Design, Construction and Monitoring of the Launch and Reception Shafts for the Corrib Tunnel

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Pat McAndrew, BAM Civil
Presentation Structure

• Introduction & brief description of the shafts
• Design requirements & constraints
• Ground conditions & design parameters
• Construction methods & details
• Soft eye & Sealing block details & analysis
• Retaining wall analysis
• Wall monitoring – comparison with FEA calculations
• Ground anchors /tension pile pull out test
• Pump tests & dewatering
Project Organisation for Corrib Tunnel Shafts

Client: SEPIL

Contractor: Bam Civil/Wyass & Freytag Joint Venture

Subcontractors:
- Murphy Piling – (Retaining walls)
- PJ Edwards – (Ground anchors & waler)
- Groundforce – (Temporary props)
- Patrick Briody & Sons (Well drilling)

Contractor’s Designer:
AGL Consulting

Subconsultant:
O’Shea Consulting – (Capping beam, props, walers, thrust frame support & base slab)
- 200m of retaining wall (sheet pile wall + secant pile soft eye)
- Sealing block
- Excavation up to 12m deep
- RC base slab
- Uplift tension piles (64 No.)
Start Shaft & Ramp

- Shaft – capping beam, “permanent” & temporary props
- Ramp – waler & ground anchors (64 No.)
Reception Shaft

- 40m of retaining wall (sheet pile & secant pile wall)
- Soft eye & sealing block
- “Permanent” & temporary props
- Capping beam
- RC base slab
- Uplift tension piles (18 No.)
Shaft Design Requirements & Constraints

• Depth
  o Tunnel cover requirements (Min 5.5m under Sruwaddacon Bay)
  o Max. Tunnel gradient of 1 in 20 (5%)
  o Tunnel Diameter (4m external)
    ⇒ Top of slab at ~11m depth for start/reception shafts (temporary excavation ~12m)

• Plan Dimensions
  o Shafts:  
    - Min internal: 17 x 9 m
    - Prop Spacing to allow TBM lift in/out
  o Ramp (at Start Shaft):  
    - Min internal of 74 x 5.5 m
    - No props for lift in of train ⇒ ground anchors
Shaft Design Requirements/Constraints

- **Wall Type**
  - Planning submission – sheet piles (based on limited SI available)
  - Impact driving **not** permitted

- **Soft eye/Sealing Block**
  - Min thickness over TBM crown = 4 m to control ground loss
  - Min thickness below crown from analysis (concrete arching)
  - Glass fibre reinforcement to allow TBM break through

- **Surcharge loading**
  - Mobile Crane pad load of 1370 kN (150kPa for 3x3m pad)
  - Gantry Crane: 150 kPa on 1m wide strip footing

- **Groundwater**
  - Dewatering – initially not permitted (but was relaxed)
  - Sealed dry shaft
Ground Conditions – Start Shaft & Ramp

- Overburden:
  - Peat up to 4.5m thick – excavated & replaced with granular fill (Class 6F/Cl. 804)
  - Glacial sands & gravels, medium dense to dense, 2 to 4m thick

- Solid Geology
  - Top of rock at 5 to 7m depth
  - Psammite & Schist bedrock (metamorphic sandstone & mudstone)
  - Weak to v. strong rock
  - Variable weathering (Fresh to highly weathered)
  - TCR: 100% in fresh to mod. weathered
    - 20 to 80% in highly weathered rock
  - RQD 0 to 60%
Ground Conditions – Start Shaft & Ramp

- Rock exposure in start shaft
- Dip of discontinuities approx 50 deg, south direction

Dip = 50 deg
## Characteristic Soil Parameters – Start Shaft

<table>
<thead>
<tr>
<th></th>
<th>Bulk unit weight $\gamma_b$ (kN/m$^3$)</th>
<th>Angle of shearing resistance $\phi'_{k}$ (°)</th>
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<tr>
<td>Clause 804 Fill</td>
<td>20</td>
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<td>Gravel/Sand</td>
<td>21.5</td>
<td>36</td>
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<tr>
<td>Moderately Weathered Rock (Passive Condition)</td>
<td>24</td>
<td>45$^1$</td>
<td>70$^1$</td>
<td>690$^2$</td>
<td>0.2</td>
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<tr>
<td>Moderately/ Highly Weathered Rock – (Active Condition, $K_a = 0.1$)</td>
<td>24</td>
<td>50</td>
<td>0.1</td>
<td>100$^2$</td>
<td>0.2</td>
</tr>
</tbody>
</table>

$^1$ From Hoek and Brown (2002) – From UCS, geological strength index, disturbance factor, etc.

$^2$ From Hoek and Diederichs (2005)
Ground Conditions – Reception Shaft

- **Overburden:**
  - Glacial sands & gravels, medium dense to dense, 3 to 5m thick

- **Solid Geology**
  - Top rock at 3 to 5m depth
  - Psammitic bedrock
  - Slightly to moderately weathered
  - Typically medium strong to v. strong, UCS = 20 to 80 MPa,
  - TCR: 100% (typically)
  - RQD 0 to 30% (Close to medium spaced discontinuities, up to 0.5m)
Ground Conditions – Reception Shaft

Sands & Gravels
Fresh to mod. weathered Psammite/Schist
Retaining Wall Options Considered

- **Secant pile wall**
  - Not permitted for general use due to planning conditions
  - However, acceptable for soft eye

- **Combi-wall**
  - Various arrangements considered (CHS/box sections grouted in drillholes & infill sheet piles).
  - However, difficulties included;
    - Verticality tolerances for full length infill piles (<1 in 200)
    - Achieving a watertight wall in rock for infill piles driven to refusal in overburden (e.g., by drill & grouting to seal rock)
Retaining Wall – Selected Construction Method

- Sheet piles driven into backfilled drillholes
  - Pre-drilled trench filled with granular material.
  - Trench formed by secant piling method with intersecting drillholes.

- Soft eye and sealing block formed by secant piles
Retaining Wall – Drillholes

- Primary, secondary and tertiary drillholes

**Primary:**
- 1200/1060mm diameter, for cased/uncased sections in overburden/rock
- Spacing = 1.5m
- Backfilled in rock with low strength concrete (~1 N/mm² at 7 days)
- Backfilled in overburden with fine gravel

**Secondary drillholes:**
- 1200/1060mm diameter (overburden/rock)
- Spacing = 1.5m
- Backfilled with fine gravel backfill (D₁₀ ≥ 2 mm and D₈₅ = 5 to 10mm)

![Diagram of drillholes]

**Notes:**
- 1.06m (in rock)
- 1.5m
Retaining Wall – Drillholes

- **Tertiary drillholes:**
  - 900mm diameter with full length drill casing to remove the low strength concrete in the primary drillholes.
  - Backfilled with fine gravel
Retaining Wall – Drillholes

- **Drilling/installation tolerances**
  - Tolerances needed to achieve:
    1. Entry of sheet piles into top of rock trench (allowing for both drillhole & sheet pile position and verticality)
    2. Width at base of trench > width of sheet piles

  - Maximum plan position tolerance = **20mm**
    - Guide wall for drillholes
    - Driving frame set up on guide wall for sheet piles

  - Maximum permitted deviation from the vertical = **1 in 150** (drillholes & sheet piles)
Retaining Wall – Installation Tolerances

At Top of Rock
Depth to Top of Rock (D): D_max = 6.7m
Positional Tolerance (p) = 25mm
Vertical Tolerance (v) = 67mm
Max Out of Position = 25 + 67 = 92mm

At Base of Drillhole
Depth to Base of Wall (L): L_max = 14m
Positional Tolerance (p) = 25mm
Vertical Tolerance (v) = 165mm
Max Out of Position = 140 + 25 = 165mm
Start Shaft Retaining Walls – Drilling

- Murphy Piling
- 3 No. Drilling Rigs – 2 No Bauer BG24 & 1 No. Soilmech R-158
- Duration of drilling = 4½ months (March to July 2012)
- 400 No. drillholes (primary, secondary & tertiary)
- 57 No. sealing block piles
- 9 No. secant wall piles
- Pre-drilling of rock in shaft
- Groundwater was lowered by well pumping to minimise wet spoil from drilling
Retaining Wall – Sheet Pile Installation

- Driving frame & vibrating hammer
- Start Shaft: PU-28, Ramp PU-18
- Reception Shaft: PU-32
- Start Shaft - duration of sheet piling 2½ months (~200m of sheet pile wall)
Drillhole – Low Strength Concrete Backfill

- Developed with TCD (Dr Roger West)
- To allow impact driving of sheet piles (through thin “neck” between drillholes)… but impact driving not permitted
- Used with tertiary drillhole arrangement system to assist drilling & driving

Requirements for controlled low strength concrete:
- Target strength ~1 MPa at 7 days and < 3 MPa at 28 days
- Self compacting: flow table dia. ~ 600mm (EN 1536 Bored Piles limit: 570 < Flow Dia < 630 mm for placement with tremie pipe below water)
- Bentonite used to give low bleed & segregation at low strength
- Mix design:
  - 180 kg cement
  - 50 kg bentonite
  - 370 kg water (W/C = 2.06)
  - 1410 kg aggregate
Sheet Pile Wall – Other Construction Details

- Sealant applied to the sheet pile clutches (Beltan/Liquafix J)
Sheet Pile Wall – Other Construction Details

- Sealed connection between the sheet piles and secant piled soft eye
- Box section cast in place
- First sheet pile driven through wet concrete

CU28-2
(cast in place)

First Sheet Pile
Box Section (CU-28)
Sheet Pile Wall – Other Construction Details

- **Proposed** grouting of backfill at wall toe
  - Reduce toe movement & ensure good contact with rock
  - Tubes welded to the sheet piles
  - End detail added to prevent gravel blocking tubes
Design Changes During Construction

- **Omit grouting of drillholes**
  - Risk of high conductivity level in groundwater – preventing discharge into Sruwaddacon Bay
  - Concrete in sealing block was noted to have an effect

- **Control external groundwater levels**
  - Silt observed in base of grout tubes (settled out of suspension)
  - \( \rightarrow \) Risk of uplift pressures at base of gravel fill
  - \( \rightarrow \) Control of groundwater levels outside shaft wall.
  - Limit head differential to \( \sim 4m \)
  - By external well pumping & weepholes in wall

- **Intermediate Temporary propping**
  - Purpose to limit forces and deflections at wall toe (rock sockets with loose gravel)
  - Groundforce Props & Frame at 2.2 mLAT (6.6m bgl)
  - Maintained \( >3m \) head clearance at excavation formation to allow uplift tension pile construction
“Soft Eye” Details

- Secant Pile Wall (1200/1060mm dia.)
- Piles 14m long
- Secondary piles reinforced with Glass Fibre Reinforced Polymer (GFRP)
- Aslan 100 (by Hughes Brothers, USA)
- Longitudinal reinforcement: 17 No. 32mm dia. bars (Design M = 1350 kNm/pile)
- Shear reinforcement: Helical 19mm dia. at 200mm c/c
Soft Eye Details

- Fabricated on site
- Composite cage (steel/GFRP bars)
- Lifting frame used to install cage
Sealing Block Details

- Formed by intersection of 57 No. secant piles with grade C5.6/7 concrete
- Diameter = 1060mm in rock
- Installation tolerance: plan = 50mm, verticality = 1 in 150
Analysis of Sealing Block

- Required to resist earth pressure & water pressure following break out of soft eye
- Relies on compressive arching stresses in concrete
- Sealing ring constructed prior to TBM drive
Analysis of Sealing Block

- Finite element analysis (Plaxis 2D)
- Limit concrete tensile stresses to a design value of 0.44 MPa
- Average tensile stress in exposed face was 0.2 MPa, locally 0.45 MPa

Compressive Stress

Tensile Stress
Analysis of Sheet Pile Wall

- Finite element analysis (Plaxis 2D)
- Additional checks carried out by limit equilibrium (Reward)
## Characteristic Soil Parameters – Start Shaft

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*¹ From Hoek and Brown (2002) – From UCS, geological strength index, disturbance factor, etc.
*² From Hoek and Diederichs (2005)
Analysis of Sheet Pile Wall

- **Design Situations**
  - DS-1: Cantilever dig to 1.5m
  - DS-2.1: Dig to 8.5m
    - ULS over dig = 0.5m
    - Upper prop
    - GWL = 2m bgl (7m LAT)
    - Surcharge = 10 kPa
Analysis of Sheet Pile Wall

- **Design Situations**
  - DS-1: Cantilever dig to 1.5m
  - DS-2.1: Dig to 8.5m
    - ULS over dig = 0.5m
    - Upper prop
    - GWL = 2m bgl (7m LAT)
    - Surcharge = 10 kPa
  - DS-2.2: Dig to Formation (11.8m)
    - ULS: Overdig = 0.5m
    - Upper prop + Temporary Prop
    - GWL = 8 m bgl (1m LAT)
    - Surcharge = 10 kPa
Analysis of Sheet Pile Wall

- **Design Situations**
  - DS-1: Cantilever dig to 1.5m
  - DS-2.1: Dig to 8.5m
    - ULS over dig = 0.5m
    - Upper prop
    - GWL = 2m bgl (7m LAT)
    - Surcharge = 10 kPa
  - DS-2.2: Dig to 11.8m
    - ULS: Overdig = 0.5m
    - Upper prop + Temporary Prop
    - GWL = 8 m bgl (1m LAT)
    - Surcharge = 10 kPa
  - DS-3: Base slab + Uplift tension piles
    - No over dig
    - Upper prop
    - GWL = At surface
    - Surcharge = 10 kPa
  - DS-3a: Mobile Crane Surcharge = 150 kPa (3x3m pad offset 1m)
Comparison of FEA & LEA

**Wall bending moment**
- Plaxis: Max M = 1050 kNm/m (DS-3)
- Reward: Max M = 1300 kNm/m - approx. 25% higher (DS-3)

**Prop/anchor force**

*Shaft*
- Plaxis: Prop Force = 387 kNm/m
- Reward: Prop Force = 380 kNm/m

*Ramp*
- Plaxis: Max Anchor Force = 408 kNm/m
- Reward: Max Prop Force = 412 kNm/m

- Prop/anchor forces are closely matched
- Note that CIRIA 580 recommends increase in LEA prop force x 1.85.
- For design multiplied by LEA prop/anchor forces x 1.25
Monitoring – Start Shaft & Ramp

- Real time inclinometers - Shape Accel Arrays (by Measurand)
- Array rigid sensors with gravity sensors
- 500mm segments (readings at 0.5m)
- 27mm dia. tube
- Installed in 50mm dia. tubes welded to sheet piles
- Installed & monitored by Geotechnical Observations
- 6 No. SAA’s at Start Shaft & Ramp
- 3 No. SAA’s at Reception shaft

- Total Station readings on capping beam
  - Pattern of displacement not logical
  - Concluded that capping beam movement was negligible (i.e. sealing block considered to be very stable)
  - Readings discounted
Monitoring – Start Shaft & Ramp

- Automatic alert system based on trigger values for Design Situations
- Readings can be viewed at any time through Atlas online interface
- Approx. 2 hr lag in “real time” data becoming available online
Monitoring Results – Start Shaft (DS-2.1)

- North wall Inclinometer (SAA-01x)
- Dig to 0.5 mLAT (8.5m bgl)
- GWL = 3 mLAT (6m bgl)
- Upper Level Prop Only
- Plaxis displacements (17.6mm) closely match inclinometer readings (19.2mm)
- South wall gave similar displacements (SAA-06x) = 17.5mm
- Trigger Limits based on a design water level of 7 mLAT (2m bgl), Max SLS $\delta = 33$mm
Monitoring Results – Start Shaft (DS-2.2)

- North wall Inclinometer (SAA-01x)
- Dig to 2.8 mLAT (11.8m bgl)
- GWL = 1 mLAT (8m bgl)
- Upper Level Prop + Temp Prop
- Groundforce prop at 2.2mLAT (Prestress = 40 kN/m)
- Inclinometer readings (21mm) > Plaxis displacements (18mm)
- Trigger Limits based on DS-2.1 with GWL = 7 mLAT (2m bgl)
Monitoring Results – Start Shaft (DS-3)

- North wall Inclinometer (SAA-01x)
- Upper Level Prop & **Base Slab** support
- Actual GWL = 9 mLAT (0m bgl)
- Plaxis displacements (35mm) give close match with inclinometer readings (38mm)
- NB Trigger Limits based on DS-3 with GWL = 9 mLAT (0m bgl) Max SLS $\delta = 65\text{mm}$

![Graph showing wall deflection and displacements](image-url)
Comparison of North & South Wall Deflection

- North wall Inclinometer (SAA-01x)
- South wall Inclinometer (SAA-06x)

Inclinometer Readings

- North wall (SAA-01x); max $\delta = 39\text{mm}$, GWL = 2.5m LAT
- South wall (SAA-01x); max $\delta = 28\text{mm}$, GWL = 0m LAT
- Difference = 11mm

Plaxis Results

- GWL = 2.5m LAT; max $\delta = 35\text{mm}$
- GWL = 0m LAT; max $\delta = 32\text{mm}$
- Influence of water level difference in FE = 3mm
- Greater movement possibly due to discontinuity dip direction
Monitoring Results – TBM Lift In (DS-3)

- North wall Inclinometer (SAA-01x)
- Lift of Tail skin (25t) on 07/11/12
- Lift of Machine Can (100t) on 08/11/12
- Lift of Shield (70t) on 09/11/12
Monitoring Results – TBM Lift In (DS-3)

- Lift in of tail skin (07/11/12)
Monitoring Results – Start Shaft (DS-3)

Effect of Mobile Crane Surcharge on Wall

- Pad load = 135t

1) Plaxis
   - To allow for some 3-D load shed 150kPa 3x3m pad is modelled as 90 kPa strip, as per CIRIA 580
   - Max deflection is **15mm** higher with Crane Surcharge compared with standard 10 kPa surcharge
Monitoring Results – Start Shaft (DS-3)

Effect of Mobile Crane Surcharge on Wall

2) Measured wall performance
   - No effect measured in inclinometers:
   - Possible reasons:
     - Bog mats used to further spread the load
     - 3D effects (2D analysis)
     - Stiffer behaviour of soil
     - Transfer of loads to underlying rock with low Poisson’s ratio in fill/gravel
Ramp and Ground Anchors
Monitoring Results – Ramp (DS-3)

- South wall Inclinometer (SAA-05x)
- Upper Level Ground Anchor support & base slab
- Ground anchor at 7 mLAT (Prestress = 300 kN/m)
- Inclinometer readings: max $\delta = 8\text{mm}$ for GWL = 3mLAT
- Plaxis displacements: max $\delta = 11\text{ mm}$ for GWL = 3mLAT
- NB - Trigger Limits based on Design GWL = 9 mLAT (0m bgl)

Ground anchors very effective at reducing wall deflection due to prestress
Influence of Wall Stiffness – Ramp (DS-3)

- Wall flexural stiffness $E_I$ was reduced in accordance with the Irish National Annex to EN1993-5

\[(E_I)_{eff} = \beta_D(E_I)\]

- $\beta_D = \text{factor to take into account possible lack of shear force transmission in U-section piles.}\]

Takes into account:
- number of supports
- welding/crimping clutches
- treatment of the interlocks with sealants
- ground conditions below formation.

- For 1 No. support levels (DS-2), $\beta_D = 0.7$
- For 2 No. support levels (DS-3), $\beta_D = 0.8$
Monitoring – Trigger Limits

- **Trigger Values** - Early detection of unexpected behaviour allowing corrective action
- **Traffic light system**
  - Green – continue construction
  - Amber – implement amber action plan (e.g., increase monitoring and investigate, early action – increase well pumping, reduce surcharge)
  - Red – Stop work & evacuate, implement red action plan (e.g., backfill, flood shaft, temporary propping etc.)

- Used approach by Patel et al (2007) – Observation method & design to EC7
  - Green \( \leq 80\% \) SLS displacement
  - Amber > 80\% SLS displacement
  - Red > SLS displacement

Monitoring – Trigger Limits

- Start Shaft

![Graph showing SLS Displacements for normal working conditions](image-url)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>SLS Characteristic: Max Deflection (mm)</th>
<th>Trigger Values (mm):</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-1</td>
<td>Counter excavation to 2.1 m BL + 0.5 m AT</td>
<td>10°</td>
<td>Green: &lt;10°, Amber: 10°, Red: &gt;10°</td>
</tr>
<tr>
<td>DS-2.1</td>
<td>Excavation to 0.5 m AT with GWL at +0.5 m AT</td>
<td>33°</td>
<td>Green: &lt;20°, Amber: 20°, Red: &gt;20°</td>
</tr>
<tr>
<td>DS-2.2</td>
<td>Excavation to formation with GWL at 1 m AT and temporary props</td>
<td>18°</td>
<td>Green: &lt;20°, Amber: 20°, Red: &gt;20°</td>
</tr>
<tr>
<td>DS-3</td>
<td>Base slab cast, GWL at surface</td>
<td>65°</td>
<td>Green: &lt;52°, Amber: 52°, Red: &gt;52°</td>
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<tr>
<td>DS-4</td>
<td>Long Term</td>
<td>65°</td>
<td>Green: &lt;52°, Amber: 52°, Red: &gt;52°</td>
</tr>
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*Note: The deflections are lower for the DS-2.2 stage than DS-2.1 due to the installation and post-tensioning of the Ground anchors. The conservative trigger values were based on considering water levels and were intended to be conservative for the calculation of temporary prop forces rather than wall deflection. Therefore, the DS-2.1 trigger levels have been applied to DS-2.2, as those movements occur they may not be recoverable.*

Table 4.1: Shaft South Wall (3) – Trigger Values
Ground Anchors

- Designed to BS 8081 (EC7, Section 8 not updated at that time)
- However, anchor loads derived from FE analysis – Effect of excavation stages considered
- Anchors prestressed to 70% of working load ($F_{serv}$)
- Design ultimate skin friction = 750 kPa (for weathered rock)
- Investigation test demonstrated > 1650 kPa
- Drillhole dia. = 150mm
- Free length 5 to 6m
- Fixed lengths 4 to 6m

<table>
<thead>
<tr>
<th>Anchor Type</th>
<th>Ramp Section 1</th>
<th>Ramp Section 2 &amp; 3</th>
<th>Ramp Section 4</th>
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<tbody>
<tr>
<td>Steel Grade</td>
<td>670/800</td>
<td>950/1050</td>
<td>950/1050</td>
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<tr>
<td>No. of anchors</td>
<td>18</td>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td>Angle of Inclination (°)</td>
<td>45</td>
<td>45</td>
<td>45</td>
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<tr>
<td>Spacing (m)</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
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<tr>
<td>Permanent Specified Working Load, SWL (kN)</td>
<td>1033.2</td>
<td>777.6</td>
<td>811.3</td>
</tr>
</tbody>
</table>
Dewatering – Start Shaft & Ramp

- Pump test in rock:
  - Well depth = 30m
  - Rock permeability $k = 3 \times 10^{-6}$ m/s
  - Flow rate, $Q = 2$ l/s
  - Drawdown = 8m

- Start & Ramp – Dewatering Design
  - Design drawdown = 10m
  - Peat removed from around shaft
  - No. of wells = 5 No. (25/30m deep)
  - Estimated pump rate = **10 to 15 l/s**
  - Well pumps, allowed for discharge volume up to 5 l/s

- Start & Ramp – During Construction
  - Drawdown = 7m
  - Well & weep holes installed in sheet pile wall
  - Actual discharge rate = 1.5 to 13 l/s
  - Typical **2.5 to 5 l/s**
Dewatering – Start Shaft & Ramp

- Layout of wells & piezometers
- Water levels outside shaft during excavation

![Water levels (mLAT)](image)

- Commence excavation
- Excavation to formation
- Base slab cast
Dewatering – Start Shaft & Ramp

Weepholes – during excavation
Acknowledgements

Thanks to the following for permission to use Corrb data in the presentation:

- BAM Civil
- SEPIL