Design considerations and construction strategies for the uMkhomazi water project phase 1

M. Nasiri[1], G.J. Keyter[1], U. Rehm[2], T. Mac Kellar[2]

[1]SRK Consulting, South Africa
[2]Knight Piesold, South Africa

The uMkhomazi Water Project Phase 1 (uMWP-1) aims to augment water supply to the uMngeni Water Supply System (MWSS) in KwaZulu-Natal to address long-term regional water demand. A key component of the scheme is a 34 km waterway tunnel driven primarily by tunnel boring machines (TBMs), connecting the uMkhomazi intake to the Baynesfield outlet. The project presents several design and construction challenges, particularly due to the constraints of working within a relatively small 3.5 m internal diameter tunnel.

This paper outlines the main engineering strategies developed to manage these challenges, with preliminary design work completed to date, focused on practical solutions for tunnel logistics, including muck removal, segment transport, sequencing of construction activities, and the efficient use of equipment within the limited tunnel space. These aspects are essential in deriving workable construction methods for these long, small-diameter TBM tunnels. The paper also summarises options for TBM removal at the Baynesfield outlet, which represents a major project milestone with implications for programme, cost, and interfaces with downstream infrastructure.

Overall, the study highlights the importance of coordinated planning, effective logistics, and careful sequencing during the preliminary design phase to better manage construction risks and ensure long-term operability in complex tunnelling projects.

Keywords: TBM Tunnelling, Small-Diameter Tunnels, Long-Distance Tunnelling

INTRODUCTION

The uMkhomazi Water Project Phase 1 (uMWP-1) forms part of a long-term regional water security strategy in KwaZulu-Natal, South Africa. The project is being implemented by the Trans-Caledon Tunnel Authority to augment the existing uMngeni Water Supply System with water from the uMkhomazi river. This system supplies water to urban centres, industrial facilities, and agricultural areas.

At the core of uMWP-1 is a 34 km long bulk water conveyance tunnel extending from the uMkhomazi river intake works to the Baynesfield outlet. This water transfer tunnel represents one of the most significant components of the overall uMWP-1 infrastructure programme.

The tunnelling works comprise a combination of conventional drill-and-blast (D&B) excavations and mechanised tunnel boring machine (TBM) drives. The main tunnel elements include (Figure 1):

- D&B tunnels and adits, including:
  - uMkhomazi tunnel intake (uMTI) connecting tunnel;
  - uMkhomazi TBM access adit (uMAA);
  - Midway TBM access adit (MAA); and
  - Baynesfield tunnel outlet (BTO) connecting tunnel.
- TBM tunnels, comprising:
  - TBM Drive 1 (TBM1): From the uMkhomazi intake to Midway; and
  - TBM Drive 2 (TBM2): From Midway to the Baynesfield outlet connecting tunnel.
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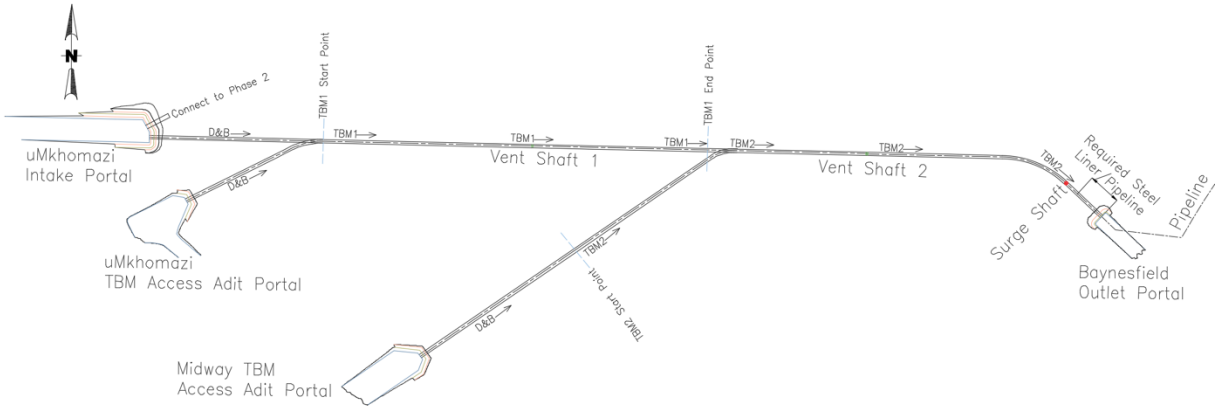


Figure 1. Tunnel alignment and project overview.

Excavation is predominantly mechanised using aTBM, with a finished internal diameter (ID) of 3.5 m. The tunnel's combination of long alignment and relatively small diameter presents distinctive engineering and logistical challenges. Constraints associated with the small-diameter tunnel include restricted space for TBM operation, backup systems, conveying infrastructure, ventilation ducts, electrical services, and emergency access. Over the 34 km tunnel, even minor inefficiencies can accumulate, significantly affecting programme performance.

Given the long TBM drive lengths, breakthrough does not represent the end of construction risk exposure. TBM2 removal at the Baynesfield outlet constitutes a programme-critical operation with direct implications for construction sequencing, downstream interface works, and commissioning milestones. The selected TBM2 removal methodology therefore forms an integral component of the preliminary design, as delays or inefficiencies during this phase could disproportionately impact overall project delivery and associated timelines.

Design Considerations and Constructability Integration

Hydraulic Requirements

The selected 3.5 m ID is governed by hydraulic design, including discharge capacity, flow velocity limits, and head loss optimisation. This diameter balances hydraulic performance with capital efficiency but also defines a strict construction envelope. Unlike large-diameter tunnels, where space allows flexibility, the current configuration requires precise spatial coordination of all systems within the available tunnel cross-section.

Constructability as a Primary Design Consideration

In long, small-diameter tunnels, constructability must be treated as a primary design variable rather than a secondary validation exercise. All systems, including ventilation, electrical reticulation, communications, dewatering lines, mucking infrastructure, and segment transport must operate concurrently within a highly constrained spatial envelope. The long tunnel alignment magnifies the impact of operational inefficiencies. Downtime events, maintenance delays, or supply interruptions that may be manageable in shorter drives become programme-critical in long tunnel drives. Accordingly,

system reliability, maintainability, and logistical resilience were adopted as core design objectives from the preliminary design stage.

Spatial Constraints and Cross-Sectional Optimisation
Within a 3.5 m ID tunnel, the segmental lining defines a strict geometric boundary within which the TBM shield, erector, backup gantries, and service systems must operate. Careful cross-sectional planning is therefore critical to ensure safe, efficient, and uninterrupted TBM operations. The tunnel cross-section must accommodate:

- Backup gantries;
- Transport systems, segment delivery and muck removal;
- Ventilation and booster stations; and
- Utilities, service lines, and instrumentation.

Figure 2 illustrates a representative tunnel cross-section.

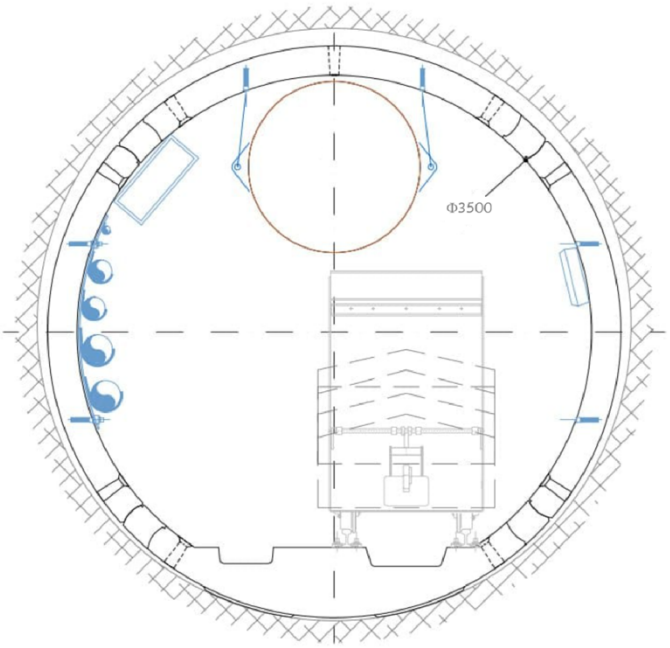


Figure 2. Typical tunnel cross section.

Multi-service vehicles (MSVs) were evaluated as a potential integrated logistics solution for combined segment delivery and muck removal within the main tunnel drives. However, they were found to be incompatible with the available spatial envelope. A fully loaded MSV requires a raised ramp system of approximately 0.8 m in height, leaving insufficient clearance for ventilation ducting, fixed services, and emergency egress provisions.

By contrast, locomotive-hauled rail wagons provide a significantly lower loading profile (approximately 0.5 m lower than equivalent MSV configurations), allowing integration of essential services while maintaining required safety clearances. The geometric constraint imposed by the 3.5 m ID therefore directly informed the selection of a rail-based logistics system.

TBM Logistics and Construction Sequencing
The extended tunnel length and restricted 3.5 m ID impose significant constraints on construction logistics and sequencing. In long single-access drives, advance rate stability is governed primarily by the interaction between muck removal, segment delivery, and concurrent service installation. Logistics planning was therefore integrated into the early design phase to ensure geometric compatibility, operational efficiency, and programme reliability.

Muck Removal Strategy
For a long tunnel, muck removal capacity directly governs achievable TBM advance rates. In a small-diameter tunnel, the available cross-sectional envelope limits the configuration of transport systems and fixed services.

Rail-based haulage using locomotive-hauled wagons was identified as the best geometrically viable solution within 3.5 m ID. Alternative systems, including MSVs, were evaluated but found to be incompatible with the available spatial envelope. Increasing the diameter to accommodate MSV ramps would require a minimum ID of approximately 4.5–5.0 m, materially affecting excavation volumes, lining quantities, hydraulic capacity, and capital cost.

Segmental Lining and Transport Logistics
Precast segmental lining provides ground support and ensures long-term hydraulic performance consistent with bulk water conveyance requirements. Within a 3.5 m ID tunnel, segment handling operations are constrained by limited working space in the TBM shield tail gap and the configuration of backup gantries.

Segment geometry will be optimised to balance structural performance, durability, individual unit weight, and erection efficiency. Design considerations include lifting constraints within the shield envelope, minimisation of manual intervention, and reduction of ring build cycle duration. Segment transport to the TBM will be undertaken using locomotive-hauled rolling stock. Train configuration and segment palletisation will be designed to optimise payload efficiency while maintaining braking performance and operational safety over extended haul distances.

Given that muck removal and segment delivery share the same rail infrastructure, logistics sequencing is subject to continuous cycle modelling to minimise production interference and avoid rolling stock congestion along the single-access alignment.

Access Adit Gradient Constraints
The TBM access adits are designed at gradients of approximately 8% for operational and long-term access efficiency. Conventional rolling stock cannot operate on such steep gradients, so alternative segment delivery systems were evaluated:

- Rubber-tyred locomotives: Limited by gradient, working space, and wet conditions within the adits; operational reliability is uncertain;
- Rack-and-pinion (cog-wheel) trains: Fully feasible within 3.5 m ID tunnels; provide traction on steep gradients, integrate with standard rail in the main tunnel, and eliminate the need for transfer caverns; and
- Winch-assisted systems: Impractical when considering access adit lengths of approximately 1 km (uMAA) and 3 km (MAA) respectively, due to safety concerns, regulatory restrictions, and mechanical risk.

Based on this assessment, cog-wheel trains were selected as the preferred solution for the steep access adits, ensuring continuous, reliable segment delivery while maintaining required safety and tunnel clearances.

Construction Sequencing and TBM Cycle Integration
The stability and efficiency of TBM advance rates along the tunnel are constrained by a tightly integrated framework encompassing excavation, lining erection, maintenance planning, and logistics coordination. Continuous monitoring and preventive maintenance scheduling reduce the likelihood of unplanned breakdowns, which can cause significant downtime, particularly on long tunnel drives. All supporting service systems, including ventilation, muck handling, and segment delivery infrastructure, will be synchronised with TBM operational cycles to minimise idle time. For single-shield TBMs, bore and segment erection cycles are performed sequentially, typically requiring approximately 50 minutes per complete cycle. In contrast, double-shield TBMs allow concurrent bore and segment ring construction, reducing the cycle to approximately 25–30 minutes.

These operational characteristics underscore that logistical support, particularly segment delivery and muck removal, is the primary determinant of sustained advance rates in long, small-diameter tunnel drives, often outweighing the influence of excavation mechanics alone.

Tunnel Diameter Sensitivity Assessment
A sensitivity study was undertaken to evaluate the technical and economic implications of increasing the tunnel ID from 3.5 m to 4.7 m. The assessment considered impacts on TBM performance, logistics efficiency, access adit functionality, geotechnical risk exposure, and overall capital cost. The objective was to determine whether a larger diameter would materially improve constructability and programme certainty sufficiently to justify the additional expenditure.

Technical Impacts
Increasing the tunnel ID to 4.7 m would materially expand the internal spatial envelope available for logistics and services. The main technical advantages identified include:

- **MSV passing ramps:** The increased cross-sectional area would allow installation of raised passing ramps for MSVs, enabling simultaneous movement of segment delivery and muck removal vehicles. This would reduce reliance on single-track rail cycles and mitigate congestion risk in long tunnels.
- **Improved service segregation:** Greater diameter facilitates clearer separation between mobile plant corridors and fixed infrastructure such as ventilation ducts, electrical reticulation, grout lines, and communication systems. Improved segregation enhances operational safety and simplifies maintenance access.
- **Enhanced maintenance accessibility:** Additional working space within the TBM shield and backup gantries would improve access for inspection, cutterhead interventions, and mechanical repairs, potentially reducing maintenance intervention duration and improving overall equipment utilisation.
- **Reduced internal congestion**: Greater clearance decreases the risk of physical conflicts between rolling stock, personnel, and fixed services, particularly during peak logistics cycles.

Despite these advantages, TBM excavation performance would remain largely unchanged. Bore cycle duration is primarily governed by cutterhead torque, thrust capacity, rock mass characteristics, and segment erection time; parameters not significantly affected by moderate increases in tunnel diameter. The production cycle assessment indicates that the net improvement in sustained advance rate would be limited to approximately 5% if the tunnel diameter is increased. In long tunnels, logistics constraints can often be mitigated through alternative systems, such as cog-wheel rail solutions, without enlarging the tunnel diameter.

Economic Assessment
Increasing the ID from 3.5 m to 4.7 m results in a substantial increase in excavation volume due to the quadratic relationship between diameter and cross-sectional area. The larger profile would require:

- Increased excavation quantities;
- A larger TBM and associated plant;
- Higher segmental lining volumes (i.e., number of segments) and reinforcement quantities;
- Increased muck handling and surface disposal requirements;
- Expanded portal and shaft geometries; and
- Enhanced surface logistics infrastructure.

High-level cost estimation indicates that these factors collectively increase base construction cost by approximately 20%. When compared with the estimated ~5% improvement in advance rate, the economic benefit of a shorter construction duration does not offset the additional capital expenditure. The modest programme acceleration achievable with a larger tunnel diameter therefore does not justify the significantly higher upfront cost.

Moreover, the implementation of rack-and-pinion (cog-wheel) segment transport in steep access adits effectively mitigates the primary logistical limitation associated with the 3.5 m ID configuration. This

approach preserves production continuity without requiring tunnel enlargement.

Accordingly, both technical and economic evaluations confirm that the 3.5 m ID remains the optimal configuration for the uMWP-1 project. This diameter satisfies hydraulic performance objectives while maintaining capital efficiency, if logistics integration and sequencing are carefully managed.

TBM Breakthrough and Removal at Baynesfield

Strategic Importance

The TBM2 breakthrough at the Baynesfield outlet represents a critical milestone in the overall programme. Unlike conventional short tunnels, breakthrough in a long tunnel does not signify completion of risk exposure, and TBM2 removal at Baynesfield constitutes a major engineered operation with significant implications for safety, programme continuity, and interface with downstream infrastructure.

The selected removal methodology directly affects:

- Programme duration;
- Scope and complexity of surface infrastructure;
- Safety exposure during dismantling;
- Interface with downstream outlet structures; and
- Timing of final hydraulic commissioning.

For long, small-diameter tunnels, TBM removal must be treated as an integrated design decision rather than a terminal construction activity, as delays or inefficiencies during this phase can disproportionately affect overall project delivery.

Constraints Imposed by Tunnel Diameter

The 3.5 m ID imposes significant limitations on underground TBM dismantling operations. The restricted cross-sectional space constrains lifting geometry and equipment manoeuvrability, requiring careful planning of TBM extraction sequences.

Furthermore, after breakthrough, the TBM remains embedded within the precast segmentally lined envelope, limiting overhead clearance for major component extraction.

TBM Removal Options Overview

Three principal strategies were evaluated for the removal of TBM2 at the Baynesfield outlet:

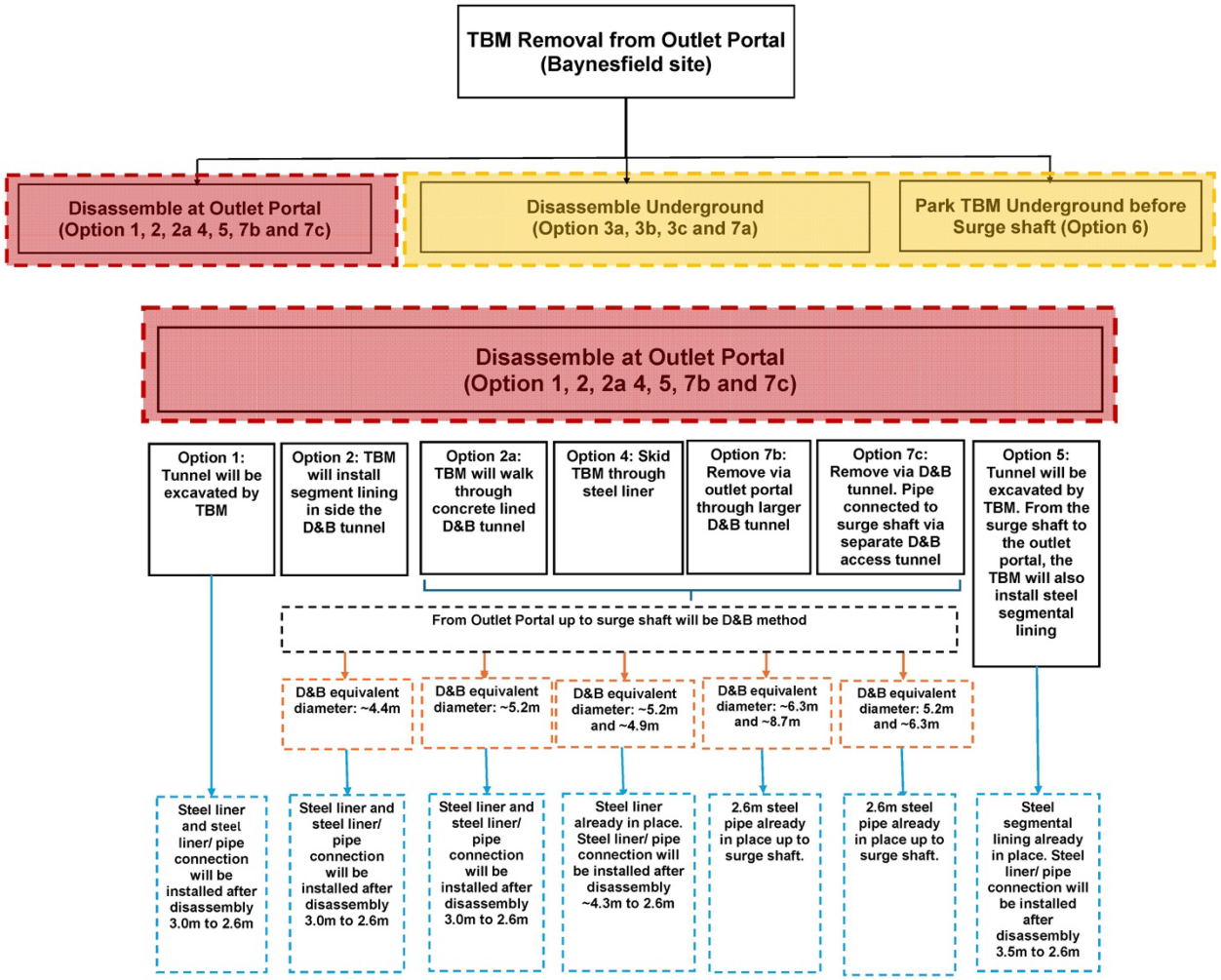
- **Strategy 1 - Surface disassembly at the Baynesfield outlet portal:** TBM2 is driven, walked, or skidded to the outlet portal, where disassembly occurs on surface within the outlet portal open cut, thereby minimising underground dismantling activities. This strategy minimises confined-space dismantling and simplifies lifting operations through conventional crane access. However, surface disassembly requires additional space within the open cut at the outlet portal and early integration with the outlet civil works.

- **Strategy 2 - Underground disassembly:** TBM2 is dismantled within a purpose-designed disassembly chamber located at the base/just upstream of the surge shaft. TBM components and the backup train are removed through one or a combination of the following routes:
  - The surge shaft;
  - The Baynesfield outlet connecting tunnel;
  - Reversing through the waterway tunnel and the Midway TBM access adit; and
  - A combination of these routes (e.g., shield removed via surge shaft or connecting tunnel, backup train removed via waterway tunnel and Midway TBM access adit).

  This approach reduces surface footprint and shaft diameter requirements but increases underground complexity. Confined-space dismantling introduces elevated safety exposure, extended dismantling duration, complex temporary lifting systems, and greater schedule uncertainty. Engineering controls such as temporary lifting frames, rail-based extraction systems, and enhanced ventilation are required to manage these risks.

- **Strategy 3 - Permanent burial / abandonment:** The TBM2 shield machine is driven offline and abandoned just upstream of the surge shaft and permanently sealed in, while the backup train is removed via the waterway tunnel and Midway TBM access adit.

Figure 3 presents a schematic comparison of the three strategies, highlighting tunnel cross-section requirements, disassembly chamber configuration, extraction routes, surface footprint implications, and interaction with downstream outlet structures. The schematic provides a consolidated visual framework supporting the multi-criteria analysis (MCA) carried out to compare the above TBM removal options, and clarifies the operational, structural, and sequencing constraints associated with the respective options.



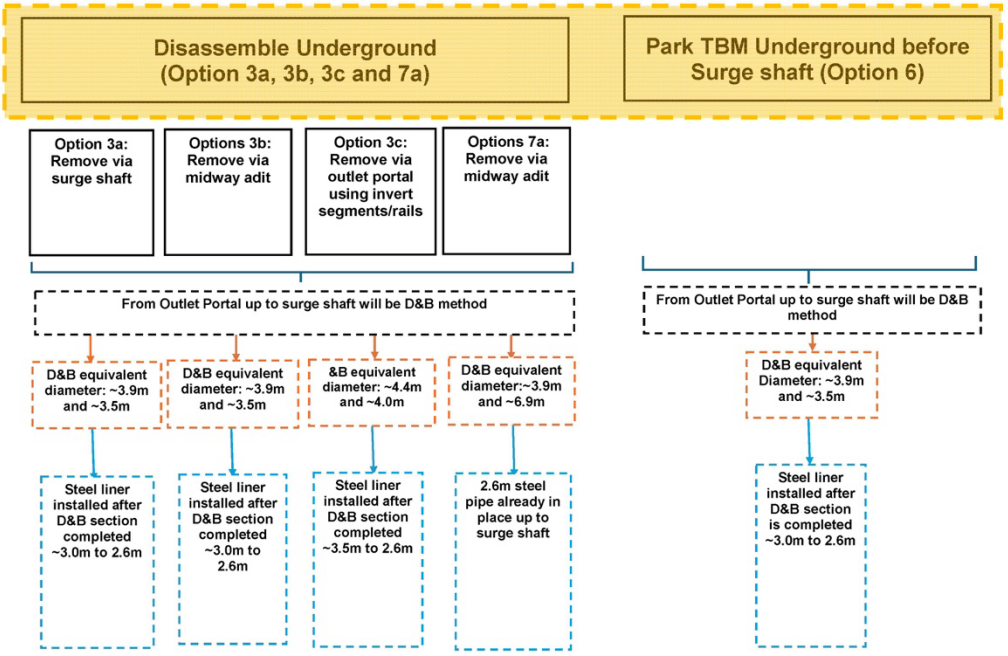


Figure 3. Overview of TBM removal options at Baynesfield outlet.

Comparative Engineering Assessment

The evaluation considered key factors including capital cost, programme duration, safety exposure, operational interface, and long-term asset implications. The assessment of the three TBM removal strategies is summarised as follows:

- **Surface disassembly (Strategy 1):** Offers the highest safety margin during dismantling and minimises confined-space exposure. Requires early integration with civil works and controlled open-cut geometry.
- **Partial underground dismantling (Strategy 2):** Reduced surface footprint but increased underground labour exposure, extended dismantling duration, temporary works complexity, and higher schedule uncertainty.
- **Burial in place (Strategy 3):** Avoids complex extraction but introduces long-term inspection, hydraulic transition, and lifecycle management concerns incompatible with a permanent strategic water asset.

Overall, the assessment confirmed that safety exposure and programme reliability outweigh marginal reductions in the required civil construction footprint.

Integration with Downstream Infrastructure

The selected TBM removal strategy at Baynesfield directly affects outlet structure sequencing and downstream construction logic. Timing of TBM breakthrough, dismantling operations, and component extraction must be coordinated with:

- Downstream concrete works;
- Hydraulic control structure installation;
- Bulkhead construction and tie-in; and
- Final hydraulic commissioning.

Misalignment between tunnelling completion and surface contractor activities can lead to redesign of outlet geometry, temporary works conflicts, restricted crane access, or inefficient double handling of structural elements. Early confirmation of the preferred TBM removal strategy therefore mitigates interface risk, reduces the likelihood of redesign, and ensures coherent sequencing between underground works and downstream civil construction.

Removal Options and MCA
To provide a structured and objective evaluation, a multi-criteria analysis was undertaken, assessing options derived from the three TBM removal strategies against five weighted criteria:

- Design and constructability;
- Financial implications;
- Social and environmental considerations;
- Programme impact; and
- Risk and uncertainty.

The weightings reflected programme certainty and safety exposure as primary evaluation considerations, recognising the disproportionate impact of removal delays in long-drive projects.

The MCA identified one of the options derived from Strategy 1, which incorporates an enlarged D&B outlet connecting tunnel with extension of the 2.6 m ID pipeline to the bulkhead interface, as the preferred solution. This option demonstrated the most balanced performance across constructability, cost efficiency, safety exposure reduction, environmental impact, and schedule reliability.

Programme and Risk Implications
Analysis indicates that inadequate planning of TBM removal can introduce disproportionate schedule risk relative to the relatively short duration of the removal operation itself. In long tunnels, project momentum, resource allocation, and contractual milestone achievements are often linked to TBM breakthrough completion. However, if TBM removal logistics are not properly integrated into the project design and construction planning, delays can occur due to limited shaft capacity, restricted lifting operations, or complex dismantling procedures. Such delays may affect demobilisation activities, delay subsequent construction works, and potentially extend the overall project programme. For this reason, TBM removal should not be treated as a final construction activity but rather as an integral design consideration influencing shaft sizing, tunnel alignment geometry, lifting capacity, and structural detailing from the early stages of project development. This approach reduces programme uncertainty and ensures that the transition from excavation to completion activities can occur without introducing unnecessary schedule risk.

Risk Management and Constructability Integration
Constructability was prioritised as a primary design driver rather than a secondary verification exercise. Logistics consideration, spatial coordination reviews, and maintenance accessibility studies were integrated into the preliminary design process.

Key construction risks identified include interruptions to the muck removal system, segment supply disruption, major TBM mechanical failure, and groundwater inflow events. Mitigation measures include incorporating system redundancy where feasible, implementing preventive maintenance strategies, and providing contingency access provisions to enable rapid intervention during critical events.

CONCLUSIONS

The uMWP-1 represents a technically demanding example of long-distance, small-diameter TBM tunnelling for bulk water conveyance. The combination of a 34 km tunnel length and a 3.5 m ID create a configuration in which logistics coordination, spatial constraints, and construction sequencing become primary determinants of programme certainty.

The paper shows that sustained productivity in long, small-diameter tunnels is governed largely by logistics efficiency rather than TBM bore cycle performance alone. Over long alignments, even minor inefficiencies in segment delivery, muck removal, or maintenance planning can accumulate into significant schedule impacts.

Tunnel diameter sensitivity analysis indicates that increasing the ID to 4.7 m would provide only modest production gains (approximately 5%) while increasing capital costs by approximately 20%. The 3.5 m diameter therefore remains technically and economically justified when supported by rail-based muck removal, cog-wheel segment delivery in steep access adits, integrated logistics planning, and preventive maintenance strategies.

The paper also highlights the importance of integrating TBM removal strategy during preliminary design. Early planning improves constructability, reduces confined-space risks, and enhances programme reliability. The multi-criteria assessment identified surface-based TBM disassembly as the most balanced solution.

Overall, the project demonstrates that constructability-driven design, integrated logistics planning, and early consideration of TBM removal are essential to achieving programme certainty in long water conveyance tunnels

ACKNOWLEDGEMENTS

The authors acknowledge the Gibb-Knight Piésold Joint Venture (GKP JV), the Trans-Caledon Tunnel Authority, the Department of Water and Sanitation, and uMngeni-uThukela Water for providing project data and operational insights, as well as their permission to publish this paper. The many discussions with and technical contributions by GKP JV colleagues working on this project are also gratefully acknowledged.

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Mehdi Nasiri
Geotechnical Tunnelling Engineer
Gibb-Knight Piésold Joint Venture

Mehdi Nasiri earned his Bachelor of Science (B.Sc.) in Mining Engineering in 1998 and his Master of Science (M.Sc.) in Rock Mechanics in 2001 from one of Iran's leading mining engineering universities. He began his career as a mining and geotechnical engineer with a consulting firm in Iran, where he worked for seven years. In 2005, his extensive experience as a senior rock mechanics engineer and project manager across mining and civil engineering projects led him to establish AZMA Rock and Tunnel Engineers, a consulting firm based in Tehran. As CEO, he managed a team of approximately twenty specialists for nine years. In 2014, Mehdi and his wife, also a mining engineer and rock mechanics specialist, relocated to South Africa to join a Johannesburg-based consulting company. He currently supports SRK Consulting on geotechnical and mining engineering projects worldwide and also serves as a Geotechnical Tunnelling Engineer for the Gibb–Knight Piésold Joint Venture. Mehdi is a registered Professional Engineer (Pr.Eng.) with the Engineering Council of South Africa (ECSA) and a member of the Southern African Institute of Mining and Metallurgy (SAIMM). He continues to apply his expertise in underground space design, slope stability, and geotechnical engineering across both mining and civil engineering sectors.