

Construction method evaluation for ventilation and surge shafts on the uMWP-1 water transfer tunnel project

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This paper presents an overview of the key considerations governing construction method selection for ventilation and surge shafts for the Phase 1 water transfer tunnel of the uMkhomazi Water Project (uMWP-1). The uMWP-1 project site is located between Impendle and Hopewell, south of Pietermaritzburg in KwaZulu-Natal, and includes two ventilation shafts (1.5 m finished diameter, with depths of 125 m and 190 m, respectively) and one surge shaft (5.0 m finished diameter and 110 m deep), to be constructed in Karoo mudrocks and dolerites.

Geotechnical characterisation of the shaft sites was undertaken using borehole logging, downhole wireline geophysical surveys, and laboratory testing. These investigations identified sequences of weathered and fresh shale, dolerite intrusions, structurally disturbed intervals, and variable groundwater conditions. Anticipated rock mass behaviour, together with structural data evaluated using Rocscience Dips and Unwedge, informed the evaluation of design risks and preliminary ground support requirements for shaft stability.

The paper compares shaft sinking methods, including reverse circulation (RC) drilling as the preferred method for the ventilation shafts, and alternative methods for the larger surge shaft. The discussion focuses on the suitability of these methods relative to anticipated ground conditions, groundwater, working footprint, cost and programme implications, and site-specific environmental constraints, particularly at the outlet end of the uMWP-1 transfer tunnel. Relevant precedent experience and comparable case studies are referenced where applicable.

The paper also considers the influence of logistical constraints, anticipated water inflows, and variable surface conditions on construction planning and risk management. Practical aspects of ground support, groundwater management, and spoil handling are discussed. The paper concludes with recommendations on method selection and risk mitigation, informed by the current investigations, precedent experience from similar shaft projects, and ongoing design of the uMWP-1 works.

INTRODUCTION

Project Context

The uMWP-1 project is being implemented by the Trans-Caledon Tunnel Authority (TCTA) to augment the uMngeni Water Supply System in KwaZulu-Natal with water from the uMkhomazi River. This paper focuses on the water conveyance infrastructure component, which comprises a 34 km water transfer tunnel with associated intake and outlet works. The project site is located between Impendle and Hopewell, south of Pietermaritzburg in KwaZulu-Natal.

The water transfer tunnel will be constructed using two tunnel boring machines (TBMs) operating from separate access adits to enable concurrent excavation. TBM Drive 1 extends 16.4 km from the uMkhomazi intake to the Midway access point, while TBM Drive 2 extends 16.1 km from Midway to the Baynesfield outlet. To support these extended TBM drives, the project requires three vertical shafts: two ventilation shafts to supply fresh air during construction, and one surge shaft to provide hydraulic transient control during operation of the uMWP-1 scheme. The shafts present particular design challenges due to their varying scales, the variable Karoo geology encountered, and environmental constraints affecting construction sequencing.

Table I summarizes the key parameters of the three vertical shafts. The ventilation shafts (VS1 and VS2) are relatively small with 2.0 m excavated diameter (1.5 m finished internal diameter) and extend to depths of 125 m and 190 m respectively, presenting opportunities for alternative construction methods not commonly employed in South African civil engineering practice. The surge shaft (SS), while shallower at 110 m depth, has a larger 6.0 m excavated diameter (5.0 m finished internal diameter) and must function as a permanent hydraulic structure during its design life. Additionally, the surge shaft location within a known breeding habitat area of the highly endangered blue swallow (*Hirundo atrocaerulea*) restricts construction to a six-month annual window (September to February), and places additional emphasis on programme-efficient method selection.

Table I: Shaft specifications and functions

Shaft	Location	Depth (m)	Excavated / Finished Internal Diameter (m)	Primary Function	Key Challenges
VS1	CH 6+720	125	2.0 / 1.5	Fresh air supply to the TBM1 drive during tunnel boring	Fractured zones, dolerite/shale mixed face
VS2	CH 27+556	190	2.0 / 1.5	Fresh air supply to the TBM2 drive during tunnel boring	6 m fault zone with expected high groundwater inflow rates
SS	CH 33+592	110	6.0 / 5.0	Surge pressure control during scheme operation	17 m weak fractured zone, blue swallow 6-month construction window

Design Approach & Scope

The design approach for the uMWP-1 shafts integrates geotechnical baseline reporting principles, as established by ASCE (American Society of Civil Engineers, 2022) and FIDIC for underground works, with the systematic construction method selection process outlined in ITACET Working Group 23 Guidelines for Shafts. The Geotechnical Baseline Report (GBR) (GKP Joint Venture, 2026) establishes anticipated ground conditions and defines contractual baselines for risk allocation, while the ITACET WG23 framework provides a structured methodology for evaluating alternative construction methods against project-specific constraints including ground conditions, geometry, programme, and environmental requirements.

The ventilation shafts serve primarily as construction infrastructure to support TBM operations, providing fresh air supply and emergency egress during the three to five-year tunnelling period. Although these shafts will form part of the permanent works for operational ventilation and maintenance access, their design criteria are governed by construction requirements rather than complex operational loading. Accordingly, the shaft design establishes baseline ground conditions and minimum dimensional requirements, including the 1.5 m finished internal diameter and verticality tolerances, while the final construction method remains the contractor's responsibility based on the conditions encountered. This also includes the decision on whether competent rock intervals can remain unlined or whether permanent lining will be required throughout.

The surge shaft, by contrast, is a permanent hydraulic structure that must withstand operational surge pressures, external groundwater loading, and satisfy stringent impermeability requirements over its design life. Its design and construction are intrinsically linked to the method of shaft construction selected as it influences achievable excavation tolerances, support installation sequencing, liner installation methodology, and programme duration.

This paper addresses the geotechnical characterisation of all three shafts, including the investigation approach, structural analysis using Rocscience Dips (Rocscience Inc., 2026) and Unwedge (Rocscience Inc., 2026), and ground behaviour assessment using the Ground Behaviour Type (GBT) framework. Construction methods are evaluated in accordance with ITACET WG23 (ITACET Working Group 23, 2019) methodology: reverse circulation drilling for the small-diameter ventilation shafts and raise boring versus conventional shaft sinking for the larger surge shaft. The comparison considers ground conditions to be encountered, programme implications, environmental constraints, surface footprint, and cost, together with practical considerations including ground support, groundwater management, and spoil handling.

Finally, although the design aims to provide contractors with clear geotechnical baselines, defined performance requirements, and reference construction methods that support informed method selection, competitive pricing, and equitable allocation of geotechnical risk, it is important to note that at the time of writing this paper, geotechnical investigations for the uMWP-1 site had only just concluded. Work continues on the geotechnical characterisation of these shafts as the tender design of the uMWP-1 scheme is being finalised, and it follows that the geotechnical characterisations as presented in this paper, may differ from that eventually presented in tender documentation being prepared for the uMWP-1 scheme.

Geological Setting

The project area is underlain by sedimentary rocks of the Karoo Supergroup, specifically the Ecca Group. The formations encountered along the tunnel alignment comprise predominantly of argillaceous rocks, including shales, mudstones, and siltstones with subordinate sandstone units, representing deep-water to deltaic depositional environments.

The sedimentary sequence has been extensively intruded by dolerite. These intrusions occur as massive sub-horizontal sills, ranging from a few metres to several tens of metres in thickness, and as sub-vertical to steeply dipping dykes with widths typically from 0.5 m to 30 m. The dolerites are characteristically very hard (UCS 180-250 MPa), abrasive, and crystalline, contrasting with the weaker sedimentary rocks (UCS 50-120 MPa). Contact metamorphism adjacent to intrusions has locally indurated the sedimentary rocks, creating zones of enhanced strength and durability, though the intrusion margins are typically fractured and altered.

Regional structural trends comprise predominantly sub-horizontal sedimentary bedding with prominent sub-vertical joint sets. Geological lineaments identified through aerial photographic interpretation and satellite imagery exhibit three dominant orientations: east-southeast to west-northwest ($303^\circ \pm 30^\circ$), north to south ($060^\circ \pm 20^\circ$), and southwest to northeast ($005^\circ \pm 20^\circ$). These lineaments, manifested as faults, shear zones, fracture zones, and dolerite intrusions, exert primary control on rock mass quality and groundwater circulation.

The shaft locations exhibit this geological variability: VS1 consists predominantly of Volksrust Formation indurated shales with dolerite sills, VS2 is dominated by massive dolerite and a fault zone and faulted sedimentary strata, and the surge shaft is located entirely within Pietermaritzburg Formation shales and siltstones with a single dolerite sill. This geological diversity necessitates shaft-specific assessment of ground conditions and construction method suitability.

GEOTECHNICAL INVESTIGATIONS & CHARACTERISATION

Investigation Methodology

The geotechnical investigation for the uMWP-1 shafts comprised field investigations, downhole geophysical surveys, laboratory testing, and hydrogeological testing undertaken to characterise ground conditions and establish geotechnical baselines for design and contractual purposes.

A single HQ-size rotary core borehole was drilled at each shaft location, positioned at or near the planned shaft centreline and advanced beyond the anticipated shaft depth to characterise the rock mass below the shaft base and through the shaft-tunnel intersection zone. Borehole TTB7.6 at VS1 was drilled to 170.71 m, TTB27.5 at VS2 to 220.97 m, and TTB33.7 at the surge shaft to 110.44 m. Core recovery was generally excellent in fresh rock, but reduced locally within weathered, fractured, and faulted intervals, which were identified as potential construction challenges.

Wireline geophysical logging was completed in each borehole following drilling and included acoustic televiewer (ATV), optical televiewer (OTV), and natural gamma logging. These data supplemented the conventional core logging, supported lithological correlation, and provided the principal structural dataset for assessment in Rocscience Dips (Rocscience Inc., 2026) and Unwedge (Rocscience Inc., 2026).

Surface geophysical investigations, including electrical resistivity profiling, were also undertaken to provide context beyond the borehole locations, including overburden thickness, bedrock depth, lithological boundaries, dolerite intrusions, and potential water-bearing zones.

Laboratory testing was carried out on representative core samples to assess intact rock strength, density, porosity, abrasivity, durability, and swelling potential. Hydrogeological testing included packer testing, water level monitoring, and groundwater quality sampling. The hydraulic parameters derived from the packer testing were used to inform groundwater inflow estimates.

The geotechnical investigations carried out at shaft positions aimed to define characteristic geotechnical baseline conditions and provides a reasonable basis for design of the shafts; however, some uncertainty remains, specifically with respect to localised structural and hydrogeological variability.

ENVIRONMENTAL & SEASONAL CONSTRAINTS

Environmental constraints are particularly important at the surge shaft location, which lies approximately 500 m from a confirmed blue swallow nesting site. In accordance with the project Environmental Management Programme (EMPr), no construction activities are permitted during the breeding season from 1 March to 31 August. Construction is therefore restricted to an annual working window between 1 September and 28 February.

This seasonal constraint is a major driver in method selection for the surge shaft, as it places strong emphasis on programme efficiency, construction sequencing, and timely surface rehabilitation in addition to the geotechnical and hydraulic requirements of the shaft.

SHAFT STRATIGRAPHY & ROCK MASS CONDITIONS

The three shaft locations are located within different parts of the Karoo sequence and therefore exhibit materially variable ground conditions. This will influence anticipated excavation behaviour, support requirements, groundwater risk, and ultimately the suitability of alternative construction methods. A simplified summary of the stratigraphy encountered in the investigation boreholes drilled at each of the shaft locations is presented in Table II.

Table II: Comparative shaft stratigraphy and geotechnical conditions

Zone	Depth (m)	VS1 (Volksrust Formation)	VS2 (Dolerite - dominated)	SS (Pietermaritzburg Formation)
Overburden	0-20	17 m residual dolerite with corestones	1.7 m thin hillwash	0.3 m topsoil over 23 m weathered shale (R1-R2) with sample loss at 17-18 m
Upper section	20-50	Dolerite sill (17-23 m, R5), Volksrust shale (R4, RQD 77-90%)	Fresh massive dolerite (R6, RQD 85-100%)	Dolerite sill (23-41 m, R5), then shale (R3)
Middle section	50-100	Volksrust shale, RQD with variable, fractured zones at 28-29 m (RQD 0%) and 42-44 m (broken core); dolerite sill at 46-48 m	Fresh dolerite continues	Critical Zone 5 (56-73 m) weak shale (R2), approximately 21 fractures/m, incl. approx. 10 m of extremely fractured rock
Lower section	>100 to shaft bottom	Volksrust shale with RQD 37% near the tunnel intersection	Faulted sedimentary strata (96-123 m) containing a 6 m wide fault zone intersection at 117-123 m (RQD 15-30%), underlain by dolerite	Fresh shale (R3)

Ventilation Shaft 1 (TTB7.6): Indurated shale with thin dolerite sills

VS1 exhibits the most uniform stratigraphy of the three shafts. It comprises predominantly of Volksrust Formation indurated shale (strong, R4) interbedded with two dolerite sills at shallow depth (17-23 m and 46-48 m). The upper 17.1 m of residual dolerite overburden, including corestones will require casing through the superficial zone during shaft construction.

Rock mass quality indicates good to fair quality throughout most of the shaft depth. Three localised fractured zones represent potential construction challenges: a 0.6 m highly fractured interval at 28-29 m depth, a 2.2 m water-bearing broken zone at 42-44 m that required grouting during borehole drilling, and a 2.5 m fractured interval at 118-120 m approaching the tunnel intersection. These zones are anticipated to influence local stability and may reduce excavation rates and/or support demand.

Ventilation Shaft 2 (TTB27.5): Dolerite-dominated with fault zone

VS2 presents the highest overall rock mass quality of the three shafts. The shaft is dominated by fresh massive dolerite, representing approximately 85% of the shaft profile. The dolerite is generally very strong to extremely strong (R5-R6). RQD values of 85-100% indicating favourable excavation conditions through most of the shaft depth. The thin overburden (1.7 m) and minimal weathered zone (0-4 m) allow rapid establishment into competent bedrock.

The principal geotechnical challenge for VS2 is associated with faulted sedimentary strata between 96 m and 123 m depth, comprising of Pietermaritzburg Formation siltstone and mudstone. Within this interval, a 6 m wide fault zone intersection at 117-123 m depth is characterised by crushed to brecciated mudstone with very closely spaced jointing. The fault zone represents the main localised hazard for the shaft and is interpreted to be the principal contributor to the estimated groundwater inflow of approximately 11 L/s. Accordingly, VS2 is expected to remain relatively stable through most of the shaft depth, with support and groundwater control requirements likely to be concentrated within this faulted interval.

Surge Shaft (TTB33.7): Shale variable quality with extended weak zone

The surge shaft stratigraphy exhibits the greatest variability in rock strength and rock mass quality. The upper part of the profile comprises approximately 23 m of weathered Pietermaritzburg Formation shale, classified as very weak to weak (R1-R2), including intervals of completely weathered material with sample loss recorded during drilling at 17–18.3 m depth. These conditions indicate low intact strength, high weathering susceptibility, and elevated moisture sensitivity in the near-surface zone.

A competent dolerite sill occurs between 23 m and 41 m depth and is underlain by fresh to slightly weathered shale and siltstone. The critical interval for the surge shaft construction occurs between 56–73 m depth, where a 17 m interval of weak shale (R2 strength class) with very closely jointed fabric, averaging approximately 21 fractures per metre, and includes about 10 m cumulative thickness of extremely fractured rock. This extended zone of poor ground quality has significantly lower strength compared to the more competent shale (R3) above and below and represents the design-governing condition for both support requirements and construction method selection.

STRUCTURAL CHARACTERISATION & KINEMATIC ASSESSMENT

Structural assessment of the shaft excavations was based primarily on acoustic televiewer (ATV) and optical televiewer (OTV) data collected in the investigation boreholes. These surveys provided continuous discontinuity orientation data and were used to identify the principal structural sets at each shaft location. Field observations of bedding and lamination were used to confirm the broader geological fabric and to compare surface observations with the downhole televiewer-derived data.

The discontinuity data were analysed in Rocscience Dips to define the principal structural sets and to assess their orientation relative to the planned shaft excavations. The purpose of the analysis was to determine whether the observed discontinuities could contribute to structurally controlled instability, including sidewall block release, local wedge formation, and ravelling within weaker intervals. Rather than predicting exact failure volumes, the analysis was used as a screening tool to identify the structural conditions most likely to influence excavation behaviour, support requirements, and construction risk. This is consistent with the broader use of structural data in the paper to inform geotechnical risk assessment and construction method selection.

The interpreted structural framework across the three shaft locations is characterised by sub-horizontal to gently inclined sedimentary fabric, together with prominent steeply dipping jointing, consistent with the regional structural pattern identified from borehole televiewer data and surface geological observations. At VS1, these structures are expected to contribute mainly to local block release and ravelling within fractured shale and dolerite contact zones. At VS2, the structural regime is dominated by generally competent dolerite, but includes localised faulted sedimentary strata and a 6 m wide fault zone intersection that is expected to control the principal interval of structurally influenced instability and groundwater ingress. In the surge shaft, bedding-parallel weakness combined with closely spaced jointing within the weaker shale interval is expected to promote sustained loosening, local overbreak, and increased support demand. The structural assessment therefore confirms that, although all three shafts are influenced by similar regional discontinuity families, the engineering significance of those structures differs materially by shaft and depth interval.

The structural interpretation is particularly important in the critical intervals identified in the boreholes, including the fractured zones in VS1, the faulted interval in VS2, and the extended weak shale zone in the surge shaft. In these areas, the orientation and persistence of discontinuities may locally reduce stability and increase the need for support, groundwater control, or more conservative construction sequencing, refer to Table III below.

Table III: Summary of principal structural features and design implications

Shaft	Principal structural framework	Design implication
VS1	Sedimentary fabric with sub-horizontal to gently inclined bedding and steeply dipping jointing; localised fractured zones at lithological contacts	Localised structurally controlled instability is anticipated, mainly as block release and ravelling in fractured intervals
VS2	Predominantly competent dolerite containing steep discontinuity sets, with localised faulted sedimentary strata and a 6 m wide fault zone intersection	Structural risk is concentrated within the faulted interval, where instability and groundwater inflow are expected to be locally elevated
Surge shaft	Bedding-dominated shale/siltstone sequence with steep jointing and an extended weak, closely fractured shale interval	Structural conditions are expected to promote more sustained loosening and support demand than in the ventilation shafts

At the shaft-tunnel intersections, the interpreted structural sets may be assessed further using Unwedge (Rocscience Inc., 2026) to evaluate the potential for removable wedges under the more complex three-dimensional excavation geometry. This is particularly relevant for the surge shaft, given the larger intersection size and the greater potential for local wedge instability. Detailed Unwedge assessment is ongoing and will be used to refine intersection-scale support requirements during detailed design.

HYDROGEOLOGICAL CHARACTERISATION

The hydrogeological setting of the project area is characterized by low primary porosity and permeability within the argillaceous rocks of the Ecca Group, with groundwater occurrence and flow governed by secondary fracture networks. Groundwater is therefore expected to occur primarily in joints, bedding planes, lithological contacts, and fault zones. The dolerite intrusions may act both as relatively low-permeability barriers within massive sill and dyke interiors and preferential flow paths along fractured intrusion margins and contact zones.

Groundwater levels in the tunnel exploration boreholes indicate that the water table generally follows topography, ranging from approximately 95 m below ground level beneath topographic highs to 6 m below ground level in valley bottoms. At the shaft locations, conservative design groundwater levels correspond to hydraulic heads of approximately 123 m at the base of VS1, 186 m at the base of VS2, and 75 m at the base of the surge shaft. These values are considered conservative for design purposes and assume groundwater levels at or near ground surface. Preliminary monitoring indicates limited seasonal fluctuation, although ongoing monitoring will further refine the baseline understanding of recharge response.

As an initial indication, groundwater inflow rates to the shafts were estimated using the Jacob-Lohman equation for radial flow to a vertical cylinder. These inflow estimates were based on hydraulic conductivity values derived from packer testing, estimated hydraulic heads, and shaft geometry. Table IV summarizes the anticipated inflow rates. At the time of writing, transient groundwater modelling was ongoing to further refine these preliminary estimates.

Table IV: Expected groundwater inflows

Shaft	Depth (m)	Shaft Radius (m)	Hydraulic Head (m)	Hydraulic Conductivity, K (m/day)	Estimated Inflow (L/s)	Critical inflow zones
VS1	125	0.85	123	0.03	1.2	Fractured zones at 42 to 44 m
VS2	190	0.85	186	0.4 (fault zone)	11.0	Fault zone at 117 to 123 m
SS	110	3.0	107	0.03	1.2	Zone 5 at 56 to 73 m

GROUND BEHAVIOUR ASSESSMENT & DESIGN RISKS

Ground Behaviour Type Framework

The Ground Behaviour Type (GBT) framework provides a systematic basis for evaluating how the rock mass is expected to respond to excavation-induced stress relief, exposure, and groundwater changes, independent of the construction method used. Unlike conventional rock mass classification systems such as RMR (Bieniawski, 1989) or Q (Barton, et al., 1974) which describe rock mass quality, the GBT framework focuses on anticipated instability mechanisms and excavation behaviour. This distinction is critical for shaft design, where excavations in rock of good quality may behave unfavourably if structurally controlled failure mechanisms are present, while an excavation in poorer quality rock may remain stable in the absence of specific ground behaviours resulting in failure.

For the uMWP-1 shafts, GBT ratings were assigned using an integration of multiple data sources including borehole logging (RQD, fracture frequency, weathering grade, lithology rock mass quality indicators), structural assessment in Dips (Rocscience Inc., 2026), laboratory testing (strength, durability), hydraulic testing (permeability, inflow potential), and precedent experience from similar shaft construction projects in comparable geological settings, such as the Lesotho Highlands Water Project Phase 1B - Mohale Tunnel (Lesotho Highlands Development Authority, 2004) (Boniface, 2000). Each GBT was assigned a likelihood rating from 1 (almost impossible) to 5 (very likely), reflecting the likelihood of encountering that particular behaviour being encountered during shaft excavation.

The GBT assessment serves three main purposes in the current study. First, it identifies the dominant ground control mechanisms likely to govern shaft behaviour. Second, it supports construction method selection by highlighting behaviours that may be more readily managed by particular sinking methods. Third, it establishes the baseline interpretation of anticipated ground conditions for design purposes.

Anticipated Ground Behaviours in Shaft Excavations in Rock

Table V summarises the GBT assessment for excavations in rock in the respective shafts and includes only those behaviours rated 3 (unlikely but possible) or higher. Behaviours rated 1 (almost impossible) or 2 (very unlikely) were excluded from this summary as these are not expected to materially influence design or construction.

Several key patterns emerge from this GBT assessment. All three shafts exhibit a similar baseline potential for structurally controlled behaviour, with kinematic instability, blockiness and structural drilling-related instability all rated as likely. This is consistent with the regional jointing pattern within the Karoo sedimentary rocks and dolerite intrusions and precedent experience during the excavation/sinking of shafts in Karoo strata, and supports the importance of structural assessment in evaluating shaft stability.

The most adverse ground behaviours during shaft excavation is expected in VS2, in fault- and shear zones encountered in Borehole TTB27.5, and associated high groundwater ingress, all rated as very likely. These behaviours are associated mainly with faulted sedimentary strata between approximately 117 m and 123 m depth and a 6 m wide fault zone intersection, where broken ground, reduced strength, increased permeability, and lithological contrasts were encountered in Borehole TTB27.5. Although this

interval represents only a small proportion of the total shaft depth, it is likely to constitute the main construction risk for VS2.

In the larger diameter surge shaft, poorer ground conditions are more distributed over the full depth of the shaft. Ravelling, poor durability, and structurally controlled loosening are all assessed as likely, particularly within the weak shale interval between 56 m and 73 m depth and the upper weathered shale profile. This extended zone of weaker rock is expected to have a greater influence on support demand, excavation sequencing, and construction method suitability than a shorter isolated fault zone.

Table V: Anticipated Ground Behaviour Types for the uMWP-1 shafts

GBT	Ground Behaviour / Failure Mechanism	VS1	VS2	SS	Key Design Consideration
GBT 1	Stable ground	4	4	4	Majority of depth, limited support required
GBT 2	Local/minor geological overbreak	4	4	4	Excavation tolerance and local support
GBT 3	Kinematic instability (sidewall wedges and/or key blocks)	4	4	4	Structural control and local support requirements
GBT 5	Blocky to very blocky ground	4	4	4	Relevant in dolerite sections, reduced support spacing
GBT 6	Ravelling in friable ground	4	3	4	Critical in fractured intervals and weak shale zones, particularly for Surge Zone 5
GBT 8	Shallow-seated rock mass shearing & yielding	3	4	3	Minor deformation potential in weaker intervals, VS2 fault zone
GBT 15	Poor durability(slaking)	4	2	4	Argillaceous rocks require limited exposure time
GBT 17	Wide fault/shear zones	3	5	4	VS2 fault zone is the dominant localised hazard, at 117-123 m
GBT 18 (boring)	Very hard, massive rock	n/a	n/a	5	High drilling resistance and higher cutter wear, especially in dolerite
GBT 19 (boring)	Structurally controlled blockiness in very hard rock	n/a	n/a	5	Potential breakout and local instability during advance
GBT 21	High groundwater ingress / inflow	3	5	4	Potentially significant inflows anticipated in the VS2 fault zone

Notes: Rating scale: 5 = Very likely, 4 = Likely, 3 = Unlikely but possible, 2 = Very unlikely, 1 = Almost impossible

Key Design Considerations

Although several behaviours are rated as likely, not all are equally significant in terms of design and method selection. The most important behaviours for the present study are structurally controlled instability, ravelling in weak ground, mixed-face conditions, faulted ground, and groundwater ingress.

Structurally controlled instability is anticipated in all three shafts and is associated with discontinuity orientation, persistence, and block geometry. Its practical significance lies in the potential for local block release, wedge formation, and overbreak, particularly where excavation is unsupported or support installation is delayed. This behaviour is therefore an important consideration in assessing construction methods which provide immediate confinement, allow rapid support installation and/or limit exposure such that the stand-up time of the excavation is sufficient to allow safe installation of primary support before shaft excavation is advanced further.

Ravelling and progressive loosening are most relevant to the fractured intervals in VS1 and, more significantly, to the extended weak shale interval in the surge shaft. In these zones, weak intact rock, close joint spacing, and poor interlock reduce stand-up time and increase the likelihood of progressive

instability if exposure is prolonged. These conditions favour construction methods that permit early stabilisation and careful sequencing.

The fault zone and associated faulted sedimentary strata in VS2 introduce sharp contrasts in strength, structure, permeability, and excavation response over short distances. This combination of broken rock, groundwater ingress, and variable material in the fault zone, introduces potential construction risk over this depth interval.

Poor durability is most relevant in the argillaceous units of VS1 and in the surge shaft, where slaking and moisture sensitivity may lead to time-dependent deterioration of any exposed excavation surfaces. From a design perspective, this requires construction sequencing and support measures that minimise exposure time and prevent deterioration following excavation.

Overall, the GBT assessment confirms that while the respective shaft excavations all exhibit a baseline likelihood of structurally controlled behaviour, the dominant risks differ in character and concentration: VS1 is influenced mainly by localised fractured intervals, VS2 by a water-bearing fault zone within otherwise competent dolerite, and the surge shaft by a more extended weak and non-durable shale interval. These differences are central to both support planning and construction method selection.

SHAFT CONSTRUCTION METHOD EVALUATION

This construction method evaluation was undertaken in the context of the key geotechnical, hydrogeological, ground support, and programme risks identified for the respective shafts. Furthermore, for the 2.0 m excavated diameter ventilation shafts, the evaluation focused on methods suited to excavate such small diameter shafts. For the surge shaft with 6.0 m excavated diameter, the assessment considered methods appropriate for larger-diameter shaft construction, with due regard to the weak shale interval and the seasonal blue swallow environmental constraint.

Excavation of Shaft Collars in Soft Overburden

The upper sections of both ventilation shafts will extend through soft overburden (transported material, residual / completely weathered rock). The ventilation shaft collars will be excavated through these soft and weak materials making use of special construction techniques such as, for example, installation of secant pile walls, or using telescopic RC drilling techniques, with the most optimal method to be selected during detailed design.

Shaft Excavations in Rock - Ventilation Shafts

For the ventilation shafts, three principal construction methods were considered, namely: (1) reverse circulation (RC) drilling, (2) raise boring, and (3) conventional shaft sinking. Each method offers distinct advantages and limitations relative to the anticipated ground conditions, programme requirements, and cost:

- **Reverse circulation (RC) drilling**
RC drilling employs a surface-mounted rotary rig with dual-wall drill pipe, allowing continuous excavation while drilling fluid transports cuttings to surface. The method is well suited to small-diameter shafts and offers particular advantages in deep shaft excavation where minimising personnel exposure at depth, reducing surface infrastructure, and maintaining efficient advance rates are important. In addition, the drilling fluid column provides hydrostatic confinement during excavation, which may assist in managing local instability in fractured or blocky intervals.
- **Raise boring**
Raise boring a 2.0 m diameter ventilation shaft is technically feasible for the ventilation shafts. However, raise boring requires access to the shaft bottom which introduces practical and programme constraints given that (i) bottom access will only be established once the TBM has been driven beyond the ventilation shaft position, and (ii) raise boring the shaft then, will require tunnel boring works to stop for as long as raise boring and shaft support / final lining works continue.

- Conventional shaft sinking
Conventional shaft sinking remains a proven and flexible method, particularly where local support installation is critical. However, 1.5 m finished diameter shafts are too small to excavate using blind sink methods, and the excavated shaft diameter will therefore have to be increased to say minimum 3 to 3.5 m to make this method of excavation feasible. The associated shaft construction costs will increase, and production rates will also be substantially lower than for the RC drilling alternative.

Based on this preliminary evaluation, RC drilling was selected as the preferred construction method for the uMWP-1 ventilation shafts in terms of programme efficiency, safety, limited surface footprint requirements, and suitability for the anticipated ground conditions. The method is used internationally to excavate ventilation and service shafts to substantial depth within a relatively small operational footprint. Where soft overburden or weak, friable material is encountered, RC drilling is used with telescopic casing to advance shaft excavations through such loose and/or unconsolidated materials to ensure hole stability. The method also offers environmental and logistical advantages, as the surface footprint is significantly smaller than that required for conventional shaft sinking infrastructure. This is beneficial in the rural project setting and reduces the extent of temporary site disturbance.

In VS1, fractured and water-bearing depth intervals may reduce advance rates locally but are unlikely to compromise overall method suitability. In VS2, the main challenge will be the shaft intersection with the faulted sedimentary strata at 117–123 m depth; however, given that this represents a relatively short section within an otherwise competent dolerite profile, it is considered manageable within an RC drilling approach, subject to appropriate contingency measures and contractor methodology.

Shaft Excavations in Rock - Surge Shaft

RC drilling has been used to excavate shafts of 4.5 m diameter or smaller, and the method evaluation for the 6.0 m excavated diameter surge shaft therefore focused on other feasible alternatives, namely: (1) conventional shaft sinking without a muck pass, (2) raise boring, and (3) conventional shaft sinking with a pre-RC drilled muck pass.

The surge shaft intersects the transfer tunnel some 300 m upstream of the Baynesfield tunnel outlet and it follows that access to the shaft bottom is required before raise boring can commence. This access constraint is particularly important when considered together with the blue swallow environmental restriction, which limits construction at the surge shaft site to a six-month annual window between September and February.

From a geotechnical perspective, the principal challenge is the extended weak, fractured shale interval between approximately 56 m and 73 m depth. This zone is expected to require sustained ground control measures to manage raveling, structurally controlled loosening, and potential time-dependent degradation of weak argillaceous material. The larger shaft diameter also increases the significance of Conventional shaft sinking without a muck pass

- Conventional shaft sinking without a muck pass

Conventional shaft sinking by drill and blast excavation is considered the reference construction method for the surge shaft at this stage. This reflects its greater flexibility for managing the anticipated weak ground conditions and its independence from prior tunnel access to the shaft bottom. The method allows excavation to proceed in controlled rounds, with direct observation of the exposed ground and installation of sidewall support as required. This is particularly advantageous through the weak fractured shale interval, where support requirements may need to be adjusted in response to actual ground conditions encountered during shaft sinking.

A further advantage is that shaft sinking from surface does not depend on completion of the tunnel to shaft base level before shaft excavation can commence. This makes it the more robust baseline method because it is less constrained by tunnel sequencing and provides the greatest flexibility for active ground control. Construction of the surge shaft is not on the overall critical path and the slower shaft sinking rate (when compared to raise boring) and potential programme risk as a result of the environmentally restricted construction window, is offset by the time available to complete this part of the works before TBM2 arrives at the Baynesfield outlet portal.

- Raise boring

Raise boring remains a technically feasible alternative for excavation of the surge shaft and theoretically may show a reduced shaft excavation duration when considering typical raise boring rates. It will also minimise the surface footprint at the shaft location which is an important environmental consideration. However, raise boring is subject to two limitations, the first being the need for prior access to the shaft bottom, and the second being the potential for significant overbreak in highly jointed/fractured dolerite intervals, and in the weak fractured shale interval in the surge shaft excavation. Other issues include the potential for pilot hole deviation, reaming difficulties in the hard, highly jointed dolerite, and difficulties installing sidewall support in sections where extensive overbreak occurred.

Accordingly, raise boring is considered an alternative should the contractor be able to demonstrate that constraints associated with shaft-bottom access requirements, construction sequence, and geotechnical risks can be satisfactorily managed.

- Conventional shaft sinking with pre-RC drilled muck pass

A variant on the above shaft excavation methods is combining a conventional shaft sinking operation with a pre-RC drilled muck pass. This offers similar benefits to that offered by a conventional shaft sinking operation from surface, but with easier muck and groundwater seepage handling via the muck pass. As for raise drilling, however, the muck pass can only be employed once access has been established to the shaft bottom. It therefore suffers from the same programme constraints as the raise boring option.

The below construction method comparison for the surge shaft therefore reflects a trade-off between geotechnical flexibility and programme efficiency. Conventional shaft sinking provides the more conservative and geotechnically robust shaft excavation method because it allows direct management of the weak ground interval and does not depend on prior tunnel access to the shaft bottom. Raise boring may offer shaft excavation rate and surface footprint advantages, particularly in relation to the restricted environmental construction window, but its suitability remains conditional on shaft bottom access, construction sequence, and management of risks associated with highly jointed and fractured ground, and weak ground.

The comparative weighting exercise (see Table VII) indicates the highest nominal score for conventional shaft sinking, mainly because of programme advantages and better control provided by incremental excavation and timely ground support installation. For baseline design, conventional shaft sinking without a muck pass was therefore selected as the reference method.

That said, shaft sinking with a muck pass, and raise boring remain viable alternatives that may be preferred based on contractor-specific sequencing or programme considerations, provided that shaft bottom access and associated programme constraints and geotechnical risks are appropriately addressed.

Table I: Surge shaft method comparison matrix

Criterion	Weight	Conventional Shaft Sinking	Raise Boring	Conventional Shaft Sinking with pre-RC Drilled Muck Pass	Comment
Programme	35%	Slower excavation rate, but can commence on appointment, earlier shaft construction completion date	Faster, but subject to shaft bottom access first being established, effectively resulting in a later shaft construction completion date	Faster excavation rate than shaft sinking without muck pass, but subject to shaft bottom access first being established - as for raise boring	The requirement for earlier project delivery places greater emphasis on overall programme and schedule efficiencies
Ground control	25%	Excellent, sidewall support installed during excavation	Moderate, sidewall support installation post-shaft excavation	As for shaft sinking without a muck pass, albeit sidewall support can be installed earlier in an excavation lift due to easier mucking and shaft dewatering.	Conventional shaft sinking offers better control and greater flexibility in highly jointed dolerite and weak shale
Cost	20%	Higher	Lower	Similar to shaft sinking without a muck pass, with the additional cost of drilling the muck pass being offset by easier mucking and shaft dewatering operations	Raise boring costs are typically 30 to 40% that of conventional shaft sinking, due to faster, less labour-intensive and safer mechanised operations
Surface footprint	10%	Larger	Smaller	Smaller than for shaft sinking without a muck pass, but larger than for a raise boring operation	Important environmentally constrained site
Safety	10%	Personnel working at depth in the shaft bottom	No personnel at depth during excavation; however, muck requires loadout at the shaft bottom during raise boring	Personnel working at depth in the shaft bottom AND muck requires loadout at the shaft bottom during shaft sinking operations	Raise boring offers a safety advantage
Weighted score:		80/100	75/100	79.5	

SURFACE CONDITIONS & WORKING AREAS

Surface conditions at the three shaft locations differ in terms of access, topography, land use, and available working area, and these factors influence site access, construction planning, temporary works layouts, spoil handling, and rehabilitation requirements.

VS1 is located at approximately 1,123 mamsl and is accessed via a provincial gravel road. The site is situated on gently sloping grassland. Spoil disposal is planned at a designated site approximately 2 km away.

VS2 is located at approximately 1,245 mamsl near the bottom of a relatively deep valley associated with erosion along the lineament of a local thrust fault. Access is provided via approximately 8 km of farm and plantation roads from the Baynesfield tunnel outlet portal. The site is situated within commercial forestry land, and shaft construction will require localised tree clearing and subsequent rehabilitation.

The surge shaft is located at Baynesfield at approximately 975 mamsl near the top of a small hill about 300 m upstream of the tunnel outlet portal. Access is via about 3 km of farm road from the Baynesfield tunnel outlet portal. The site lies within an active agricultural field and construction will require temporary suspension of crop production and subsequent rehabilitation. The natural veld immediately adjacent to the surge shaft location is considered a blue swallow habitat and associated environmental constraints apply. Eskom overhead powerlines are located approximately 200 m north of the site, but no direct conflict has been identified.

The anticipated working areas are relatively modest for the two ventilation shafts, particularly if constructed by RC drilling, whereas the surge shaft requires a larger construction footprint, especially if conventional shaft sinking is adopted. These differences are relevant to method selection, surface disturbance, and rehabilitation planning.

Table VII: Summary of surface conditions and working area requirements

Shaft/Method	Reference Method	Estimated Footprint (ha)	Estimated Laydown Area (m ²)	Approximate Spoil Volume (m ³)	Principal Rehabilitation Requirement
VS1	RC drilling	0.3	500	250	Topsoil replacement and grassland reinstatement
VS2	RC drilling	0.3	500	430	Rehabilitation and re-establishment of forestry area
SS	Conventional shaft sinking	1.2	1,500	3,100	More extensive restoration of agricultural land due to larger surface working area
	Raise boring	0.5	1,200	3,100	Restoration of agricultural land
	Shaft sinking with muck pass	0.9	1,500	3,100	Similar to that for conventional shaft sinking without a muck pass

PRACTICAL DESIGN & CONSTRUCTION CONSIDERATIONS

Ground Support Strategy & Final Lining

Ground support and final lining requirements were considered at a preliminary level in relation to anticipated ground conditions, shaft excavation method, and long-term function of each shaft.

For the ventilation shafts, where RC drilling is adopted as the reference method, primary stabilisation during excavation will be provided by the drilling fluid/mud column, and by the steel casing to be installed as the final lining.

The surge shaft, as a permanent hydraulic structure, requires installation of permanent ground support (bolts, mesh and shotcrete) during/after shaft excavation followed by installation of a permanent final lining over its full depth irrespective of the construction method adopted. The permanent ground

support in the shaft sidewalls, will be designed to carry all rock loads with an adequate Factor of Safety, while the cast-in-situ reinforced concrete final lining, approximately 500 mm thick, will be designed to resist external groundwater pressures under operational conditions. The sidewall support design, and final lining design including reinforcement, as well as shaft-tunnel intersection layout and detailing, will be developed during detailed design.

In the case of a raise bored surge shaft, no support can be installed during raise boring and the permanent ground support required (bolts, mesh and shotcrete), will have to be installed working top-down after raise boring work has been completed.

In conventional shaft sinking with/without a muck pass, permanent ground support (bolts, mesh and shotcrete) will be installed progressively as shaft excavation advances. This is particularly advantageous within the highly jointed/fractured dolerite, and in the weak fractured shale, where more active ground control will be required at an early stage in the excavation and support cycle. In practice, the larger support demand in the surge shaft is one of the factors favouring conventional shaft sinking as the more robust baseline method.

Groundwater Management

Groundwater management requirements will vary according to the selected shaft sinking method, but in all cases water handling, temporary storage, and water quality control will form part of the construction planning.

For RC drilling, the primary requirement is management of the drilling fluid circuit, including settlement capacity for cuttings removal, recirculation of clarified water, and disposal of dried solids.

For conventional shaft sinking without a muck pass, groundwater inflows will be managed by collection in shaft sumps and pumping to surface, with temporary settlement and treatment where required. For raise boring and for shaft sinking with a muck pass, water inflows will be handled at shaft bottom level.

In the surge shaft, areas of groundwater inflow (i.e., wet areas, water-bearing joints and fissures, more permeable strata) will require local treatment and / or installation of water control measures, during excavation and support for conventional shaft sinking, or post-excavation during installation of ground support in a raise bored shaft. Such measures may include installation of cusped drainage sheets before meshing and shotcreting, drilling of drainage holes, installation of drain pipes, consolidation grouting, etc., as may be appropriate.

Groundwater quality also requires consideration. The project investigations indicate the potential for acidic water and elevated dissolved metals associated with pyritic shale, particularly within the Pietermaritzburg Formation. Temporary treatment measures such as neutralisation and settlement may therefore be required prior to discharge, subject to the applicable Water Use Licence conditions

LOGISTICAL & ACCESS CONSIDERATIONS

Logistical requirements differ materially between the shaft construction methods and are therefore relevant to the overall constructability assessment.

For the ventilation shafts, RC drilling offers the simplest mobilisation and the smallest surface footprint. The method requires a drill rig, mud pumps, surface tanks / sumps, and associated service infrastructure, with comparatively limited site establishment requirements. This is advantageous at the relatively constrained ventilation shaft construction sites and reduces temporary disturbance and associated rehabilitation requirements.

For the surge shaft, raise boring requires mobilisation of specialist large-capacity equipment, with higher demands in terms of transportation logistics, longer lead times, and more extensive site establishment than the ventilation shaft works. Conventional shaft sinking, while based on equipment and skills that are more readily available locally, requires the largest surface infrastructure footprint owing to the need for a headgear, winding arrangements, ventilation, mucking systems, and associated temporary works. It also results in the longest site establishment period of the considered methods.

Site access at all three shaft locations is generally feasible using existing farm or forestry roads, although local upgrades along access routes will be required. These access requirements are of particular importance at the surge shaft because road works and site establishment must be planned in accordance with the blue swallow environmental constraints. Temporary power, water supply, and communications will also be required at each site, but no exceptional service constraints have been identified in this regard.

Overall, the logistical and access considerations reinforce the broader method comparison: RC drilling is well suited to the ventilation shafts because of its limited footprint and relatively simple mobilisation, while surge shaft construction involves a trade-off between the smaller operational footprint of raise boring and the greater flexibility, but larger infrastructure demand, associated with conventional shaft sinking.

CONCLUSIONS & RECOMMENDATIONS

The assessment confirms that shaft construction method selection for uMWP-1 is governed by a combination of shaft geometry, ground behaviour, groundwater conditions, support demand, and programme constraints, rather than by depth alone.

1. Scale is the primary discriminator in method selection

For the 1.5 m diameter ventilation shafts, RC drilling provides the most favourable balance of speed, safety, limited surface footprint, and programme certainty. For the surge shaft with 6.0 m excavated diameter, larger-diameter shaft excavation methods are required, and the selection becomes a trade-off in terms of geotechnical flexibility and overall programme efficiency.

2. Ground behaviour is a critical design input

The geotechnical evaluation shows that structurally controlled instability is relevant to all three shafts, while the dominant local challenges differ between them. Shaft stability at VS2 will be governed by a short faulted and water-bearing interval at approximately 117-123 m depth, whereas the surge shaft is governed by a more extended weak fractured shale interval between approximately 56 m and 73 m depth as well as a highly jointed / fractured interval in dolerite. These differences directly influence both support demand and method suitability.

3. Programme constraints are particularly significant for the surge shaft

The blue swallow environmental restriction, which limits construction to a six-month annual working window at the Baynesfield outlet, places strong emphasis on programme efficiency for the surge shaft. However, the requirement for prior shaft-base access in a raise boring arrangement, and shaft intersections with weak and / or highly jointed ground, means that conventional shaft sinking provides the more robust shaft excavation method, while raise boring remains a conditional alternative where access, sequencing, and weak-ground risks can be satisfactorily managed within the overall project schedule.

4. Groundwater and weak / poor ground intersections remain key considerations

Groundwater will require appropriate management during construction. In the surge shaft, the extended weak interval is expected to require more sidewall support.

Overall, based on the evaluation completed to date, the preferred construction methods are shaft-specific and reflect the interaction between shaft geometry, geology, groundwater, support demand, and project constraints.

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REFERENCE

- American Society of Civil Engineers, 2022. Geotechnical Baseline Reports: Suggested Guidelines. 3rd ed. Reston: s.n.
- Barton, N., Lien, R. & Lunde, J., 1974. Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, pp. 189-236.
- Bieniawski, Z., 1989. *Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering.* New York: Wiley-Interscience.
- Boniface, A., 2000. Tunnel Boring Machine Performance in Basalts of the Lesotho Formation. 15(4), pp. 391-397.
- GKP Joint Venture, 2026. Geotechnical Baseline Report: uMWP-1 Water Conveyance Infrastructure. Report No. 19041-R-1193-0027 (Rev 0), Johannesburg.: GIBB Knight Piésold.
- ITACET Working Group 23, 2019. Contractual Framework for Tunnelling. Lausanne: International Tunnelling Association (ITACET).
- Lesotho Highlands Development Authority, 2004. Lesotho Highlands Water Project Phase 1B - Mohale Tunnel As-Built Report, Maseru.: Lesotho Highlands Development Authority.
- Rocscience Inc., 2026. Dips (Version 9.002), Toronto: Rocscience Inc..
- Rocscience Inc., 2026. UnWedge (v5.019), Toronto: Rocscience Inc..
- Weir, R. & Oudshoorn, F., 2020. Generic Environmental Management Programme (EMPr) for the LandCare Programme , s.l.: Muvuledzi Consulting .

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She has worked on projects across Southern Africa, Canada, the Middle East, South America, and Europe, gaining exposure to diverse geological environments and rock mass conditions. Her experience spans weak, highly weathered mudstones through to strong, competent norites of the Bushveld Complex. Bridget's technical strengths include site investigation planning and execution, geotechnical logging and interpretation, empirical and numerical analysis, ground support design, and the development of geotechnical models for both open pit and underground applications.

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