvium

**Max. Excavation Depth**

**Mercia Mudstone**

- IV
- III
- II
Geotechnical Properties – Plasticity

![Graph showing geotechnical properties with liquid limit on the x-axis and plasticity index on the y-axis. The graph is divided into categories of low, intermediate, high, very high, and extremely high plasticity. Each category is color-coded and marked with respective symbols (CL, CI, CH, CV, CE, MV, ME, ML, MI, MH) for identification. The graph also highlights different soil classes (IV, III, II/I, Other) based on their position on the graph.]
Geotechnical Properties – OMC

OMC (%)

Depth (mBGL)

OMC = 13-23% for Grade IV material, 12-15% for Grades III and I/II
Geotechnical Properties – Permeability

Permeability (m/s)

Depth (mBGL)

Re-worked Mercia Mudstone
Characteristic permeability = 1e-8 m/sec

In-situ Mercia Mudstone
Characteristic permeability = 1e-7 m/sec

Packer pressure too high leading to possible hydraulic fracturing

- Packer tests
- Packer test with high pressure
- Rising head tests
- Recompressed (MM4)
- Recompressed (Head)
- Recompressed (Aluvium)
- Recompressed (MM3)
- Undisturbed (MM4)
- Undisturbed (Head)
- Undisturbed (MM1&2)
Geotechnical Properties – Strength

Cu (kPa)

Depth (mBGL)

Cu = 60 kPa

Cu = 60 - 40z kPa

z₀ = 4 mBGL

- MM - Triaxial (remoulded)
- SPT N correlation (MMG only)
- MM - Hand vanes
- MM - Triaxial (in-tact)
- Design line
Geotechnical Properties – Drained Parameters

<table>
<thead>
<tr>
<th>Weathering Grade</th>
<th>c’</th>
<th>φ’</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>&lt;20</td>
<td>32° - 25°</td>
</tr>
<tr>
<td>III</td>
<td>&lt;20kPa</td>
<td>42° - 32°</td>
</tr>
<tr>
<td>I-II</td>
<td>&gt;25kPa</td>
<td>&gt;40°</td>
</tr>
</tbody>
</table>

The literature suggests the above drained strength parameters.
Bulk characteristic strength parameters of phi’ = 30 and c’ = 2kPa are assumed for the reworked Mercia Mudstone.
Geotechnical Properties – Residual Shear

Residual Shear stress (kPa)

Normal stress (kPa)

Linear trend line passing through origin

\[
y = 0.195x
\]

\[
\phi^\text{\text{r residual}} = 11.0^\circ
\]
Geotechnical Properties – Stiffness

\[ E' = 11 + 7.3z \text{ MPa} \]

\[ z_0 = 4 \text{ mBGL} \]

SPT N correlation (MMG only)

Design line
## Design Parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Mercia Mudstone</th>
<th>Head</th>
<th>Alluvium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I/II</td>
<td>III</td>
<td>IV</td>
</tr>
<tr>
<td>$\gamma$ (kN/m$^3$)</td>
<td>22</td>
<td>20.5</td>
<td>20.5</td>
</tr>
<tr>
<td>$\phi_{peak}$ ($^\circ$)</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$c'$ (kPa)</td>
<td>20</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>$\phi_{residual}$ ($^\circ$)</td>
<td>11$^\circ$</td>
<td>11$^\circ$</td>
<td>11$^\circ$</td>
</tr>
<tr>
<td>$c_u$ (kPa)</td>
<td>60+40z</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$E'$ (MPa)</td>
<td>11+7.3z</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>$v'$</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$k$ (m/sec)</td>
<td>1e-7</td>
<td>1e-7</td>
<td>1e-7</td>
</tr>
</tbody>
</table>
## Stability Considerations – Critical cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Embankment side</th>
<th>Required factor of safety</th>
<th>Pore water pressure condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of construction</td>
<td>Both, down stream critical due to steeper gradient</td>
<td>1.3</td>
<td>Undrained in all materials</td>
</tr>
<tr>
<td>During operation</td>
<td>Down stream</td>
<td>1.5</td>
<td>$r_u=0.15$ in the embankment, $r_u=0.5$ in the underlying geology</td>
</tr>
<tr>
<td>During rapid drawdown</td>
<td>Up stream</td>
<td>1.2</td>
<td>$r_u=0.5$ everywhere</td>
</tr>
<tr>
<td>Seismic loading during operation</td>
<td>Down stream</td>
<td>1.0</td>
<td>$r_u=0.15$ in the embankment, $r_u=0.5$ in the underlying geology</td>
</tr>
</tbody>
</table>
Stability Considerations – Side slopes

![Graph showing stability considerations for side slopes with a diagram illustrating FoS (Factor of Safety) against embankment slope (1/x). The graph includes lines for upstream and downstream slopes with target FoS values indicated.]
Seepage – Geometric Configuration

- Embankment body
- Foundation material (MMG or Head)
- Core/cut-off
- Down-stream drainage and chimney
Seepage – Down Stream Drainage – Head above phreatic

**Without** drainage blanket/chimney

**With** drainage blanket/chimney
### Seepage – Output summary

<table>
<thead>
<tr>
<th>Set</th>
<th>Case</th>
<th>Total flow (m³/day/m)</th>
<th>Total flow, assuming 3.5km perimeter (m³/day)</th>
<th>Total equivalent loss (l/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No cut-off on MMG foundation</td>
<td>0.037</td>
<td>130</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>No cut-off on Head foundation</td>
<td>0.407</td>
<td>1425</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>No cut-off on MMG foundation with down-stream drainage</td>
<td>0.061</td>
<td>214</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>No cut-off on Head foundation with down-stream drainage</td>
<td>0.591</td>
<td>2069</td>
<td>23.9</td>
</tr>
<tr>
<td>2</td>
<td>Cut-off on MMG foundation</td>
<td>0.037</td>
<td>130</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Cut-off on Head foundation</td>
<td>0.086</td>
<td>301</td>
<td>3.48</td>
</tr>
<tr>
<td></td>
<td>Cut-off on MMG foundation with down-stream drainage</td>
<td>0.058</td>
<td>203</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Cut-off on Head foundation with down-stream drainage</td>
<td>0.091</td>
<td>319</td>
<td>3.7</td>
</tr>
<tr>
<td>3</td>
<td>Core on MMG foundation</td>
<td>0.037</td>
<td>130</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Core on Head foundation</td>
<td>0.116</td>
<td>406</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Core on MMG foundation with down-stream drainage</td>
<td>0.060</td>
<td>210</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Core on Head foundation with down-stream drainage</td>
<td>0.122</td>
<td>427</td>
<td>4.9</td>
</tr>
<tr>
<td>4</td>
<td>No cut-off on MMG foundation with Head material on down-stream reservoir side</td>
<td>0.039</td>
<td>137</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>No cut-off on Head foundation with Head material on down-stream reservoir side</td>
<td>0.408</td>
<td>1428</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>Cut-off on MMG foundation with Head material on down-stream reservoir side</td>
<td>0.039</td>
<td>137</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Cut-off on MMG foundation with down-stream drainage and Head material on down-stream reservoir side</td>
<td>0.058</td>
<td>203</td>
<td>2.3</td>
</tr>
</tbody>
</table>
## Settlement

<table>
<thead>
<tr>
<th></th>
<th>Embankment crest</th>
<th>Top of natural material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate settlement</td>
<td>0.2m</td>
<td>0.1m</td>
</tr>
<tr>
<td>Consolidation settlement</td>
<td>0.25m</td>
<td>0.02m</td>
</tr>
<tr>
<td>Total settlement</td>
<td>0.45m</td>
<td>0.12m</td>
</tr>
</tbody>
</table>

### Graphical Representation

- **Time (days)**
- **Settlement (m)**
  - \( k = 1e^{-10} \text{ m/s} \)
  - \( k = 1e^{-8} \text{ m/s} \)
  - \( k = 1e^{-9} \text{ m/s} \)

**31 years for 95% consolidation**

**3.2 years for 95% consolidation**

**0.4 years for 95% consolidation**
Embankment Design

1 in 3

1 in 4
Concluding Remarks

• Cheddar 2 is a suitable site for Bristol Water Requirements
• The natural topography and geology can provide cut/fill balance
• Bulk of embankment materials from Mercia mudstone/Head
• Minimal foundation soils problems
• Acceptable long term stability at proposed gradients
• Minimal seepage/cut-off/clay core/drainage requirements
• No adverse effects on macro-ecology/hydrology.
A 21st Century Reservoir is not just the design of a major piece of infrastructure…

…this is the collaborative master planning of a new place (that happens to contain a major piece of infrastructure utilising a deep understanding of geology, hydrology and ecology)!

ANY QUESTIONS?