

A Review of the New Austrian Tunnelling Method (NATM): Principles, Rock Mass Classification, Support System Design, and Application in Deccan Basalt Geology

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Abstract - NATM, or the New Austrian Tunneling Method, is characterized as a sequential excavation technique that enhances the stability of underground openings by utilizing the bearing capacity of the surrounding ground. This is achieved through the application of sprayed concrete and various support elements, with a strong emphasis on measurement and observational feedback throughout the construction process. The review focuses on a specific case study involving a 2.9 km NATM railway tunnel constructed in Deccan basalt terrain, along with a training document centered on NATM processes and relevant technical literature concerning observational tunneling, rock mass classification, support elements, variability in volcanic rock, and numerical modeling for tunnel design.

The methodology of the review is based on a qualitative synthesis of foundational NATM concepts. It highlights the importance of monitoring-driven optimization and flexible support systems, alongside empirical approaches for rock mass characterization. The review also discusses the concepts of primary and final lining systems, which include shotcrete, rock bolts, steel ribs or lattice girders, and advance support. Additionally, it addresses the geological and hydrogeological challenges specific to basalt that influence excavation risks and the selection of support systems.

Key findings from the review indicate that the practical effectiveness of NATM relies heavily on the timely application of shotcrete and systematic bolting, which are crucial for maintaining a load-bearing ring and controlling deformation. The review underscores the necessity of robust classification and face mapping to effectively choose and adapt support patterns. Furthermore, it emphasizes the importance of monitoring criteria and decision rules that can prompt upgrades in support. Explicit management of groundwater, including strategies for drainage, waterproofing membranes, and pre-support or ground improvement measures, is also highlighted as essential.

In the context of Deccan basalt, the inherent heterogeneity of flow units and the presence of fracturing and jointing lead to rapid spatial variability, while groundwater ingress at tunnel portals and along flow contacts can significantly

impact constructability, necessitating iterative design and risk management throughout various stages of construction.

Key Words: NATM; sequential excavation; rock mass rating; Q-system; shotcrete; rock bolts; Deccan Traps basalt; tunnel monitoring

1. INTRODUCTION

NATM is commonly described as the sequential excavation method (SEM) or sprayed concrete lining (SCL) approach, characterized by sophisticated monitoring used to optimize reinforcement techniques according to the ground encountered as tunnelling progresses.[5, 9] Across multiple technical sources, NATM is framed as an observational method in which support and construction sequence are adjusted based on measured convergence/deformation and mapped ground conditions—often summarized as “design as you go” or, more precisely, “design as you monitor.”[2, 5, 9]

The need for a Deccan basalt-focused NATM synthesis arises because the Deccan Trap terrain is a layered volcanic province in which lithology and rock mass quality vary strongly with flow architecture (e.g., vesicular flow tops and massive flow bottoms), and tunnel alignment conditions can change rapidly over short distances, influencing excavation stability and groundwater behaviour.[2, 4, 10] Project documentation for a 2.9 km railway tunnel explicitly situates the alignment in the Deccan basaltic range and reports intact UCS values in the range 150–220 MPa, while also documenting highly fractured and weathered zones and high groundwater ingress at the Nanded-side portal area.[2, 3]

This review therefore aims to (i) consolidate NATM principles as an observational and monitoring-driven design-and-construction approach, (ii) synthesize rock mass classification practices relevant to tunnel support selection, (iii) summarize primary support and lining components used in NATM practice with emphasis on shotcrete and bolting systems, (iv) connect these aspects to basalt geology and hydrogeological constraints, and (v) summarize modelling and stability-analysis tools used to

support NATM decision-making and portal-slope design in such terrain.[1, 2]

2. Principles of the New Austrian Tunnelling Method

NATM is repeatedly presented as both a construction method and a design philosophy that uses the bearing capacity or strength of the surrounding ground as an active structural component, rather than relying solely on thick, rigid linings.[9, 11, 12] Multiple sources also emphasize that NATM is not a fixed set of excavation and support techniques; instead, it integrates ground behaviour under load with monitoring of performance during construction to drive decisions on support and sequencing.[5, 9, 13]

2.1 Historical development and philosophy

NATM is described in historical summaries as emerging in the period 1957–1965 and being developed during the late 1950s and early 1960s, with the initial intent of addressing weak ground requiring support due to overstressing around the opening.[12, 14] Conceptually, the method is described as conventional heading with sparing use of support (mainly shotcrete) while following observational principles, in which ground distortion is controlled—kept minimal enough to avoid softening and loss of strength, yet sufficient to mobilize ground strength and achieve a stable equilibrium state.[14, 15]

2.2 The observational method and design adaptation

NATM is often summarized as “design as you go,” but sources explicitly refine this to “design as you monitor,” where observed convergence/divergence and mapping of prevailing rock conditions determine support optimization and construction adjustments.[2, 5, 9] In the Wardha–Nanded tunnel project documentation, NATM is explicitly associated with “Design as you Go,” and the use of 3D monitoring data is described as enabling designers to optimize design during construction.[2]

Monitoring-based adaptivity is also presented as a core “element” of NATM: potential deformations must be monitored using sophisticated instrumentation embedded in lining, ground, and boreholes, and additional supports are installed when movements are observed and support demands change.[5, 9, 13] Practical execution sequences used in NATM training materials similarly embed monitoring within the recurring excavation cycle that includes profile marking and drilling, blasting and mucking, face mapping/classification by a geologist, installation of initial support, and regular monitoring.[3]

2.3 Role of the rock mass as a structural element

A core statement across sources is that NATM mobilizes the inherent strength or self-supporting capability of the ground so that the rock mass contributes to support, achieving economy in support installation while maintaining safety by limiting loosening and excessive deformation.[1, 8, 9] Operationally, this concept is linked to immediate shotcrete protection just behind the face

advance and to flexible combinations of reinforcement (rock bolts, wire mesh, steel ribs) that form a confinement “ring” and reduce deformation rather than simply increasing lining thickness.[1, 9, 13]

2.4 Primary and final lining concepts

NATM practice is frequently described as a dual-lining approach in which initial (primary) support is installed early and a final concrete lining is installed later, typically after deformations of the primary support have reached an acceptable and decreasing trend.[2, 12] Project documentation for the Wardha–Nanded tunnel states that a second lining—concrete final lining—shall be installed later, and that initial lining is installed immediately after excavation round length is achieved, including wire mesh, shotcrete, lattice girder/ribs, and then rock bolting.[2]

This dual-lining concept is commonly associated with incorporation of waterproofing between linings, as SEM/NATM references describe a waterproofing membrane inserted between initial shotcrete and final cast-in-place concrete lining, and training material describes waterproofing membranes laid between primary and final lining with polymeric materials such as PVC and HDPE.[3, 8]

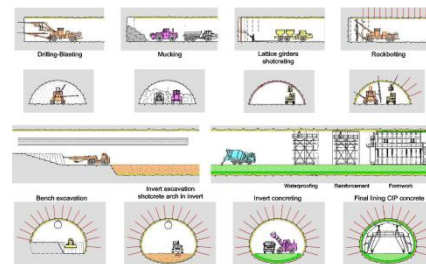


Fig No – 1 NATM New Austrian Tunnelling sequence

3. Rock mass classification systems for tunnel design

Across both project and literature sources, rock mass classification is treated as an operational decision tool linking observed ground conditions to support pattern selection and allowing support to change with geological conditions during construction.[5, 7] In the Wardha–Nanded project, rock mass classification is explicitly used to define five main rock mass categories for tunnel and portal-slope support design, and RMR (Bieniawski) and Q-system (Barton et al.) are stated as the primary empirical systems used to define generic rock classes.[2]

3.1 Rock Mass Rating system

RMR is described in supporting literature as an empirically based system divided into six empirical parameters whose rating is used to classify rock strength and infer support requirements for underground openings.[6] The Wardha–Nanded project documentation describes grouping of the rock mass into classes depending on strength, RQD, joint parameters, groundwater condition, and stress state, and provides an

example that fractured basalt has an RMR value in the range 20–25 at Portal 2 conditions.[2]

The use of RMR in Deccan trap contexts is also reflected in tunnelling performance studies that relate excavation method performance to RMR ranges, reporting maximum TBM performance in RMR range 40–75 in a Deccan trap tunnel case study, which underscores how RMR is used as a proxy for rock mass quality and expected excavation response.[16]

3.2 Q-system

The Q-system is described as being developed at the Norwegian Geotechnical Institute (NGI) in 1974 and later modified, and it is treated as an empirical rock mass classification approach used in tunnel design alongside RMR.[6] Project documentation also identifies the Q-system as a key method for defining generic rock classes and implies its use for class-based support selection along the alignment.[2]

In construction-stage applications, the Q-system is explicitly linked to quantitative description and classification under Indian Standards, with one case study reporting classification performed under IS 11315 and IS 13365 “as per Q system (Barton, 1974)” during construction-stage mapping.[17] The same case study reports the proportion of rock mass classes encountered (e.g., 76% Class II good rock, 18% Class III fair rock, 6% Class IV poor rock), illustrating how Q-based classes can be used to communicate expected and encountered ground conditions over tunnel length.[17]

3.3 Geological Strength Index

A tunnel-classification review source lists GSI among commonly used rock mass characterization systems alongside RMR and Q, indicating its role as an established option in tunnel construction classification practice.[18]

3.4 Comparison and applicability to Indian conditions

The comparative evidence in the included sources supports four practical comparison points: (i) RMR and Q are both empirical systems based on component parameters derived from available geological data such as joint frequency and intact UCS, (ii) construction-stage mapping can implement IS-based quantitative description and classification using Q-system procedures, (iii) classification inputs are uncertain and may benefit from probabilistic treatment rather than deterministic single values, and (iv) classification schemes may require caution or modification in volcanic rock masses due to features such as columnar jointing and high porosity zones.[4, 17, 19]

Table 1. Summary comparison of rock mass classification approaches highlighted in the reviewed sources.

System	Role in tunnel design decisions	Inputs or structure emphasized in sources	Notes for volcanic and basaltic rock masses
RMR	Used to define generic classes of rock for tunnel and slope support design in the Wardha-Nanded project.[2]	Empirical method described as divided into six empirical parameters for rating and support type inference.[6]	Basalt example shows fractured basalt at Portal 2 with RMR 20–25, illustrating poor-quality rock mass conditions at a water-affected portal area.[2]
Q-system	Used (with RMR) to define generic rock classes and select support patterns; used with IS 11315 and IS 13365 for construction-stage classification as per Q-system procedures. [2, 17]	Developed at NGI in 1974 and modified; used empirically with rock classes reported as proportions along tunnel length in a case study.[6, 17]	Sources state Q-system needs adjustment to reduce the impact of columnar jointing in basalt lava and that classification schemes may need modification for volcanic rock masses and should be used with caution in highly porous units.[4]
GSI	Listed among commonly used systems in tunnel construction practice alongside RMR and Q.[18]	Used as a recognized classification framework in tunnel construction literature listings (no parameterization provided in the quoted excerpt).[18]	Volcanic-rock variability is emphasized as requiring characterisation of porosity and alteration, indicating that any classification approach must accommodate strong spatial and temporal variability in volcanic units.[4]

4. Tunnel support system design

NATM support is consistently described as a staged system in which initial support is installed immediately after excavation to prevent collapse or excessive deformation and to control loose rock falls, with subsequent permanent support (often concrete lining)

installed later as conditions stabilize.[2, 3] Both project documents and external sources emphasize that shotcrete is a key support component because it can provide interlocking and continuous support and can be applied rapidly to protect the excavation directly behind the face advance.[8, 13]

4.1 Shotcrete and steel fibre reinforced shotcrete

Project documentation specifies that shotcrete design for slopes and tunnels will be carried out as per IS 15026 and IS 456, using FEM analysis to decide thickness and grade, and it specifies minimum shear strengths: plain shotcrete at least 3 MPa and reinforced shotcrete (wire mesh or SFRS) at least 5.5 MPa.[2] Training material defines shotcrete as wet concrete sprayed onto tunnel walls and roof, which aligns with NATM's immediate protection concept stated in broader NATM references.[3, 13]

SFRS is described as sprayed concrete incorporating steel fibres to improve mechanical properties, and the training document enumerates benefits including improved tensile and flexural strength (crack bridging), improved toughness and energy absorption (resistance to impact and seismic loads), reduced cracking, simplified construction (sometimes eliminating traditional steel mesh), and improved durability with proper protection.[3]

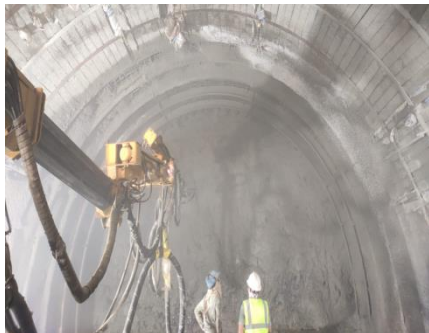


Fig no 2 - Shotcrete and steel fibre reinforced shotcrete

4.2 Rock bolts and anchoring systems

Project documentation states that fully grouted or end-anchored rock bolts/anchors, or spot bolting, using FE 500 grade steel are commonly proposed for slopes and tunnels, and that initial lining installation is completed with rock bolting shortly after excavation round length.[2] Training material describes rock bolts as long steel anchor rods installed into rock for stability and further describes grouted rock bolts as embedded in cementitious or chemical grout, providing improved load transfer via stronger bond between bolt and rock.[3]

Technical literature further interprets rock bolting as producing pressure beam and artificial arching around the excavation periphery when installed with immediate support after excavation, and it emphasizes bond strength mechanisms between bolt, grout, and rock and the role of

pull-out tests in quantifying bonding capacity and deriving stiffness and load-bearing capacity parameters.[6]



Fig no 3 Rock bolts

4.3 Lattice girders and steel ribs

Project documentation identifies lattice girder/ribs among initial support elements installed immediately after excavation together with shotcrete and wire mesh, and it states that lattice girder design will use empirical methods and site-specific simulation using Phase2/RS2 FEM analysis.[2] Training material describes steel ribs/sets/lattice girders as curved steel frames supporting weak ground and notes they are often combined with shotcrete, consistent with staged support concepts in NATM sources.[3]



Fig No 4 Steel Ribs

4.4 Forepoling and advance support

Pre-support measures are presented in contemporary SEM/NATM practice as including dewatering, grouting, ground freezing, and spiling to widen applicability in difficult grounds and increase stand-up time prior to or during tunnelling.[8] In adverse ground experiences, forepoling is described as being adopted in response to changes in backflow water colour and penetration rate, with installation of 25 mm diameter forepoling rods at the crown level and spacing adjustments in very critical reaches, illustrating a monitoring-triggered advance support tactic.[20]

4.5 Final lining design

Project documentation states that a second lining—concrete final lining—shall be installed later and that the final lining is designed to sustain all loads without considering the load capacity of the primary lining, representing a conservative structural assumption for long-term capacity.[2] The same project documentation defines a stable-condition criterion for the primary lining as a displacement rate of less than 3 mm per month before proceeding under the observational framework of staged support decisions.[2]

Table 2. Support elements and selected specifications stated in project and training documents.

Support element	Function in NATM support cycle	Selected specifications or design notes from sources
Shotcrete	Installed as part of initial lining immediately after excavation to protect walls and roof and to control deformation and fall of loose material.[2, 3, 13]	Designed per IS 15026 and IS 456 with FEM used to decide thickness/grade.[2] Plain shotcrete shear strength ≥ 3 MPa; reinforced/SFRS shear strength ≥ 5.5 MPa.[2]
Rock bolts/anchors	Installed to stabilize ground and complete initial lining support; grouting improves bond and load transfer.[2, 3]	FE 500 steel fully grouted/end-anchored or spot bolting is proposed in the project documentation.[2]
Lattice girders / steel ribs	Provide framed support in weak ground and work in combination with shotcrete; part of initial lining immediately after excavation where required.[2, 3]	Lattice girder design to use empirical methods and Phase2/RS2 FEM simulations according to project documentation.[2]
Waterproofing membrane (between linings)	Supports durability by preventing water ingress and is placed between primary and final lining in dual-lining systems.[3, 8]	Materials listed include PVC and HDPE sheets; installation described as between primary and final lining.[3]

5. Geological challenges in Deccan basalt terrain

Deccan basalt terrain is described in the project documentation as the setting for the entire region of the Wardha-Nanded tunnel alignment, with basaltic lava flows of Upper Cretaceous to Lower Palaeocene age occupying major portions of the area.[2] Both project and training sources describe a typical flow architecture in which vesicular basalt occurs at the top and massive basalt at the bottom, while the massive basalt is described as fractured and jointed, indicating that intact strength and rock mass quality may diverge strongly within short vertical or lateral distances.

5.1 Characteristics of Deccan Trap basalt

The Deccan basalt is additionally characterized in broader geological sources as a large flood basalt province covering approximately 500,000 km² and consisting of multiple layers of solidified basalt with cumulative thickness exceeding 2,000 m in some accounts, highlighting the scale of layered volcanic stratigraphy relevant to tunnel planning across the province.[21] The structural and facies variability of Deccan basalt sequences is supported by critical-zone studies reporting multiple lava flows separated by interflow 'bole' horizons formed by in situ weathering of flow tops during eruptive quiescence, indicating that weak, weathered horizons may recur systematically between stronger flow interiors.[10]

5.2 Geotechnical properties and rock mass variability

For the Wardha-Nanded tunnel alignment, the UCS of intact rock mass is reported as 150–220 MPa, indicating high intact strength typical of competent basalt, yet the project documentation simultaneously reports that at Portal 2 fractured basalt has RMR 20–25 and that the alignment is expected to pass through multiple rock classes with classes III and IV most commonly encountered.[2] Training material reports that along the tunnel alignment basaltic rocks are present with weathered outcrops at the surface, while strong, hard, and highly fractured basalt is expected at formation level, reinforcing the concept of variable rock mass quality even when intact strength is high.[3]

The variability of volcanic rock masses is further emphasized in volcanic tunnelling literature, which notes that volcanic rock masses can range from high-porosity, clay-rich, fractured, soil-like material to low-porosity, high-strength, brittle, massive rock, and that porosity can negatively impact uniaxial compressive strength and Young's modulus—parameters central to excavation design.[4] This variability supports the need for rock mass characterisation that includes not only mechanical properties (strength and stiffness) but also petrophysical properties such as porosity and geological conditions such as alteration, which can vary strongly within volcanic stratigraphy.[4]

5.3 Groundwater and hydrogeological challenges

Hydrogeological challenges in basalt settings are prominent in the Wardha–Nanded project documentation, which reports that Portal 2 area is relatively flat with surface streams present and high groundwater ingress, and that Portal 2 is completely filled with water, implying that portal works may require extensive dewatering and additional water management arrangements.[2] The same project documentation notes that geological mapping at such a water-filled portal location may not be possible unless water is drained so that the rock section is visible, emphasizing practical constraints on characterization and construction staging in high-water conditions.[2]

Independent studies of Deccan basalt hydrogeology support the importance of permeable fracture networks and layered facies contrasts, reporting evidence for deep groundwater percolation in Deccan basalt and noting that although non-massive parts of lava flows facilitate groundwater storage, water-saturated permeable fractures in massive basalt can favour deep hydrological networks.[22]

6. Numerical modelling for tunnel analysis

NATM-related guidance emphasizes that engineering calculations and numerical simulations are based on simplified models whose validity must be carefully reviewed, and that results must be verified by geotechnical measurements and observations during construction with modifications made as needed, consistent with observational tunnelling practice.[1] This verification principle is aligned with project documentation stating that 3D monitoring data helps optimize design during construction and that stable conditions for primary lining are checked using a displacement-rate criterion before proceeding with final lining decisions.[2]

6.1 Finite element and continuum approaches

The Wardha–Nanded project documentation states that tunnel stability analysis will be carried out using Phase2/RS2 as a continuum finite element program with Mohr–Coulomb yield criteria to estimate stresses and deformations around the tunnel, providing a defined modelling approach for support assessment.[2] The same documentation specifies that the numerical model is conceived as a plane strain model with external boundaries located about three times the opening size from excavated tunnel boundaries, indicating a boundary placement rule used in the design modelling workflow.[2]

Volcanic-rock tunnelling literature additionally notes that numerical modelling of tunnel behaviour requires full failure criteria such as Mohr–Coulomb or Hoek–Brown, and that failure criteria and parameters depend strongly on texture, porosity, and alteration in volcanic rocks, reinforcing the need to integrate geologic characterization with modelling assumptions and parameter selection.[4]

6.2 Phase2/RS2 applications

Within the Wardha–Nanded project, Phase2/RS2 is stated as the primary numerical tool for continuum modelling to estimate stresses and deformations and check stability, and the same project documentation also states that lattice girder design will include site-specific simulation using Phase2/RS2 based on FEM analysis, indicating consistent FEM tool usage across support components.[2]

The project documentation further states that seismic loadings are not considered in analysis and design of the primary support system, while also stating separately that the project area lies in seismic zone III and that portal slopes and portal linings should be checked for seismic forces, highlighting a differentiated seismic design scope between deep tunnel primary support and portal/cut-and-cover components.[2]

6.3 Discontinuity and wedge analysis

Beyond continuum FEM, the Wardha–Nanded project documentation states that discontinuity analysis and wedge formation/tunnel stability checks will be performed using Unwedge, and that kinematic analysis of planar and wedge formations and toppling failures will be checked using Dips if necessary, representing a combined continuum–discontinuity workflow for stability assessment.[2]

Construction-stage evidence from other tunnel case studies reinforces the engineering relevance of discontinuities and shear zones, reporting mapped joint sets and multiple shear zones associated with seepage and overbreak cavity formation during drill-and-blast excavation, and linking such zones to Q-value variations and adverse ground reaches that required modified support measures.[17]

7. Tunnel drainage and waterproofing systems

Water management is treated as a central durability and constructability concern in NATM practice because water ingress can compromise structural integrity and long-term durability, and waterproofing membranes are described as being installed between primary and final lining using polymeric materials such as PVC and HDPE sheets or synthetic rubber.[3] SEM/NATM literature similarly describes a dual-lining cross section with a waterproofing membrane inserted between initial shotcrete and final cast-in-place concrete lining, establishing a general NATM waterproofing architecture consistent with the training material description.[3, 8]

7.1 Construction phase drainage

Project documentation for the Wardha–Nanded tunnel states that drainage systems must be designed for both construction and operating phases, indicating that temporary construction drainage and long-term operational drainage must be integrated in design

intent.[2] The tender drainage design described in the same documentation includes 150 mm diameter side wall pipes on both sides to manage groundwater ingress, rectangular drains on each side to handle surface water, and a 400 mm diameter main collector pipe below the bed concrete receiving flow from both surface and side drains.[2]

7.2 Permanent drainage systems

Because portal 2 conditions include significant groundwater seepage and surface streams, project documentation states that perforated drainage pipes with geotextile along portal slopes may be necessary, linking observed hydrogeological conditions to required drainage interventions aimed at reducing pore pressure and improving stability.[2] The same documentation specifies provision of a flushing system at suitable intervals, and it also calls for an oil and silt separator to isolate particles before routing water to a sewage treatment plant, reflecting operational and environmental management considerations for tunnel drainage discharge.[2]

7.3 Waterproofing membranes

Training material emphasizes that waterproofing prevents water ingress when combined with a waterproof membrane and is installed between primary (temporary) and final lining, and it lists common waterproofing materials including PVC and HDPE sheets and related polymeric membranes.[3]



Fig NO- 5 Water proofing Installed temporary

8. Portal design and slope stability

Portal conditions strongly influence construction risk and drainage requirements in NATM tunnels, as the Wardha-Nanded project documents sharply different portal environments, including a 50 m high portal slope at Portal 1 and a waterlogged, stream-influenced portal area at Portal 2.[2] The same project documentation situates Portal 1 at chainage 55+151 m founded on massive basalt, with completely weathered rock/soil at the surface grading with depth to hard intact, strong, highly fractured basaltic rock at the portal location, illustrating vertical weathering variability relevant to cut slope stability and portal support design.[2]

8.1 Portal slope stability analysis methods

Project documentation indicates that portal slopes and portal linings are checked for seismic forces because the project area belongs to seismic zone III, establishing that portal and cut-and-cover components include seismic checks even when primary support may omit seismic loading in analysis.[2] High groundwater ingress at Portal 2 and potential submergence requiring extensive dewatering arrangements are reported as specific portal risks, reinforcing that slope and portal stability design must account for pore pressure and water control measures at that location.[2]



Fig no 6 Portal Design

8.2 Kinematic analysis

The Wardha-Nanded project documentation states that kinematic analysis of wedge formations (planar and wedge) and toppling failures will be checked by discontinuity analysis using Dips software if necessary, reflecting a kinematic analysis approach for discontinuity-controlled failures at portal slopes and potentially at tunnel faces.[2]

8.3 Global stability assessment

Project documentation states that stability analysis will be carried out using Phase2/RS2 with Mohr-Coulomb yield criteria to estimate stresses and deformations and to check tunnel stability, and this continuum modelling approach can also support global stability assessments where slope-structure interaction or stress redistribution around excavations is important.[2]

9. Discussion and future directions

The reviewed sources collectively indicate that NATM effectiveness depends on a closed-loop framework that integrates (i) continuous monitoring and interpretation, (ii) flexible modification of support and construction sequence, and (iii) rigorous safety and risk management processes supported by contracts and decision-making structures appropriate for observational construction.[1, 9] A guideline-oriented source stresses that even with extensive investigation programs and up-to-date design, uncertainties remain in ground model, properties, and behaviours, and therefore continuous information

collection and targeted monitoring programs with warning/alarm criteria and mitigation measures are required as part of geotechnical safety management.[1]

For Deccan basalt and volcanic rock masses, the literature indicates that classification schemes may need adjustment (e.g., Q-system adjustment for columnar jointing) and should be applied with caution in highly porous or poorly lithified volcanic units, and that advance borings in the tunnel face are important for reducing the risk of unexpected poor geological conditions.[4] This caution is consistent with broader volcanic-rock tunnelling observations that rock mass characterisation must address strong variability and anisotropy and should include porosity and alteration in ground models, while numerical modelling must use failure criteria sensitive to texture and alteration effects and must be validated against observations.[1, 4]

A second cross-cutting theme is the tendency for designed support patterns to be exceeded during construction due to geological conditions, as one study notes that support patterns used during construction are frequently heavier than designed, increasing cost, and proposes scoring methods that align preliminary investigations and construction-stage classification criteria including negative points for water seepage and deterioration.[7] Complementary work shows that deterministic rock mass classification can be biased relative to probabilistic classification distributions when inputs are uncertain, motivating probabilistic approaches (e.g., Monte Carlo sampling) to quantify classification uncertainty and support system selection risk over tunnel length.[19]

Finally, project and case-study evidence emphasizes that groundwater and seepage can dominate schedule and safety risk in basaltic tunnels, with examples of Portal 2 waterlogging and high ingress in the Wardha–Nanded tunnel, and independent Deccan trap tunnelling experience reporting that heavy ingress of water was a main impediment to achieving targeted progress and requiring extensive grouting before final lining to control seepage.[2, 23]

10. Conclusions

NATM is consistently framed as an observational and monitoring-driven approach in which support and construction sequence are optimized based on measured deformation and mapped ground conditions, rather than fixed pre-defined support prescriptions.[2, 5]

Dual-lining concepts—early installation of primary support followed by later installation of concrete final lining—are explicitly used in the Wardha–Nanded NATM tunnel and are widely described in SEM/NATM literature, often with waterproofing membranes between initial shotcrete and final concrete lining.[2, 3, 8]

In practice, rock mass classification is central to NATM decision-making and is used to define rock classes and

select support patterns, with the Wardha–Nanded project explicitly using RMR and Q-system frameworks and expecting predominant class III and IV ground while encountering portal-specific poor RMR (20–25) fractured basalt at Portal 2.[2]

Project documentation and training materials emphasize primary support systems built around shotcrete, rock bolts/anchors, and lattice girders/steel ribs installed immediately after excavation, with IS-based shotcrete design and quantified minimum shear strength requirements for plain and reinforced/SFRS shotcrete.[2]

Numerical modelling in the Wardha–Nanded project explicitly uses Phase2/RS2 FEM with Mohr–Coulomb yield criteria and plane strain boundary placement rules, supplemented by discontinuity and kinematic tools such as Unwedge and Dips, reflecting a combined continuum and discontinuity stability assessment workflow.[2]

Deccan basalt tunnelling requires explicit treatment of layered flow architecture (vesicular tops and massive bases) and rock mass variability (fracturing, weathering) alongside hydrogeological controls, as evidenced by portal-specific high groundwater ingress and water-filled portal conditions requiring drainage and dewatering measures.[2, 3]

Future NATM improvements for basalt and volcanic terrains are strongly linked to reducing uncertainty through targeted monitoring and safety management, careful verification of modelling results against measurements, and cautious or modified use of rock mass classification where volcanic variability (porosity, alteration, jointing) challenges deterministic design assumptions.[1, 4]

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