The uMkhomazi Transfer Tunnel: Background, Geotechnical Conditions and Tunnel Design Considerations

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ABSTRACT: The uMkhomazi Water Project Phase 1 (uMWP-1) currently represents the largest civil tunnelling project in South Africa in three decades. Its centrepiece is the uMkhomazi Transfer Tunnel, a 31.2 km long, 3.5 m diameter tunnel designed to transfer water from the proposed Smithfield Dam to a new Water Treatment Works (WTW) which will supply potable water to the eThekwini metropolitan area in the KwaZulu-Natal Province (KZN), South Africa. The tunnel will be excavated through sedimentary and intrusive igneous formations using Tunnel Boring Machines (TBMs), following some initial drill and blast excavation of tunnel portals and access declines.

Feasibility study investigations indicated a mixed geological setting comprising horizontally bedded sedimentary sequences of shales, mudstones, siltstones, and sandstones, which are variably indurated and with significant variation in strength. These sedimentary strata have been extensively intruded by dolerite dykes and sills, while zones of fractured and weathered rock also occur. While rock mass conditions are generally favourable to TBM tunnelling, site-specific concerns such as mixed (hard-soft) face conditions, high water pressures, potentially gas-bearing rock, chemical aggressivity, weak/sheared shale horizons, rock durability and potential squeezing conditions will have to be considered during design.

The design phase underway now, includes comprehensive geotechnical investigations comprising rotary core drilling, geophysical (seismic and resistivity) surveys, wireline logging, packer testing, hydrofracture and overcoring in-situ stress testing. This is required to ensure optimal final tunnel alignment, ground support and final lining designs, excavation method selection, and waterproofing strategies, to mitigate technical and contractual risks. These investigations were developed to support the development of a Geotechnical Baseline Report (GBR) in line with ASCE and FIDIC Emerald Book Guidelines.

This paper presents the background and layout of the project, the scope of the geotechnical investigations, and expected key tunnel design considerations.

1 INTRODUCTION

The uMWP-1 will augment Umgeni Water's supply system that serves eThekwini (Durban and surrounds) in KZN and, once completed, will comprise a storage reservoir (i.e. Smithfield Dam) on the uMkhomazi River downstream of Impendle, and water conveyance infrastructure (WCI) comprising a 31.2 km long, 3.5 m diameter tunnel (the uMkhomazi Transfer Tunnel) and a 4.9 km long, 2.6 m diameter pipeline, through which raw water will be conveyed to a WTW which will be built at Baynesfield south of Pietermaritzburg. Following a 2014 feasibility study, the Trans-Caledon Tunnel Authority (TCTA) appointed the GIBB–Knight Piésold JV (GKP JV) to design the WCI component (i.e. the tunnel and pipeline), and construction supervision thereof. The uMWP-1 WCI is being designed for a maximum transfer rate of 8.65 m^3/s, with provision for a future Phase 2 (uMWP-2) expansion to approximately 14.86 m^3/s.

2 SITE AND ENVIRONMENTAL CONDITIONS

The project site is located in the KZN Midlands between the Drakensberg and the subtropical coastal belt. The climate is warm, humid, summer-rainfall (approximately 1,000 mm/yr) with mild, drier winters. Land use in the project area ranges from grasslands and agriculture in the west, commercial forestry centrally, and intensive farming on the Baynesfield Estate in the east.

A critical constraint is the presence of the Blue Swallow (Hirundo Atrocaerulea), a critically endangered grassland swallow which nests in subterranean burrows (typically disused aardvark burrows) during the summer breeding season. With an estimated global population of roughly 250 individuals, the species' occurrence in the broader project area has directly informed route optimisation, the placement and footprint of surface infrastructure, and the direction of the respective TBM drives.

3 PROJECT DESCRIPTION

The plan and long-section of the project is provided in Figure 1. Following drill-and-blast excavation of access adits and initial sections of tunnel at the inlet and outlet ends, most of the transfer tunnel will be excavated by TBM, with site-based precast segment production. Given the presence of Blue Swallow nesting sites in the Baynesfield area on the eastern side of the project site, development in this area has been reduced as much as possible. As a result, two TBM drives are planned, one from the inlet to midway, and the other from midway to the outlet.

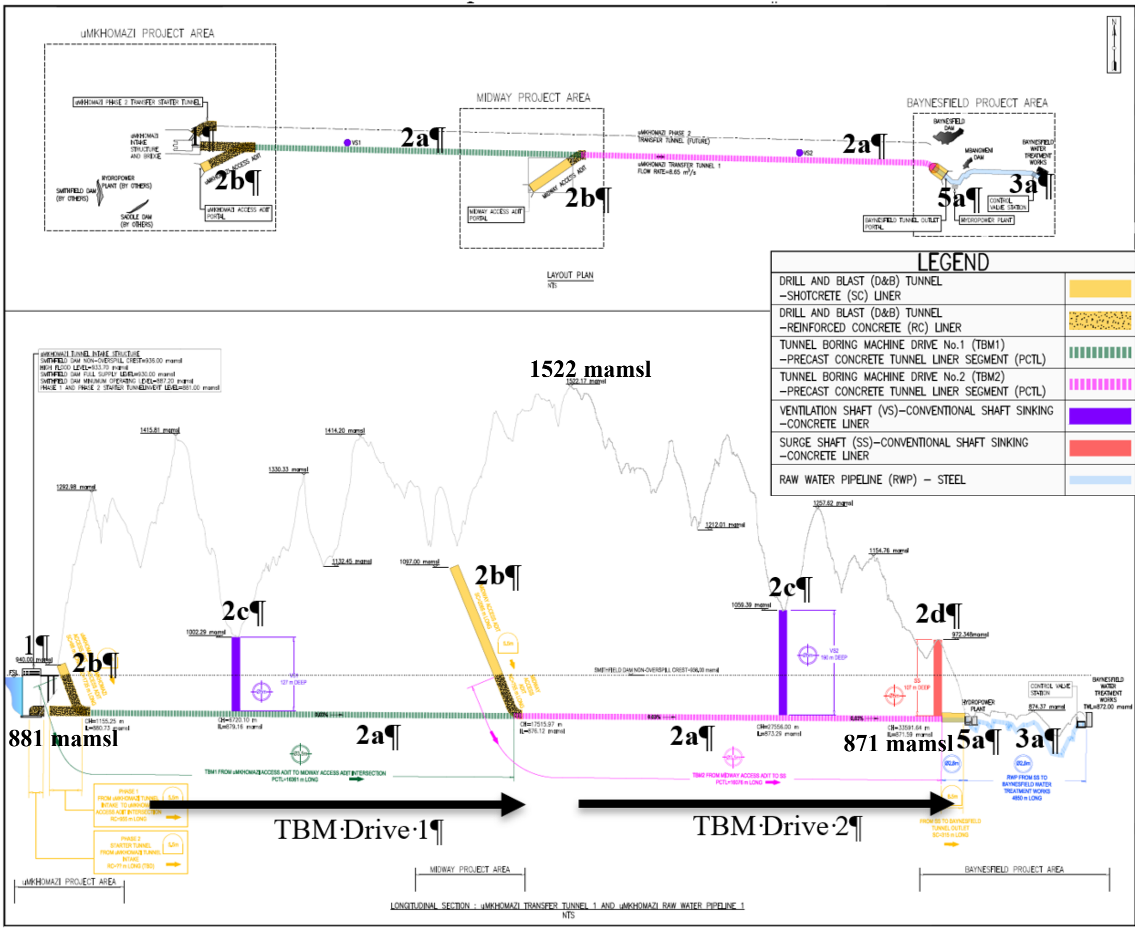


Figure 1: Schematic Project Plan and Long-Section Layout

Notes accompanying Figure 1:

1. Intake structure (multi-level intakes and access bridge within Smithfield Dam)
2. uMkhomazi Transfer Tunnel, comprising, a 31.2 km long, 3.5 m diameter tunnel, with a constant 1:3,700 gradient from the tunnel intake to its outlet, TBM access adit declines at the intake and at midway, and two ventilation shafts and a surge shaft.
3. Outlet works which includes a 4.9 km, 2.6 m diameter raw water steel pipeline:
4. Ancillary works in the different works areas, e.g. access roads, security, lay-down areas, contractor facilities, workshops, batch plants, segment factory, TBM muck and spoil disposal areas; and quarry/borrow sources.
5. Potentially a 3 MW hydropower plant at the outlet.

4 GEOLOGICAL SETTING

4.1 Site Geology

The project area is underlain by the Karoo Supergroup as shown schematically in plan and section in Figure 2.

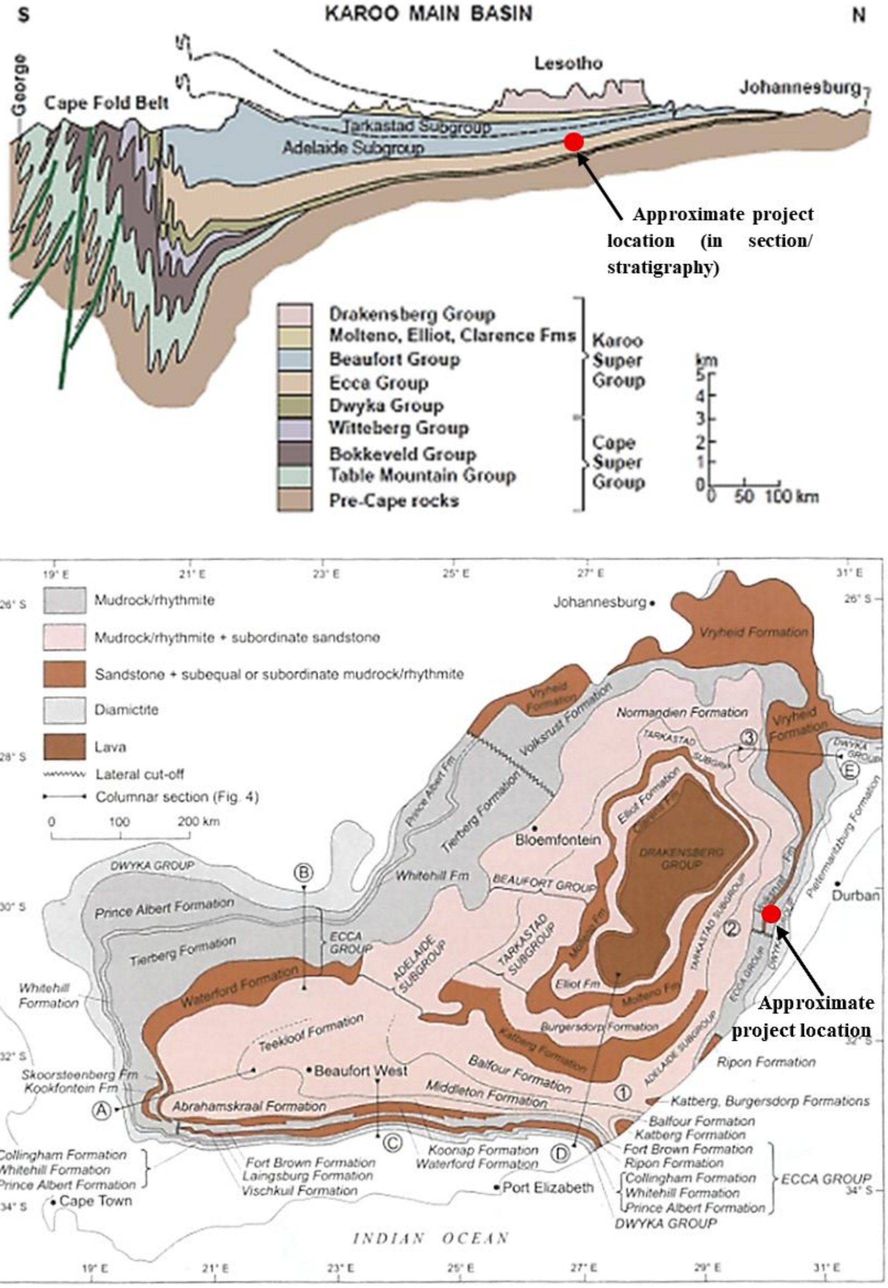
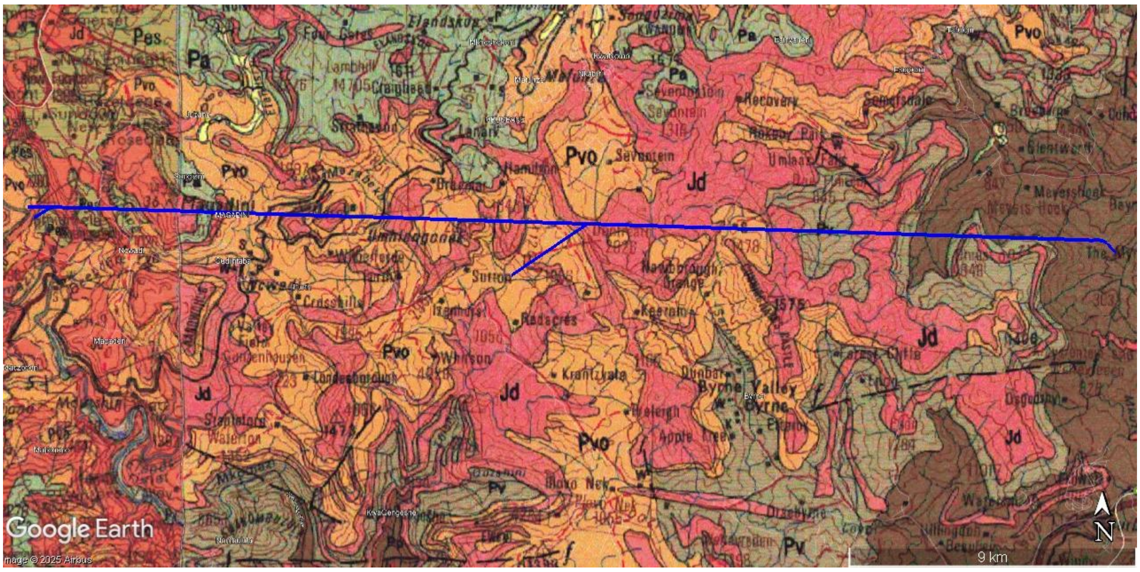


Figure 2: Stratigraphy of the Karoo Supergroup (after Johnson et al., 2006)

As shown in Figure 3, the western part of the tunnel will be underlain by rocks of the Lower Beaufort Group, comprising siltstone and sandstone with subordinate mudrock of the Adelaide Formation and shale, siltstone, sandstone and conglomerate of the Estcourt Formation, while the central and eastern parts of the tunnel will be underlain by predominantly shales and sandstones of the Vryheid and Pietermaritzburg Formations of the Ecca Group. Geological contacts between these Formations are often conformable and gradational, reflecting overlapping depositional processes. These rock strata are furthermore extensively intruded by dolerite dykes and sills, and the sedimentary rocks around these intrusions are often indurated.



(Approximate uMWP-1 Transfer Tunnel horizontal alignment superimposed on the above map as a blue line)

Legend	Stratigraphy	Lithology
Jd	Jurassic Dolerite Intrusions	**Jd**: Dolerite
Pa / Pe	Adelaide and Estcourt Formations, Beaufort Group, Karoo Supergroup	**Pa:** Siltstone, fine-grained sandstone, subordinate mudstone / **Pe:** dark grey shale, siltstone, medium to coarse grained sandstone, subordinate thin conglomerate
Pvo	Volksrust Formation, Ecca Group, Karoo Supergroup	**Pvo**: Dark blue-grey shale, subordinate thin sandstone
Pv	Vryheid Formation, Ecca Group, Karoo Supergroup	**Pv**: Medium to coarse grained sandstone, subordinate thin conglomerate
Pp	Pietermaritzburg Formation, Ecca Group, Karoo Supergroup	**Pp**: Dark-grey shale, siltstone, subordinate sandstone

Figure 3: Geological Map of the Project Area (extracted from 1:250 000 geological series, map sheets 2928 Drakensburg (CGS, 1981) and 2930 Durban (CGS, 1988))

4.2 Structural Geology

Several geological lineaments intersect the tunnel alignment, these include dykes, faults and shears, with lineaments predominantly trending NW-SE and roughly E-W. The E-W trending features are generally thought to represent thrusting as a result of the Cape Fold Belt orogeny, whilst the NW-SE trending features are thought to present horst-graben formation and normal faulting (crustal extension) during the breakup of Gondwanaland, which breakup may have reactivated the E-W trending features, which allowed dolerites to intrude many of these structures.

Sedimentary rocks on site generally exhibit sub-horizontal bedding with prominent sub-vertical joint sets, and fracture-controlled groundwater flow. Jointing in the dolerites comprises prominent tectonic sub-vertical joints, and variable joints due to thermal fracturing.

5 TUNNEL DESIGN CONSIDERATIONS

Mixed-face conditions: Mixed-face conditions are likely where softer shale horizons alternate with harder sandstone layers or dolerites. These transitions can trigger face instability, make TBM steering erratic, and cause variable penetration and tool damage. As mitigation, TBM drives should be preceded by routine probe drilling, with targeted pre-grouting and/or forepoling where weak ground is encountered. The TBMs should furthermore allow adjustment of face support pressure, and the cutterhead should be configured for mixed-face transitions, with controlled advance and ramming procedures to improve directional control of TBM boring.

Shale durability and swelling: The Karoo mudrocks are prone to break down rapidly when exposed to air and water and can develop swelling pressures which can impose additional high loads on TBM shields, final linings and ground support over time, while cyclic wet–dry conditions will lead to accelerated slaking and ravelling. Mitigation typically relies on rapid sealing of fresh faces with shotcrete in drill and blast excavations, installation and grouting of the final precast segmental lining in TBM tunnels, and control of water ingress to minimize wetting and erosion.

Low TBM penetration rates in thick dolerite sills: Low TBM penetration rates are expected in dolerite sills where intersected during tunnel boring because of its hardness and strength. This will be mitigated schedule-wise, by identifying the extent of tunnel drive length in such thick dolerite sills, and adjusting the overall construction programme accordingly.

High groundwater pressures and inflows: High groundwater pressures and transient inflows pose risk to the tunnel construction, with higher groundwater pressures expected in shales and mudstones particularly, and high inflows at dolerite dykes and at geological structures. However, it is expected that many of these lineament-type aquifers will dewater rapidly due to low storage capacity. Where indicated by probing, pre-excavation grouting will be undertaken in mitigation.

Abrasive rock: Tunnel intervals in abrasive rocks, particularly in hard dolerites and in quartz-rich, coarse-grained sandstones, will drive high cutter wear, ring chipping at hard contacts, and unplanned downtime. The mitigation is a high-torque, impact-resistant cutterhead fitted with robust hard-rock cutter discs, coupled with wear monitoring and disciplined maintenance windows. On-board conditioning and a crusher sized for dolerite blocks, backed by good TBM spares management, will help sustain utilisation and overall TBM performance.

Squeezing conditions: Weak and / or sheared shale zones in tunnel excavations at depth (i.e. at high in-situ stress) may deform and squeeze, which may lead to convergence, shield entrapment, ring distortion, and overbreak. Squeezing may also be caused or exacerbated by swelling rock. Several measures can be considered to mitigate the extent of the convergence, including consolidation grouting, rapid installation of precast liner, specifying a powerful TBM, increasing the overcut annulus, and opting for a single-shield machine. That said, where this is an issue during TBM tunnelling notwithstanding, drill and blast relief tunnelling around the TBM cutterhead and shield will be required locally to release the TBM shield.

Aggressive groundwater: Pyrite observed in borehole cores, particularly in the Ecca Group rocks, indicates the possibility of chemically aggressive groundwater, and risk of sulphate attack on concrete structures and final precast lining. Appropriate concrete mix designs and other mitigation measures will be required to prevent corrosion, with the annulus grout chemistry amended to resist attack, and with drainage paths controlled to limit exposure.

Hazardous gas: Hazardous gas, principally methane with the possibility of H_2S, as well as CO_2, introduce explosion and toxicity risks during tunnelling. Continuous multi-gas monitoring and testing of probe holes will therefore be required, together with using intrinsically safe equipment, well-defined ventilation and purge protocols, and a well-defined and rehearsed emergency response plan.

Segment integrity and water tightness: Segment integrity and water-tightness will be tested at transitions and under high external heads, to evaluate the potential for gasket damage, joint leakage, and ovalisation in weaker ground. Twin gaskets, strict QA/QC of ring building, packer checks and secondary grouting will be used to provide resilience. Segment design should cater for external water pressure and local deformation, while jacking forces and alignment will have to be carefully controlled.

Tunnel logistics: The relatively small 3.5 m diameter of the uMWP-1 Transfer Tunnel, as well as the relatively long TBM drives will present logistical challenges. A robust design will therefore be required to cater for ventilation, mucking and segment supply lines.

6 SCOPING THE EXTENT OF GEOTECHNICAL INVESTIGATIONS

Benchmarking of drill metres versus tunnel length (
Figure 4) shows that the planned drill metres for the uMWP-1 to be slightly below global averages. The borehole-to-tunnel length ratio is 0.25 (Figure 5) which is associated with an approximate 30% cost overrun in empirical datasets. However, these correlations mostly reflect tunnels of shorter length and higher geological complexity. Given the relatively long uMWP-1 transfer tunnel length, relatively uniform stratigraphy and extensive complementary testing, the investigation density for uMWP-1 is considered appropriate and proportionate to the anticipated levels of geotechnical risk.

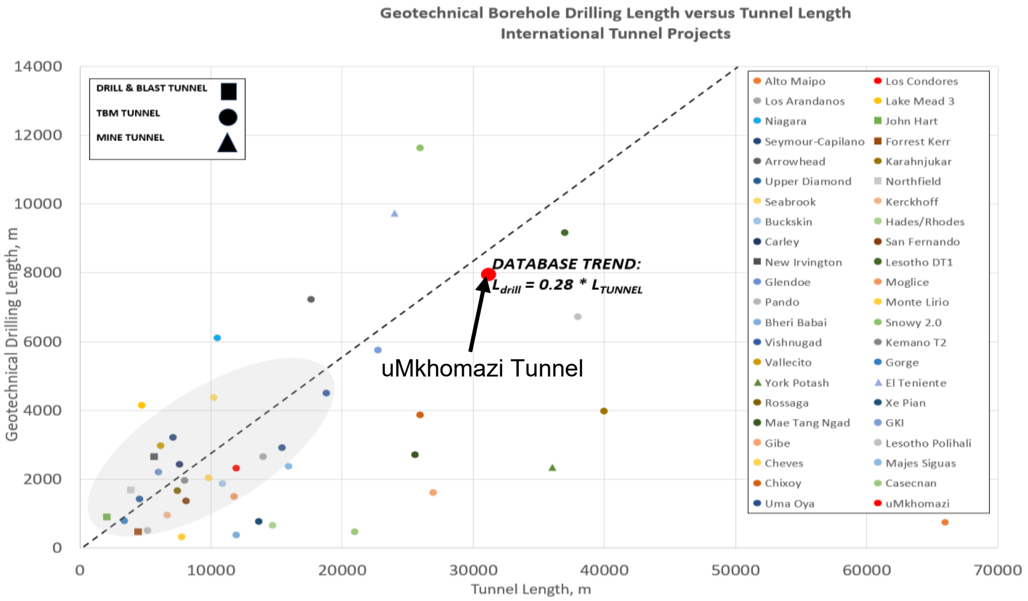


Figure 4: Geotechnical Borehole Drilling Length vs Tunnel Length (adapted from Brox, 2018).

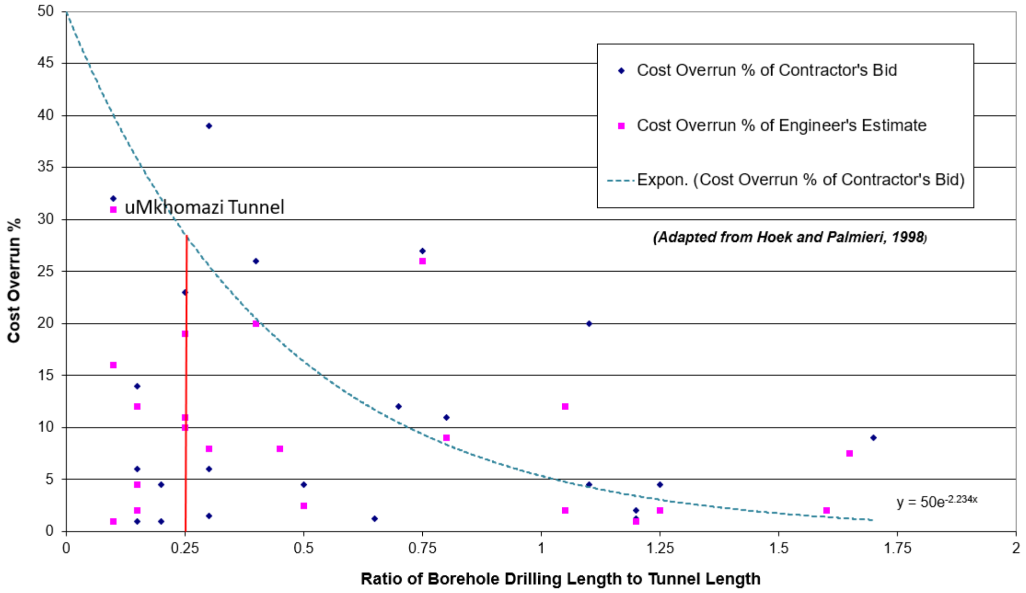


Figure 5: Ratio of Borehole to Tunnel Length vs Percentage Cost Overruns (adapted from Hoek & Palmieri, 1998, modified by Brox, 2017)

7 INVESTIGATIONS UNDERTAKEN

Desktop and literature review:

- Review feasibility investigation data, geological mapping, literature and information on tunnels built in similar stratigraphy (in particular, at the Ingula PSS).
- Stereoscopic aerial photographic interpretation, using overlapping stereo-pair photographs.

Non-intrusive investigations comprised:

- Electrical Resistivity Tomography (ERT): Scanning a total of 7.4 km of traverses, at tunnel portals, adits, shafts, key lineaments, and quarries (weathering/ saturation and structural contrasts).
- Seismic refraction: A further 7.4 km coincident traverses to determine depth-to-bedrock and to provide information on rock type, hardness and stiffness.
- Airborne EM/magnetics: Two 35 km traverses along the corridor to identify geological lineaments, their width and their orientation across the tunnel alignment.

Intrusive investigations and in-situ testing:

- Rotary core drilling: 77 boreholes (7,940 m) at portals, adits, shafts, quarries and along the tunnel alignment, to determine rock mass conditions, intercept contacts and structural geological lineaments, determine fracturing and fracture orientation, allow for samples and in-situ testing, and investigate potential quarry sites. Most boreholes on the tunnel alignment were inclined to intercept the prominent sub-vertical fracture sets;
- Downhole geophysics: 47 surveys (acoustic/optical televiewer, gamma, sonic, calliper, magnetic susceptibility, trajectory) to determine permeability, and the characteristics and orientation of fractures and lineaments;
- Packer tests: 470 single/double Lugeon tests in boreholes to derive interval permeabilities, for inflow estimates and waterproofing;
- Stress testing: 5 overcoring (Sigra) and 7 hydrofracture in-situ stress tests (Solexperts) to determine principal stress magnitudes and orientations, and to calculate representative K-ratio values
- Test pits/trenches: 99 pits (to 3–5 m depth) to determine shallow geotechnical conditions along the pipeline route, and at other surface infrastructure and material sources;
- Percussion boreholes: Large-diameter twin hole drilling for test pumping and monitoring, and methane screening of a select number of boreholes in the vicinity of the project area.
- Instrumentation: 5 multi-level VWP strings (3–5 sensors per string) and 20 level loggers to establish pore pressures/groundwater levels and calibrate hydrogeological models.

Materials and laboratory testing:

- Local geotechnical testing: Classification and index properties, P/S-wave velocities, petrography/XRD, point load testing, uniaxial and triaxial strengths, Brazilian tensile strengths, joint shear strengths, swelling (confined/unconfined/ semi-confined), durability (ethylene glycol durability index , water absorption, freeze–thaw, slake), alkali reactivity.
- TBM-focused testing (SINTEF/NTNU): CAI, DRI/BWI/CLI, RIAT, brittleness metrics for TBM selection, cutterhead design, advance-rate and cutter wear forecasting.

Finally, key objectives of geotechnical investigations being carried out now, are as follows:

- Defining overburden thickness/weathering for surface works areas and pipeline alignment.
- Characterising intact rock and discontinuities, quantify rock mass quality and anisotropy.
- Mapping faults, shears, and dykes, geological contacts, and potential high-permeability zones.
- Measuring in-situ stresses for ground support and TBM design, and for lining design.
- Quantifying permeability and anticipated groundwater inflows.
- Determining the corrosivity of soils for pipeline cathodic protection.
- Proving and testing construction materials (aggregates, backfill).
- Generating design-grade laboratory data, including TBM design parameters.
- Compiling factual, interpretive, and baseline reports to underpin tender designs.

8 CONCLUSIONS

The proposed uMkhomazi Transfer Tunnel is vital to water security of the eThekwini metropolitan area in KZN in South Africa, and to maintaining momentum in civil tunnelling design and construction in the region. The transfer tunnel will cross a varied Karoo stratigraphic sequence with dolerite intrusions as well as several major geological structures and lineaments.

The proposed transfer tunnel will encounter predominantly horizontally bedded shales, mudstones, siltstones and sandstones of the Ecca Group, extensively intruded by dolerite sills and dykes and cross-cut by NW–SE and E–W dykes, faults and lineaments. However, there is extensive precedent tunnelling experience in these sedimentary strata and geological conditions are generally well understood, with generally favourable hard rock TBM tunnelling expected, punctuated by mixed faces, sections of tunnel in hard dolerite sills, contact-metamorphosed sandstones, and structurally disturbed intervals.

The geotechnical investigation program includes core drilling, downhole geophysical logging, surface geophysics, and in-situ stress and permeability testing, to assist with the development of geological, structural geological, hydrogeological, rock mass and geotechnical models which can be used for design and tendering purposes. Tunnel design considerations include mixed-face excavation at shale–sandstone–dolerite contacts, low durability mudrocks, low TBM penetration rates in thick dolerites, localised high groundwater pressures and inflows, abrasive rock, chemically aggressive water in pyrite-bearing shales, possible gas, and squeezing / deformation in weak or sheared shales. These considerations can generally be mitigated through correct design and construction, employing measures such as systematic probe drilling, consolidation grouting, rapid precast segment ring building and annulus grouting, segment designs focused on durability (sulphate-resistant mixes) and good water and gas management. The GBR should furthermore provide a reliable baseline on which tunnelling expectations, ground support requirements and pricing can be based, for adopting an observational approach consistent with ASCE and FIDIC Emerald Book Guidelines, with defined trigger levels for adjusting tunnel support and construction methods.

The scope and extent of geotechnical investigations (i.e., drilling density) being carried out for the uMWP-1 Transfer Tunnel, is generally aligned with international norms for longer tunnels constructed in relatively consistent stratigraphy, and the defined investigation scope is therefore deemed appropriate. Also, empirical cost-overrun correlations which rely solely on borehole-to-tunnel length are deemed of limited applicability in this particular case study because available empirical datasets used for such benchmarking, are dominated by shorter tunnels in more structurally complex geological settings. That said, given the defined scope and extent of geotechnical investigations for the uMWP-1 Transfer Tunnel, and the mitigations outlined above, significant material cost and/or schedule overruns related to unforeseen ground conditions as a result of an inadequate level of investigation, is considered unlikely.

Finally, because common benchmarks track metres of core more than the breadth of testing and monitoring required for design and baseline characterisation, an index-based framework is recommended to better link project drivers to investigation scope; to reduce subjectivity, improve risk allocation, and provide a clearer technical/contractual basis when investigating major tunnelling projects.

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