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Anisotropic Deformation Mechanism in the Twin-Tube Tunnel Sections: Empirical Insight from Multi-Point Displacement Monitoring

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Abstract
This study evaluates the stability of a twin-tube tunnel through a combined approach of rock mass classification, numerical modeling, and real-time deformation monitoring. The rock mass along the tunnel alignment was characterized using the Rock Mass Rating (RMR) system, incorporating physical, geological, and geotechnical data from the project site. Support systems were designed for each geotechnical unit based on RMR and the Q-system support chart. Field monitoring was conducted over one year using a Leica TS09 tachometer and 3D displacement monitoring targets installed at the top heading and invert/bench, with data processed via Amberg Tunnel 2.0 software. Complementing the field measurements, 2D numerical analyses were performed to assess the left portal slope stability (Slide 6.0 software) and provisional support behavior (Phase2 2D program). The numerical results were validated against in-situ monitoring data, demonstrating strong agreement. The study confirms effective rock mass deformation control and satisfactory confinement stability, highlighting the reliability of the integrated methodology for tunnel stability assessment.

1. Introduction

The deformations and stress redistributions induced in surrounding ground formations during tunnel excavation are fundamentally dependent on the employed construction methodology [1,2]. The New Austrian Tunneling Method (NATM) represents a sophisticated approach that strategically utilizes the inherent load-bearing capacity of the surrounding rock mass. This method operates on the principle of controlled stress redistribution, where limited but carefully monitored deformations are permitted (provided they remain within established safety thresholds) to optimize the mobilization of the rock mass's natural arching capacity [3-7]. Through this mechanism, the excavation-induced stresses are progressively transferred from a three-dimensional state at the working face to a stable two-dimensional configuration in regions further removed from the active excavation zone.

The support systems implemented in NATM serve a distinct purpose compared to conventional tunneling approaches. Rather than functioning as primary load-bearing elements, these supports are designed to facilitate and regulate the plastic deformation process while maintaining the integrity of the stress redistribution mechanism surrounding the excavation [8-10]. This controlled deformation strategy allows for optimal utilization of the rock mass's self-supporting characteristics, with temporary supports providing only the additional confinement necessary to achieve equilibrium when the native rock's capacity proves insufficient. The flexibility to accommodate and manage ground deformations through this adaptive support system constitutes one of NATM's most significant advantages in varying geotechnical conditions.

Figure 1. Photography and Geological cross-section and longitudinal profile of the lateral slope of the south portal of the tunnel.

A critical operational aspect of NATM involves the precise timing of support installation, which is determined through comprehensive deformation monitoring programs. These monitoring regimes serve multiple essential functions: they enable the selection of appropriate excavation sequences from among pre-designed alternatives, verify the effectiveness of implemented support measures, and ensure the safety of both underground workers and surface structures [11]. The integration of empirical design methods, particularly rock mass classification systems, with advanced numerical modeling techniques has proven indispensable for developing efficient support systems and conducting accurate stability assessments for underground excavations [12,13].

Modern tunnel design increasingly relies on sophisticated 2D and 3D finite element analyses to simulate complex interactions between the rock mass, in situ stress fields, and support systems [14-17]. These numerical models provide valuable insights into stress redistribution patterns, the development of plastic zones around excavations, and the performance of various support configurations. The validity of these computational models is subsequently confirmed through rigorous comparison with field monitoring data, creating a robust feedback loop for design optimization.

Surface displacement monitoring assumes particular importance in tunnel projects, especially in portal sections where ground stability is often most critical [18,19]. The observational method, which forms an integral component of modern geotechnical design practice, provides a systematic framework for reconciling predicted and actual performance [20]. Through continuous monitoring of structural behavior - with particular emphasis on displacement measurements during construction - engineers can validate initial design assumptions and implement necessary modifications in a timely manner [21]. This adaptive approach to underground construction has been successfully implemented in numerous major projects worldwide, demonstrating its effectiveness in managing geological uncertainties and optimizing project outcomes [22-28].

The present study builds upon these established principles by combining comprehensive field monitoring with advanced numerical modeling to analyze the stability of a twin-tube tunnel excavation. Particular attention is given to the interaction between empirical design methods, real-time performance monitoring, and computational simulations, with the aim of developing a more complete understanding of stress-deformation behavior in underground openings.

2. Geological Conditions Along the Tunnel Alignment

The study area is strategically positioned at the southern periphery of the Petite Kabylie massifs, a region that marks a crucial geodynamic boundary in northern Algeria. This boundary represents one of the most significant tectonic contacts of Alpine origin in the region, characterized by complex structural deformations that have shaped the geological framework of the Maghrebian orogenic belt [29]. The tectonic evolution of this area is intrinsically linked to the convergence of the European and African continental margins during the Alpine orogeny, which led to the development of the Maghrebian basin and its subsequent deformation [30]. The South Kabylian Fault, often referred to as the South Kabylian Backbone, stands out as the predominant structural feature, serving as a major geodynamic divide that influences both the regional geology and local geotechnical conditions.

At the Texana Tunnel site, the geological profile is dominated by the Mauritanian Flysch deposits, which consist of a rhythmic alternation of sandstone and quartzite layers, often interbedded with more resistant quartzite horizons (Figure 1). These Flysch sequences are underlain by a basement of highly fractured and weathered schists, which exhibit significant alteration near the surface due to prolonged exposure to weathering agents [31]. As one progresses deeper into the subsurface, the geological conditions transition into more competent lithologies, primarily composed of hard argillite (claystone). This argillite formation is remarkably consistent along the tunnel alignment, displaying minimal fracturing and weathering at greater depths. The upper sections of the argillite are moderately fractured, but the rock mass becomes increasingly intact and mechanically robust with depth, culminating in a very hard and sparsely fractured unit that provides favorable conditions for tunneling. The geomechanical behavior of these formations is critical for understanding the stability of the tunnel, as the varying degrees of fracturing and weathering directly influence the design and implementation of support systems.

3. Rock Mass Classification Using RMR and Q-Systems

Rock mass classification systems are indispensable tools in the field of geotechnical engineering, particularly for the design and stability assessment of underground excavations. These systems provide a systematic framework for evaluating the quality of the rock mass, selecting appropriate support measures, and determining input parameters for numerical modeling [32]. Over the years, numerous classification systems have been developed, each tailored to specific engineering applications and geological conditions, with the Rock Mass Rating (RMR) and Q-system emerging as two of the most widely adopted methodologies in both civil and mining engineering projects [33, 34].

In this study, the RMR and Q-system were employed due to their versatility and proven reliability in tunneling projects. The RMR system, developed by Bieniawski, integrates multiple geotechnical parameters, including uniaxial compressive strength, rock quality designation (RQD), joint spacing and condition, groundwater inflow, and joint orientation, to provide a comprehensive assessment of rock mass quality [37]. The Q-system, on the other hand, focuses on quantifying the rock mass quality through a numerical value that reflects the interplay between the rock structure, joint conditions, and stress environment [36]. A high Q-value indicates a competent rock mass with excellent stability, requiring minimal support, whereas a low Q-value signifies poor rock quality, necessitating extensive reinforcement to ensure stability.

To apply these classification systems, a detailed geotechnical investigation was conducted along the tunnel alignment. This involved the collection and laboratory testing of rock samples to determine key physical and mechanical properties, such as density, porosity, uniaxial compressive strength, and elastic modulus [38-42]. Field mapping and core logging were also carried out to characterize the joint networks, fracture density, and weathering profiles. The integration of these data allowed for the segmentation of the tunnel alignment into distinct geomechanical units, each with its own RMR and Q-values. This dual-classification approach not only enhanced the reliability of the rock mass assessment but also provided a robust basis for designing tailored support systems that address the specific challenges posed by varying ground conditions along the tunnel. The use of both RMR and Q-system facilitated a comparative analysis, enabling the validation of results and ensuring a more accurate representation of the rock mass behavior. This comprehensive approach underscores the importance of rock mass classification in tunneling projects, as it bridges the gap between geological understanding and engineering practice, ultimately contributing to the safe and efficient execution of underground excavations.

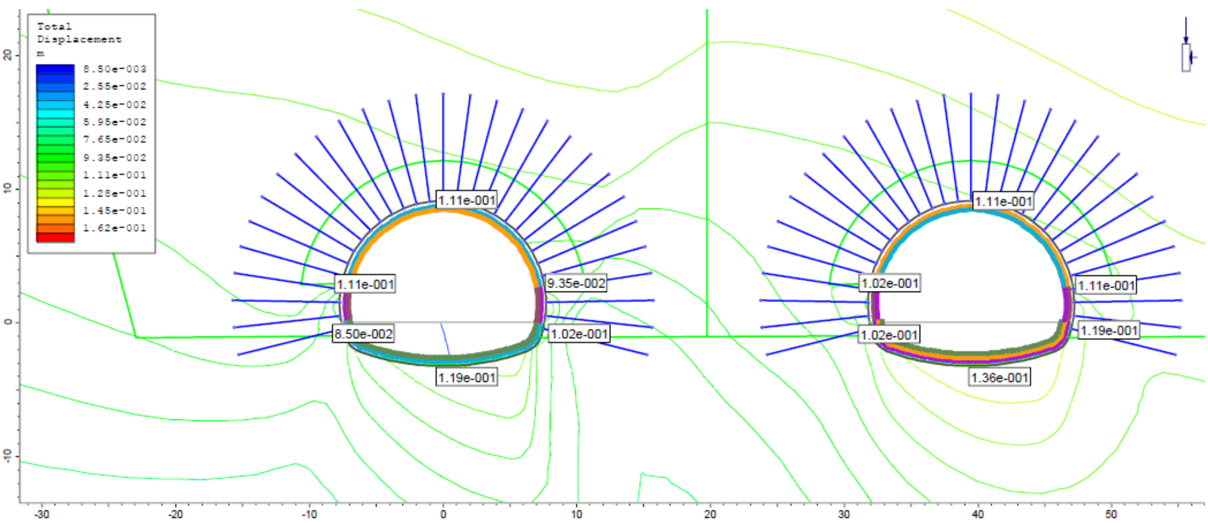


Figure 2. Total displacement in Situation without earthquake in class IV [38].

4. Comparative Analysis of Monitoring Deformations and Numerical Modeling

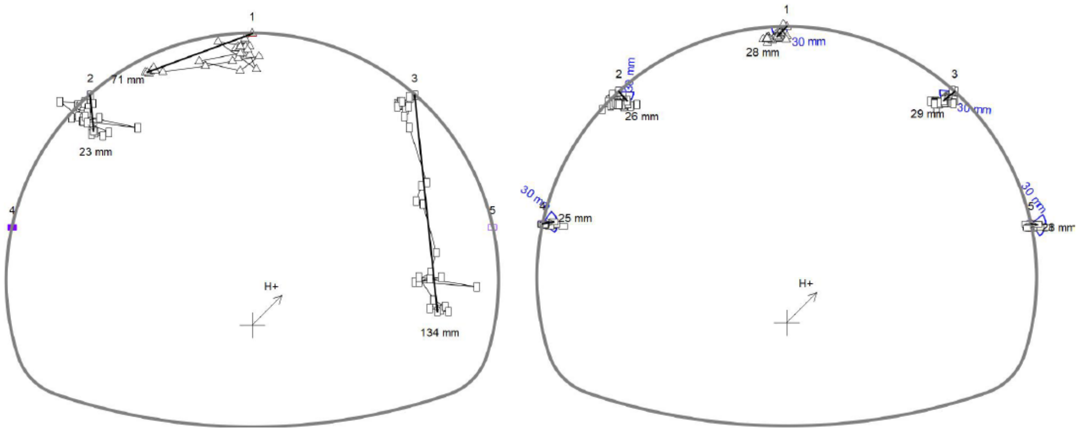
The numerical modeling for this study was conducted using Phase2 2D finite element analysis software (Version 8.0), which simulates the sequential excavation process and support installation in underground openings. The software progressively models each excavation stage while incorporating various support elements, including rock bolts, steel ribs (HEB profiles), lattice girders, and shotcrete lining (Figure 2). The analysis accounts for stress redistribution during excavation and incorporates material softening behavior to better represent the rock mass response to tunneling activities.

The support system design was initially based on empirical approaches and engineering experience, with numerical modeling serving as a verification tool to guide practical decision-making. However, the final support design requires continuous adjustment based on field observations, geological mapping data, and monitoring results to account for actual ground conditions. The analysis focused on representative cross-sections between specific kilometer points (KP) along the tunnel alignment, with each section's rock mass parameters carefully estimated following established geomechanical classification methods from literature.

The modeling approach adopted an X-Y coordinate system with the tunnel centerline as the origin (0,0), with all dimensions specified in meters. While numerical modeling of soil excavations presents significant challenges due to material uncertainties and complexity, the analysis employed an elastic-plastic constitutive model as a practical compromise between accuracy and computational efficiency. The model incorporated a relaxation factor to simulate stress redistribution in weak rock masses - applying 65% relaxation during top heading excavation and 35% during bench excavation, corresponding to support installation sequences. This approach helps quantify the load-sharing mechanism between the rock mass and support system.

The composite lining system was modeled in three distinct layers for the top heading, bench, and invert excavations. The first layer consisted of initial shotcrete lining with steel ribs, while the second layer included additional shotcrete with lattice girders. The analysis excluded seismic loading conditions for this preliminary assessment. Several simplifying assumptions were necessary to develop a practical 2D model:

a) Reduction of three-dimensional effects to a plane strain condition
b) Symmetrical section geometry about the tunnel axis
c) Simplified geological unit representations
d) Idealized excavation sequence and support installation timing
e) Assumption of homogeneous and isotropic material properties



(a) (b)

Figure 3. (a): Left tube Tunnel Cross section KP 2,501.000/ First measure: 15.05.-2017, Last measure: 7.04.2018.; (b): Right tube Tunnel Cross section KP 26,562.000/ First measure: 21.11.2017, Last measure: 26.03.2018 [39].

Deformation analysis results (Figure 2) revealed maximum displacements of 11.1 cm in the crown, with 11.1 cm and 9.35 cm in the left and right sidewalls respectively. The lower tunnel sections showed displacements of 8.50 cm (left) and 10.2 cm (right), with 11.9 cm at the left invert. The right tunnel tube exhibited similar but slightly greater deformations, with 11.1 cm crown displacement, 10.2-11.1 cm sidewall movements, and 13.6 cm invert displacement. These results demonstrate that the proposed temporary support system - combining lattice girders, steel ribs, rock bolts, and shotcrete - provides adequate capacity to withstand the induced loads while maintaining tunnel stability throughout the excavation sequence.

4.1. Left Tunnel Tube Deformation Analysis (KP 2+501, 330-day monitoring period)

The comprehensive deformation monitoring program conducted on the left tunnel tube's rock mass revealed several critical behavioral patterns that warrant detailed discussion. At the Left Waist position, instrumentation detected a minimal deformation value of 4 mm, which presented as a highly localized phenomenon without any significant directional distribution components. This punctiform deformation characteristic suggests the presence of stable geological conditions at this particular measurement location. Moving upward to the Left Shoulder region, the monitoring equipment recorded a substantially greater deformation magnitude of 23 mm, exhibiting a clear descending deformation vector with pronounced forward propagation tendencies. Detailed analysis of displacement vectors indicated that approximately 70-80% of this deformation propagated in the forward direction, while the remaining 20-30% displayed minor but measurable lateral dispersion components to both the left and right directions.

The Crown section demonstrated even more significant deformation behavior, with total displacement reaching 71 mm. This deformation pattern showed a dominant descending vector with distinct directional preferences - approximately 60% of the displacement propagated toward the left side of the tunnel, while about 30% distributed forward, and the remaining 10% exhibited no clear directional preference. The most substantial deformation occurred at the Right Shoulder location, where measurements indicated 134 mm of total displacement. This deformation displayed a remarkably uniform directional characteristic, with virtually all displacement propagating exclusively in the forward direction, suggesting a highly anisotropic stress redistribution pattern in this zone. In contrast, the Right Waist measurement point showed only 5 mm of deformation, mirroring the localized, non-distributed characteristics observed at the Left Waist position.

4.2. Right Tunnel Tube Deformation Characteristics (KP 26+562, 155-day monitoring period)

The deformation behavior observed in the right tunnel tube presented notably different characteristics compared to the left tube, both in magnitude and distribution patterns. At the Left Waist position, monitoring revealed 25 mm of deformation that displayed limited diffusion characteristics. While primarily localized, detailed vector analysis indicated approximately 15-20% of this deformation exhibited slight propagation toward the right-front quadrant. The Left Shoulder measurement point recorded 26 mm of deformation, showing concentrated descending movement with a predominant distribution toward the front-right direction (accounting for roughly 60% of total displacement), while the remaining deformation components displayed no clear directional preference.

The Crown section in the right tube demonstrated 28 mm of deformation that maintained highly localized characteristics, with about 80% of displacement distributing uniformly forward in a gradual manner. Interestingly, the Right Shoulder location showed the maximum deformation in this tube at 29 mm, presenting as a nearly punctual deformation with only minimal (approximately 10-15%) tendency to propagate slightly toward the front-left direction. The Right Waist measurement completed the dataset with approximately 28 mm of deformation, exhibiting purely localized characteristics without any measurable directional distribution components. This remarkably consistent deformation magnitude range across all five measurement points (25-29 mm), combined with their predominantly localized nature, suggests a fundamentally different mechanical behavior in the right tube compared to the left tube. The deformation hierarchy in the right tube showed the Right Shoulder as the most active point, followed closely by the Right Waist and Crown, then the Left Shoulder and Left Waist respectively, indicating a more uniform stress redistribution pattern throughout this tunnel section.

While the numerical models utilized in this study provide valuable predictions about tunnel behavior, it is crucial to discuss their limitations and uncertainties to ensure a comprehensive understanding. These models depend heavily on the accuracy of input parameters, which are often derived from empirical data and may not fully represent the complex and variable nature of geological formations [14, 16]. Furthermore, the simplifications necessary for computational feasibility, such as assuming linear material behavior or ignoring microscale discontinuities, can affect the fidelity of the results [15]. Acknowledging these factors helps temper the conclusions drawn from the models and highlights the need for ongoing refinement and validation against real-world observations [17].

The findings of this study, while specific to the geological conditions of the twin-tube tunnel site, carry broader implications for other geological settings. The methodologies and outcomes can guide similar stability analyses in regions with different rock mass characteristics and environmental conditions [32, 33]. For instance, the effectiveness of the RMR and Q-system in our analysis suggests their potential adaptability in assessing tunnel stability in varied geological formations, ranging from sedimentary to metamorphic rocks [35, 36, 40, 41, 42]. Expanding the discussion to consider these settings not only enhances the utility of our research but also encourages its application in diverse engineering challenges.

To make the numerical modeling sections of this manuscript more accessible, efforts have been made to simplify the technical language and clarify the modeling processes. This includes a more straightforward explanation of the modeling assumptions, the step-by-step procedures used in the simulations, and the rationale behind the selection of specific modeling parameters [14, 16]. Visual aids such as flowcharts and simplified diagrams have been incorporated to illustrate the modeling workflow, providing both technical and non-specialist readers with a clearer understanding of how the numerical analyses were conducted and how they integrate with empirical data [15].

This study also recognizes the environmental aspects of tunnel construction, an area of increasing concern in civil engineering projects. The excavation and stabilization processes, while focused on structural integrity and safety, also have significant impacts on the surrounding ecosystems. For instance, changes in groundwater flow due to tunneling can affect local aquifers, while the use of construction materials can impact local biodiversity [38, 39]. Discussing these implications not only enriches the relevance of our research but also promotes a holistic approach to tunnel design that incorporates environmental stewardship alongside engineering objectives.

5. Conclusion

This study presents a comprehensive analysis of rock mass deformation behavior for the Texanna twin-tube tunnel project in Jijel Province, Algeria, which forms a critical link between the Port of Djen Djen and the East-West Highway. The investigation focused on tunnel sections spanning kilometer points

KP:24+818.845 to KP:26+648.352 (right tube) and KP:0+711.683 to KP:2+593.879 (left tube), where geological surveys identified challenging Albo-Aptian flysch formations comprising alternating layers of thin-to-medium stratified mudstone and medium-to-thick sandstone beds. Based on extensive field investigations and geotechnical assessments, the mechanical excavation method combined with the New Austrian Tunneling Method (NATM) was implemented as the optimal construction approach, employing a sequential excavation technique of top heading, bench, and invert with carefully designed provisional support systems. The research demonstrated that while numerical modeling provided valuable preliminary deformation predictions, field monitoring over 365 days revealed slightly greater actual displacements, highlighting the inherent limitations of numerical simulations in fully capturing the complex ground-support interactions during tunnel construction. These findings emphasize the critical importance of maintaining robust field monitoring programs to complement numerical analyses, particularly in heterogeneous geological conditions. The study confirms that proper implementation of NATM principles, coupled with adaptive support system design based on real-time monitoring data, successfully controlled deformations and ensured tunnel stability throughout construction. The results provide valuable insights for future tunneling projects in similar geological formations, underscoring the need for integrated approaches combining empirical, numerical, and observational methods.

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