

Article

A Novel Approach for the Optimization of Segmental Linings in TBM Tunnels Through Steel Ring Reinforcement

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Abstract

Mechanized tunneling with Tunnel Boring Machines (TBMs) is essential for rapid urbanization, yet traditional thick concrete segmental linings incur high material costs and geometric challenges in deep projects. This study investigates an innovative hybrid reinforcement strategy to optimize structural efficiency by reducing segment thickness through steel rings, a concept inspired by the proactive support principles of the New Austrian Tunnelling Method (NATM). Three finite element numerical models were developed using PLAXIS 3D to evaluate this design under approximately 69 m overburden in claystone. The results demonstrate that 25 cm concrete segments reinforced with structural steel rings achieve mechanical performance comparable to traditional 40 cm unreinforced segments, despite a 37.5% reduction in lining thickness. This structural optimization facilitates a 43.7% reduction in concrete consumption, reduces the outer excavation diameter, and simplifies manufacturing and construction logistics while keeping structural forces and displacements safely within engineering thresholds. The findings confirm that the proactive integration of steel rings provides a lining configuration demonstrating potential material optimization advantages for modern TBM tunnel designs in demanding ground conditions.

Keywords: Tunnel Boring Machine; tunnel; steel ring; segmental lining; numerical model

1. Introduction

The rising demands of global urbanization and the ongoing necessity for strong infrastructure have established Mechanized Tunnelling, mainly using Tunnel Boring Machines (TBMs), as the most effective approach for constructing underground facilities in heavily populated urban areas and complex lithological settings [1–6]. The effective implementation and sustained performance of these projects are primarily reliant on the structural effectiveness of precast concrete segmental linings [7–10]. These linings act as the main structural support, withstanding intricate geotechnical loads and ensuring tunnel stability. Precast concrete segments are widely employed because of their quick installation, excellent strength performance, and modular design, enabling accurate and controlled assembly as the tunnel progresses [8,11–13]. These components are required to resist a complex set of loads, such as radial ground pressures, bending moments, and axial forces that are transferred through the interconnected tunnel ring system [14–17].



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Despite their many benefits, TBM segmental linings also present certain structural challenges. A major issue is the formation of high stress concentrations, commonly occurring at the joints between segments, which act as critical zones of structural vulnerability [18–20]. Moreover, in adverse geotechnical environments—such as squeezing grounds, shear and fault zones, highly deformable soft clays, or zones with considerable ground relaxation—segmental linings may undergo excessive deformation, which can adversely affect their long-term stability and structural integrity [21–23]. This challenge is further intensified by uncertainties associated with insufficient in situ geotechnical information. Such gaps can result in overly conservative designs—leading to unnecessary resource consumption and higher costs—or, more critically, under-designed systems that introduce significant structural and safety problems [3,24–26]. To reduce material usage and construction costs while improving structural performance, various alternative approaches have been investigated, such as employing high-performance concrete or implementing prestressed lining systems [22,27–29]. Although successful in certain applications, these techniques possess inherent limitations, such as increased construction complexity or reliance on costly specialized materials, which can diminish the expected benefits. Consequently, finding a practical and efficient way to enhance the mechanical performance of thinner segments without these practical drawbacks continues to be an important research challenge [13,21,27].

TBM linings resist ground pressures through axial compression and flexural resistance [30–34], though segment joints often create stress concentrations that results in structural damage [8,16,17,35,36]. While reducing segment thickness offers economic and environmental benefits by decreasing volume of excavation, it significantly lowers lining stiffness and increases vulnerability to deformation [12,13,17,29,31,37,38]. Whereas existing research focuses on the use of steel plates for the rehabilitation and strengthening of over-deformed segmental linings [39,40], this study addresses a significant research gap by investigating their proactive integration during the initial design phase. Inspired by the efficiency of steel arches in NATM [24,33,41–43], this study explores steel rings to maintain stability in thinner TBM segments.

In recent years, continuous theoretical and numerical advancements in rock mechanics have significantly improved the prediction of complex geological failures and material degradation profiles under multi-axial stress fields [44,45]. However, a distinct gap remains in integrating these numerical simulation capabilities to systematically quantify the structural efficiency of steel rings within mechanized TBM linings. Despite the prevalence of numerical modeling in tunnel engineering [23,31,46–48], a literature gap exists in quantifying the specific impact of steel rings on TBM lining performance. This study is designed to bridge this literature gap. By performing a rigorous numerical comparative analysis using PLAXIS 3D, the structural performance is evaluated across three distinct model configurations: (1) 25 cm thin segments without reinforcement, (2) reference 40 cm thick segments without reinforcement, and (3) 25 cm thin segments strategically reinforced with steel rings. The analysis focuses on key performance indicators, including total displacement, the distribution patterns of axial (N_2) and shear forces (Q_{12}), and critical bending moments (M_{11}), with the goal of definitively ascertaining whether this integrated system can reliably achieve superior structural performance while allowing for substantial structural resource efficiency. This approach aligns with the broader objective of achieving performance-based optimization for future TBM-driven tunneling projects.

2. Materials and Methods

2.1. Numerical Modeling Software and Approach

For the numerical modeling in this study, the PLAXIS 3D software (Version 21.01.00.479, Bentley Systems, Exton, PA, USA) was utilized [23,49]. The dimensions

of the numerical models were carefully determined to be sufficiently large, thereby encompassing the full influence zone of the tunnel excavation within the surrounding ground. Consequently, for all three distinct tunnel models investigated, the overall dimensions were consistently set at 25 m (width) $\times$ 85 m (depth) $\times$ 100 m (length). The tunnel excavation process was specifically modeled to advance along the Y-axis of the coordinate system. Due to the inherent symmetrical nature of the tunnel structure, which implies symmetrical distributions of resulting deformations and stresses, modeling only the left half of the tunnel was sufficient for obtaining accurate and representative results.

2.2. Ground Conditions and Material Properties

The numerical analysis intentionally utilizes a uniform claystone profile and a fully bonded steel–concrete interface to establish a controlled baseline for evaluating the structural performance of the proposed lining configurations. By keeping the geomechanical domain and interface parameters constant across all developed models, the structural efficiency of the steel rings can be systematically isolated and compared directly against the conventional unreinforced lining framework. While geological heterogeneity, structural joints, and interfacial slippage significantly influence real-world tunnel behavior, these complex localized mechanisms are excluded from the current scope to focus strictly on the macroscopic load-sharing capacity of the steel rings, serving as a foundation for subsequent multi-layered and non-linear interface modeling stages.

The tunnel axis center was placed at an elevation of -13.25 m. Measured from the ground surface (El. $+60.00$ m), this configuration yields an absolute structural depth of exactly 73.25 m to the tunnel center, resulting in a significant nominal geostatic overburden depth of approximately 69 m from the ground surface to the tunnel crown (varying between 68.85 m and 69.00 m depending on the specific lining profile thickness; see Figure 1). The groundwater table was positioned at 0.00 m to ensure saturated conditions around the tunnel and to contribute to the high-stress environment. The Hoek–Brown failure criterion was utilized to simulate the rock mass behavior because it effectively accounts for the non-linear relationship between principal stresses and the interlocking nature of rock blocks. This model is particularly suitable for the jointed claystone rock mass investigated here, as it provides more realistic strength and deformation estimates compared to the linear Mohr–Coulomb model in fractured or jointed rock environments. The specific parameters for the Claystone are presented in Table 1.

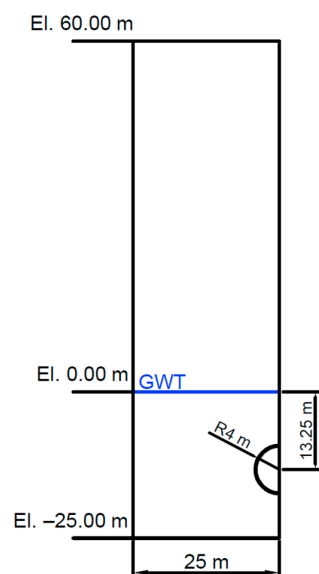


Figure 1. Vertical cross section of the tunnel model.

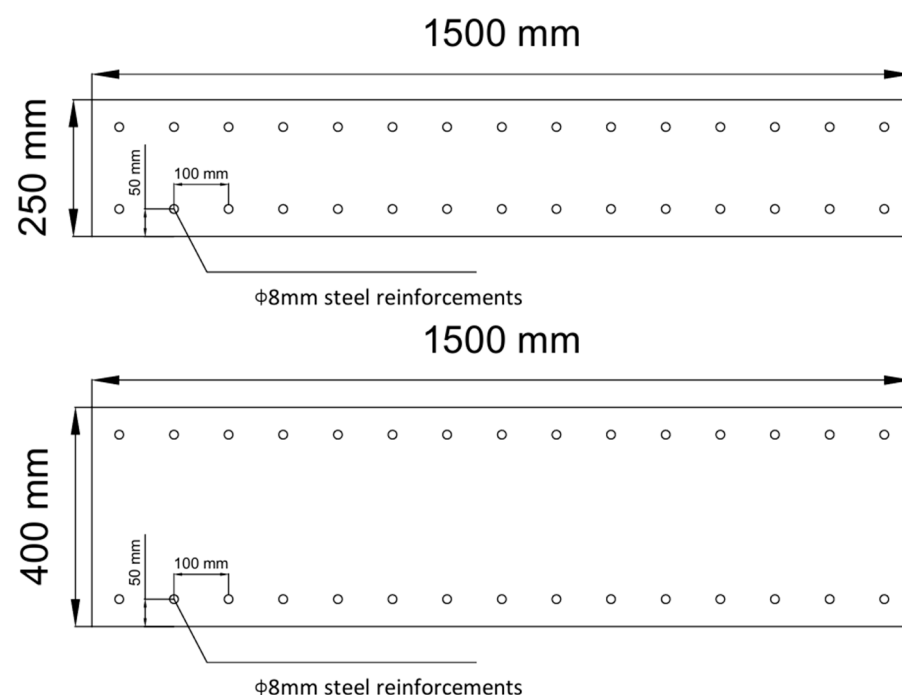
Table 1. Rock mass parameters of Claystone employed in the numerical analysis, showing inputs for the Hoek–Brown failure criterion.

Parameter	Value
Elevation Range (m)	+60.00 m to −25.0 m
Uniaxial Compressive Strength (intact rock), σ_{ci} (MPa)	20
Geological Strength Index (GSI)	25
Material Constant (intact rock), m_i	5
Disturbance Factor, D	0.8
Unit Weight, γ (kN/m ³)	23
Rock Mass Deformation Modulus, E_{rm} (GPa)	1.5
Poisson's Ratio, ν	0.3

To compare axial loads, shear forces, and moments in the reinforced concrete lining more reliably, the parameters have been used to reflect linear elastic behavior suitable for shell elements. The specific properties for the concrete lining, which were defined for plate elements in PLAXIS 3D, are detailed in Table 2. Representation of lining elements is avoided as continuum soil elements in PLAXIS 3D to facilitate the direct extraction and comparison of internal structural forces, such as axial loads, shear forces, and bending moments. Reinforcement placement of the concrete segments is shown in Figure 2 for both 25 cm and 40 cm thick segments.

Table 2. Linear Elastic Parameters for Concrete Segmental Linings.

Parameter	Value
Thickness (d) (m)	0.25 (Model 1 and 3) 0.40 (Model 2)
Unit Weight, γ (kN/m ³)	24
Material Model	Linear Elastic
Isotropic	Yes
Young's Modulus, E (GPa)	30
Poisson's Ratio, ν	0.20

**Figure 2.** Reinforcement placement of the concrete segments.

We did not explicitly model the internal steel reinforcements as geometric elements in PLAXIS 3D. Instead, it is verified that the structural safety of the sections during post-processing by comparing the extracted internal forces (N_2 , M_{11}) against N-M interaction diagrams. For the interface between the steel rings and concrete, it is assumed that a perfect bond to simulate full composite action.

We defined the steel ring elements—the central focus of this study—using a linear elastic material model and represented them as shell elements. For Model 3 (25 cm segments with rings), the thickness of these elements was set at 0.25 m. The specific material properties used for the steel rings are detailed in Table 3. It is assumed that a perfect bond between the steel rings and concrete segments to simulate full composite action and ensure structural integrity. While the macro-level global behavior in these models is evaluated using a perfect bond assumption to maintain numerical stability, the physical execution incorporates detailed structural joints. The S355 structural steel rings are designed as segmented arcs matching the division of the concrete segments, joined inside the TBM tail skin via high-strength, flush-bolted longitudinal flanged joints. Axial force and transverse shear transfer along the tunnel axis are maintained through mechanical shear keys or structural dowels embedded at the concrete–steel interfaces. To counteract durability risks in humid or chemically aggressive underground environments, the exposed structural steel surfaces are specified to undergo hot-dip galvanization or receive protective epoxy coatings prior to installation. Furthermore, to eliminate vulnerabilities to structural fire loads, the exposed internal faces of the steel rings are designated to be coated with a passive fire protection (PFP) layer, such as an intumescent paint or fiber-reinforced fireproofing mortar, ensuring complete compliance with international RWS or ISO thermal resistance regulations without requiring an initial concrete cover. The cross section of the steel ring and complete ring structure from tunnel cross section are shown in Figure 3.

Table 3. Linear Elastic Parameters for Steel Rings.

Parameter	Value
Thickness (d) (m)	0.25
Unit Weight, γ (kN/m ³)	78.50
Material Model	Linear Elastic
Isotropic	Yes
Young's Modulus, E (GPa)	210
Poisson's Ratio, ν	0.30

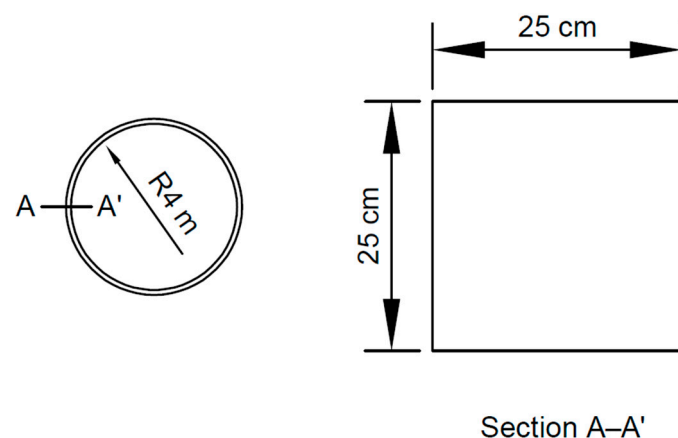


Figure 3. Steel ring cross section and complete steel ring structure.

We incorporated a simplified representation of the TBM shield body into the numerical model. This TBM body is defined by using plate elements with linear elastic properties

to simulate the presence and effect of the advancing machine during excavation. The specific parameters utilized for the TBM shield are presented in Table 4. Unit weight of 247 kN/m^3 is adopted for the TBM shield, following the recommendations in the PLAXIS 3D manual [50].

Table 4. Linear Elastic Parameters for the TBM Shield Body.

Parameter	Value
Thickness (d) (m)	0.17
Unit Weight, γ (kN/m^3)	247
Material Model	Linear Elastic
Isotropic	Yes
Young's Modulus, E (GPa)	200
Poisson's Ratio, ν	0.00

The 3D and profile views of the model are shown in Figures 4 and 5, respectively. To ensure numerical convergence and high spatial accuracy, the numerical domain is discretized utilizing a fine finite element mesh. The continuous rock mass is modeled using 10-node tetrahedral soil elements, which effectively capture non-linear stress gradients and plastic deformations. The tunnel lining segments, the TBM shield body, and the steel rings are systematically discretized using 6-node plate (shell) elements that incorporate both bending and shear stiffness formulations. The fully developed computational mesh consists of approximately 145,000 elements and 210,000 nodes, with local mesh refinement applied specifically within a 20-m zone surrounding the active tunnel perimeter to accurately capture the steep stress concentrations at the segment-ring interfaces. This targeted high-density refinement approach ensures mathematical stability and grid-independence for the extracted internal force gradients, without requiring an expanded global iterative mesh convergence matrix.

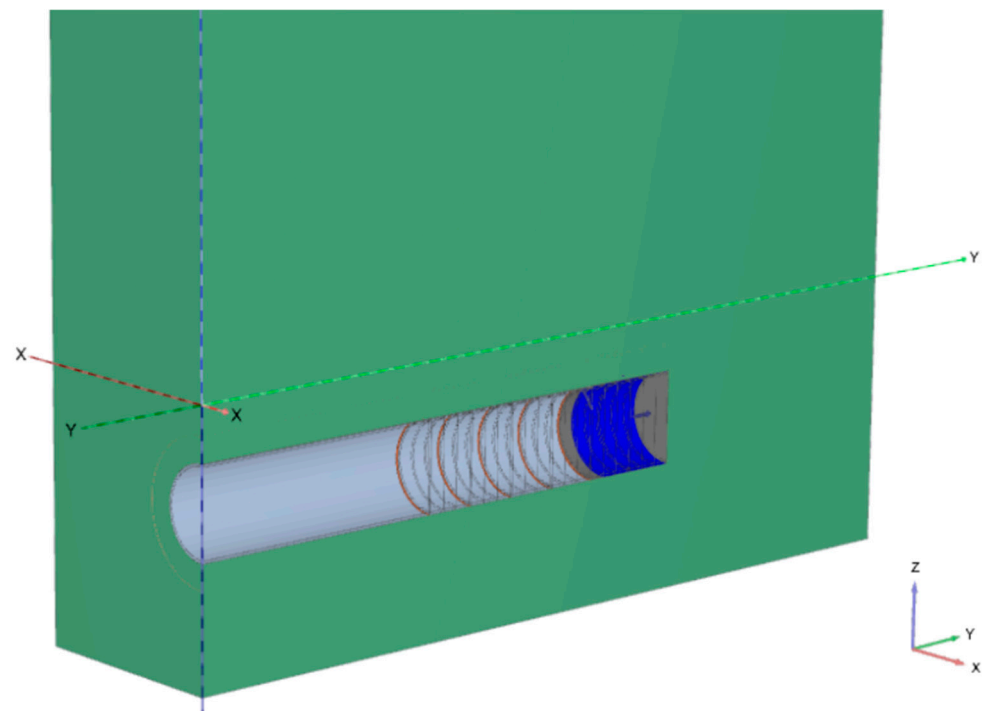


Figure 4. 3D view of the PLAXIS 3D model. The axes indicate the global coordinate system (X, Y, and Z). The blue segments represent the TBM Shield, while the orange lines indicate the steel rings.

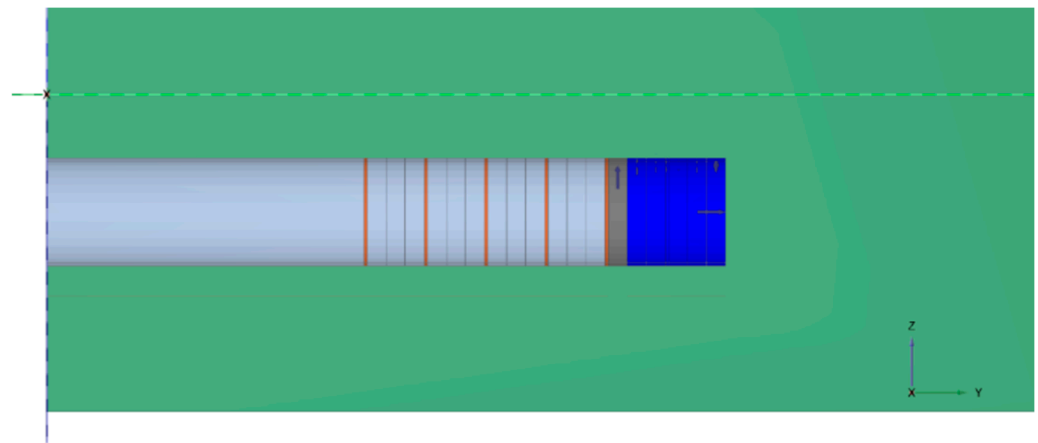


Figure 5. Profile view of the PLAXIS 3D model. The axes indicate the global coordinate system (Y and Z). The blue segments represent the TBM Shield, while the orange lines indicate the steel rings.

2.3. Geometric Model and Discretization

The internal diameter of the tunnel was set at 8 m for each individual model configuration. For sections with a segment thickness of 25 cm, the external tunnel diameter was 8.50 m, while for sections with a segment thickness of 40 cm, the external tunnel diameter was 8.80 m. The total tunnel length is defined to minimize boundary effects. The depth of the tunnel axis from the ground surface was 73.25 m. This depth was selected to evaluate the proposed lining system under high geostatic pressure conditions, representing a typical deep-tunneling scenario where conventional segments often reach their structural limits.

We modeled the lining segments with rectangular cross-sections, curving them to match the tunnel's circular geometry. Each segment possessed a constant width of 1.5 m in the longitudinal direction of the tunnel axis, corresponding to a single excavation step of 1.5 m during the tunnel advancement simulation. The segment thicknesses varied according to the specific model configuration:

- Model 1: 25 cm thick concrete segments without steel rings;
- Model 2: 40 cm thick concrete segments without steel rings;
- Model 3: 25 cm thick concrete segments with strategically placed steel rings.

We designed the steel rings with a solid square cross-section. Based on preliminary design assessments for structural efficiency and load distribution, a ring width of 0.25 m was adopted. These rings were positioned along the tunnel axis to provide optimal stability for the thinner segmental lining. A longitudinal placement strategy that installs steel rings every three segments has been chosen, resulting in a consistent 4.5 m spacing (3 segments $\times$ 1.5 m/segment). This configuration ensures robust load redistribution while balancing structural stiffness with the spatial constraints of the TBM trailing gear. In the numerical model, these rings are presented using shell elements. While the same geometric placement for the steel rings is maintained in Models 1 and 2, the primary distinction lies in the concrete segment thickness, which is defined as 0.25 m and 0.40 m, respectively. The placement of the steel rings along the tunnel axis is shown in Figure 6.

The mechanical connection between the adjacent concrete segments and structural steel rings along the tunnel axis is established through a shared node configuration at their coincident mesh boundaries to enforce continuity. Detailed mechanical connection components and time-dependent grout hardening characteristics are not explicitly incorporated into the model, as these parameters extend beyond the immediate comparative scope of this study and are designated for subsequent research stages.

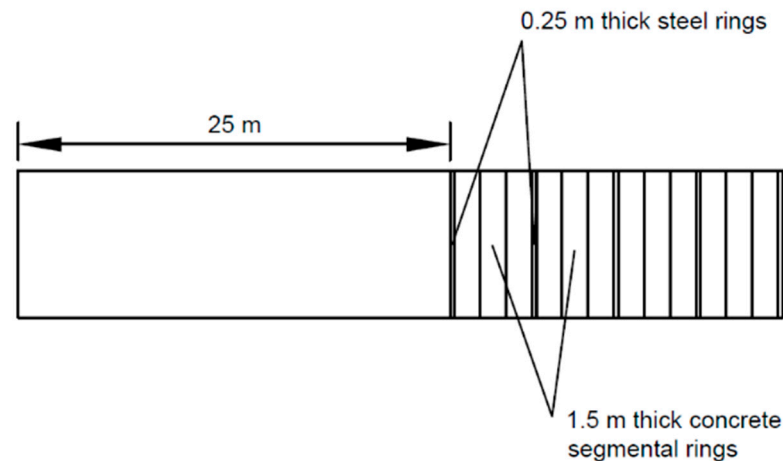


Figure 6. Longitudinal arrangement of steel rings, illustrating the 4.5 m spacing strategy (one ring per three segments) to optimize structural stiffness.

We performed the numerical simulation of the TBM tunneling process using a staged construction approach in PLAXIS 3D to replicate the sequential steps of excavation and lining installation.

In the initial phase, the in situ stresses are generated within the ground model using the K0 procedure to establish the pre-excavation stress state based on the defined soil properties.

Following the initial stress generation, the simulation proceeded through a series of sequential excavation and lining installation steps. It is assumed that the first 25 m of the tunnel were already excavated and lined. Subsequent excavation stages are modeled incrementally, with each phase representing a tunnel advancement of one standard segment length (1.5 m), within which the alternating structural steel rings feature a longitudinal width of 0.25 m.

During the excavation stages, three primary load conditions were applied uniformly:

- **TBM Face Pressure:** A uniform pressure of -750 kN/m^2 is applied normal to the excavation face to represent active ground resistance.
- **Tail Void Grouting Pressure:** A uniform pressure of -500 kN/m^2 is applied immediately behind the shield to model the stabilization of the annular void.
- **TBM Jacking Force:** A constant thrust pressure of 3500 kN/m^2 is applied normal to the segmental lining cross-section at the tunnel tail to simulate the machine's advancement force. This thrust load is applied uniformly to focus strictly on the steady-state operational performance of the lining system, whereas localized eccentric or non-uniform jack loading parameters are excluded from the current scope.

The staged analysis over 18 distinct phases have carried out for all three models to ensure a direct and consistent comparison. This uniform phase count has established because the steel rings were strategically placed (in Model 3) and their reinforced concrete equivalents (in Model 1 and Model 2) every third segment. Specifically, five of these 18 phases are dedicated to the installation and activation of these special elements, allowing for a precise evaluation of structural behavior across all design configurations.

All deformation, force, and moment values were compared among the tunnel models using the results from the final staged construction phase. This phase represents the full simulated tunnel length and reflects long-term equilibrium conditions.

We extracted a suite of key performance indicators (KPIs) from the PLAXIS 3D simulations to quantitatively assess and compare the structural benefits of each model. Although displacement values may not always show dramatic differences due to the nature of TBM tunneling, our analysis is primarily focused on internal forces and moments. These param-

eters are prioritized, as they serve as critical indicators of structural integrity and potential failure. The selected KPIs included the following:

- Deformations: Total displacements at segmental lining ($|u|$ or u_{total}).
- Axial Forces: Axial forces in the longitudinal direction (N_1) and axial forces in the cross-sectional direction (N_2).
- Shear Forces: Shear forces in the 1–2 (local axis) plane (Q_{12}), shear forces in the 2–3 (local axis) plane (Q_{23}), and shear forces in the 1–3 (local axis) plane (Q_{13}).
- Bending Moments: Bending moments in the 1–1 direction (M_{11}) and bending moments in the 2–2 direction (M_{22}).
- Torsion Moments: Torsion moments in the 1–2 direction (M_{12}).
- Moment Interaction Diagrams for Reinforced Concrete Segments: The diagrams are showing the capacity of the reinforced concrete segments with the corresponding axial forces (N_2) and moments (M_{11}).

3. Results

We present the findings in terms of ground and lining deformations and the distribution of axial forces, shear forces, bending/torsion moments within the lining elements, and moment interaction diagrams of the segmental linings. The data from the numerical models are extracted, specifically focusing on critical points and overall distributions to provide a comprehensive comparison.

3.1. Total Deformations

The simulation results indicate distinct deformation patterns for each tunnel model. Figure 7 illustrates the total deformation at the lining system in a bar chart. For every point of the models, the deformations of the Model 3 are equal to or smaller than those of the Model 2.

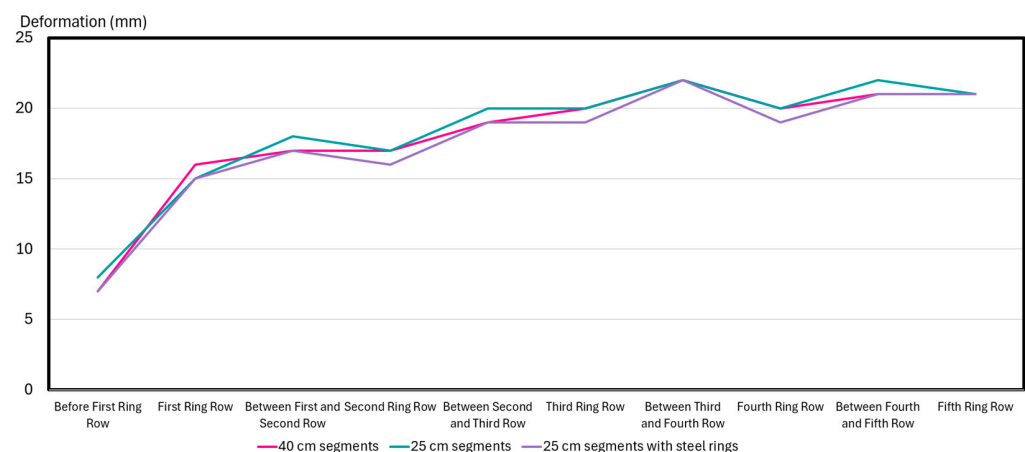


Figure 7. Comparison of total displacement across the three models; Model 3 demonstrates a significant reduction in deformation despite the thinner 25 cm lining.

3.2. Axial Forces in Cross-Sectional Directions

Since the segmental rings experience their primary load-carrying mechanism and most critical stresses in the cross-sectional plane, N_2 (the axial force in the cross-sectional direction) is selected as the most appropriate metric for comparison. To comprehensively assess the performance of both segments and steel rings, the maximum N_2 axial forces across the three design configurations were extracted and compared (see Figure 8).

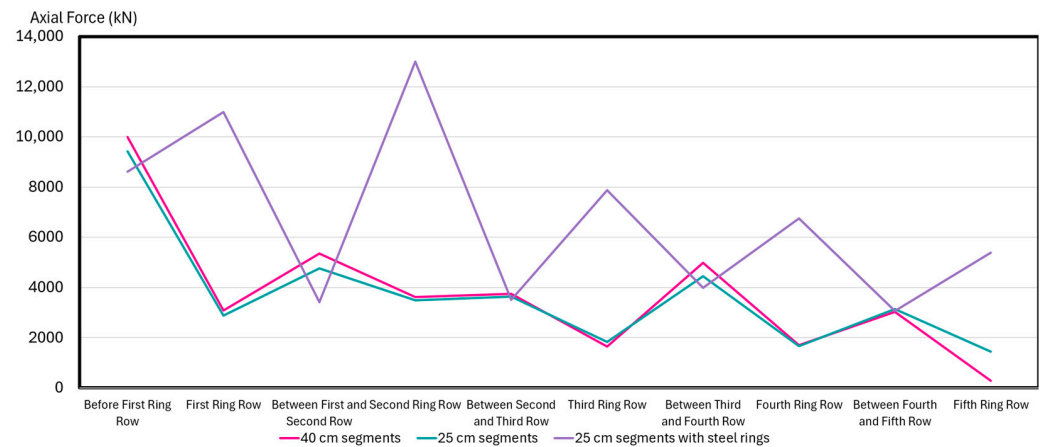


Figure 8. Distribution of axial forces (N_2) along the lining, highlighting how the steel rings effectively redistribute geostatic loads.

3.3. Shear Forces

To perform a direct and relevant structural comparison, the shear force in the 1–2 direction (Q_{12}) was selected as the primary indicator. This selection was based on its direct relevance to the load transfer across segment interfaces and the composite action between the concrete and steel rings. Accordingly, the maximum shear forces (Q_{12}) are presented and compared in Figure 9, highlighting the performance differences across the three tunnel models.

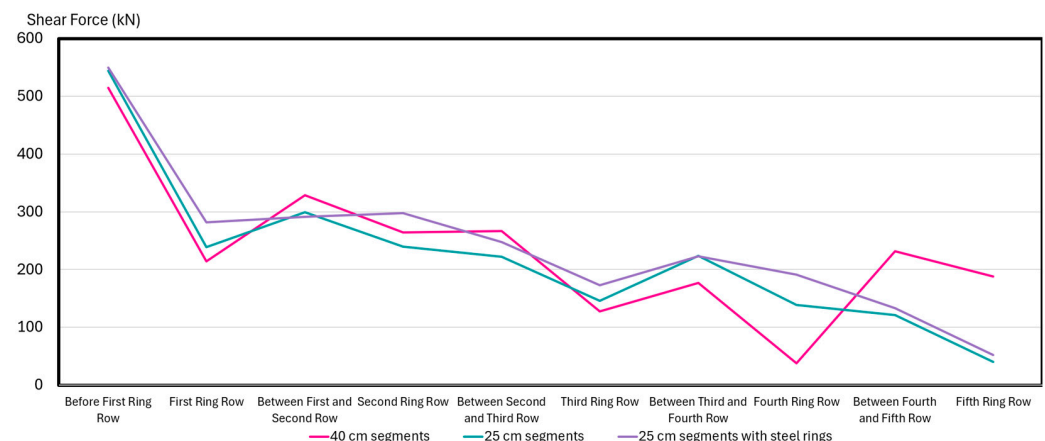


Figure 9. Shear force (Q_{12}) analysis, confirming that the hybrid segment-ring system maintains structural integrity within safe engineering limits.

3.4. Bending Moments

We established the M_{11} bending moments as the key comparative criterion to assess structural performance and the efficiency of the steel ring reinforcement. This selection is based on the critical observation that the M_{11} moment represents the bending demand that forces the tunnel cross-section inward, analogous to the bending in a column. Since the lining's most critical load-bearing mechanism and potential failure modes relate to this transverse flexural behavior, the M_{11} moments are considered to be the most defining values. Accordingly, the maximum M_{11} values are systematically compared in the subsequent figures to quantify the structural benefits across the three model configurations (see Figure 10).

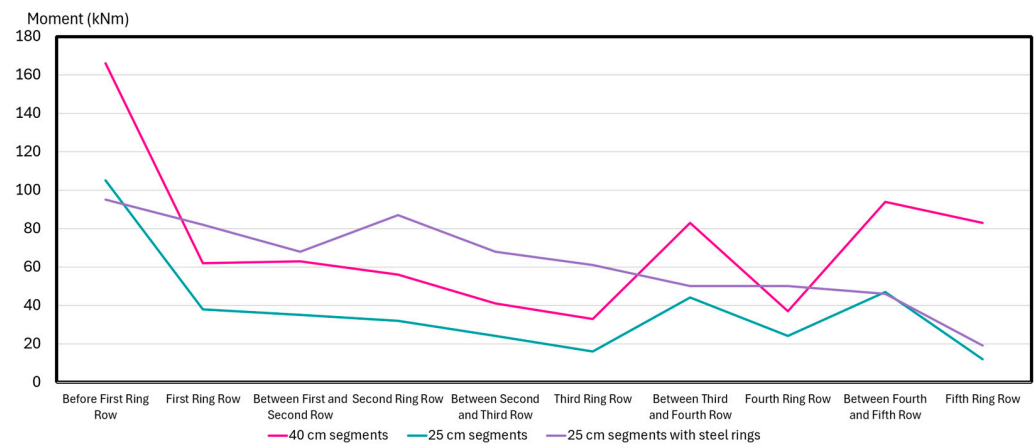


Figure 10. Bending moment (M_{11}) distribution, showing the stabilization effect of the proactive reinforcement system in high-pressure conditions.

3.5. Member Forces in Steel Rings

We performed a simple interaction check for combined axial load and bending moment to confirm the structural viability of the proposed steel ring, using the maximum forces derived from the PLAXIS 3D model. The steel ring, defined with a $0.25 \text{ m} \times 0.25 \text{ m}$ solid rectangular cross-section and S355 steel, is subjected to the maximum calculated axial load ($N = 13,000 \text{ kN}$) and bending moment ($M = 87 \text{ kNm}$). The resulting interaction ratio of 0.658 confirms that the steel ring possesses sufficient structural capacity to sustain the transferred ground loads. This result validates the robustness of the integrated reinforcement, demonstrating its ability to effectively support internal forces with a reliable safety margin and serving as a feasible supplementary element for optimized TBM linings.

3.6. Segmental Lining Interaction Curves

We generated the interaction curves based on the relationship between the transverse axial force (N_2) and the longitudinal bending moment (M_{11}) acting on the segments. To define the ultimate capacity of the reinforced concrete sections, the following details are used:

- Section Width (b): 1500 mm.
- Section Depths (h): 250 mm or 400 mm.
- Reinforcement Details: Each segment cross-section included two layers of $\phi = 8 \text{ mm}$ diameter reinforcement bars, placed at 100 mm center-to-center spacing.

We plotted the N_2 and M_{11} force–moment pairs, extracted from every node in the PLAXIS 3D analysis, directly onto the segment's theoretical N–M capacity curve to assess the structural demand relative to the ultimate capacity. Our analysis focuses on the most critical zone—the region between the first and second steel ring rows—where axial forces reach their peak. The resulting interaction curves and corresponding data points are presented in Figure 11 (40 cm without steel ring) and Figure 12 (25 cm with steel ring). Finally, absolute values for the moments were used, as the capacity diagram is symmetrical along the axial force axis.

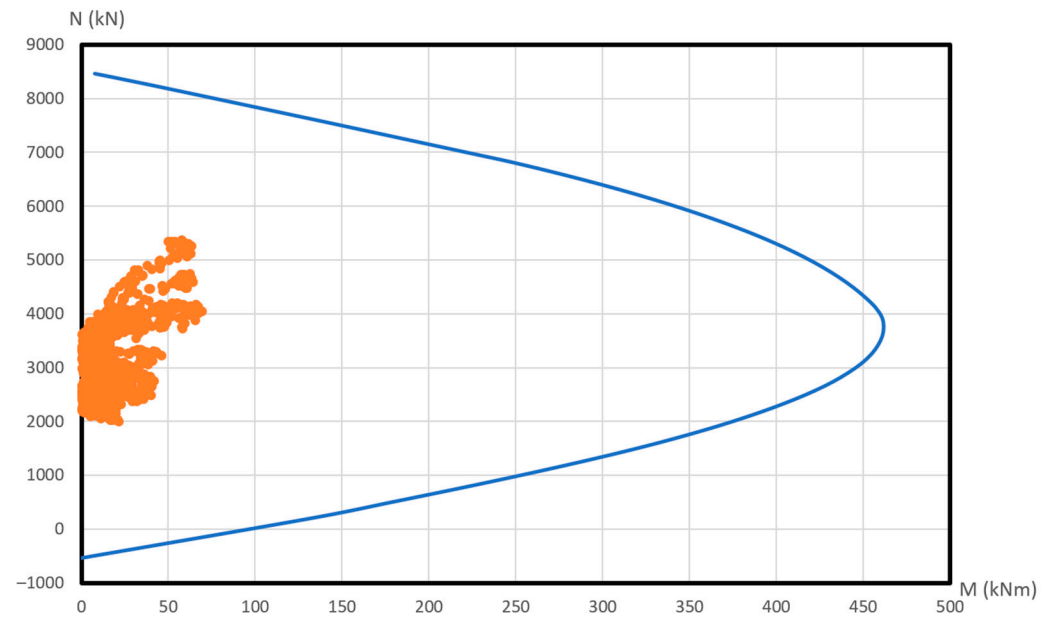


Figure 11. N-M curve of segmental lining between the first and second ring row of Model 2. The orange points represent the combined axial force (N) and bending moment (M) values acting on the segment cross section, while the blue line indicates the capacity limit boundary.

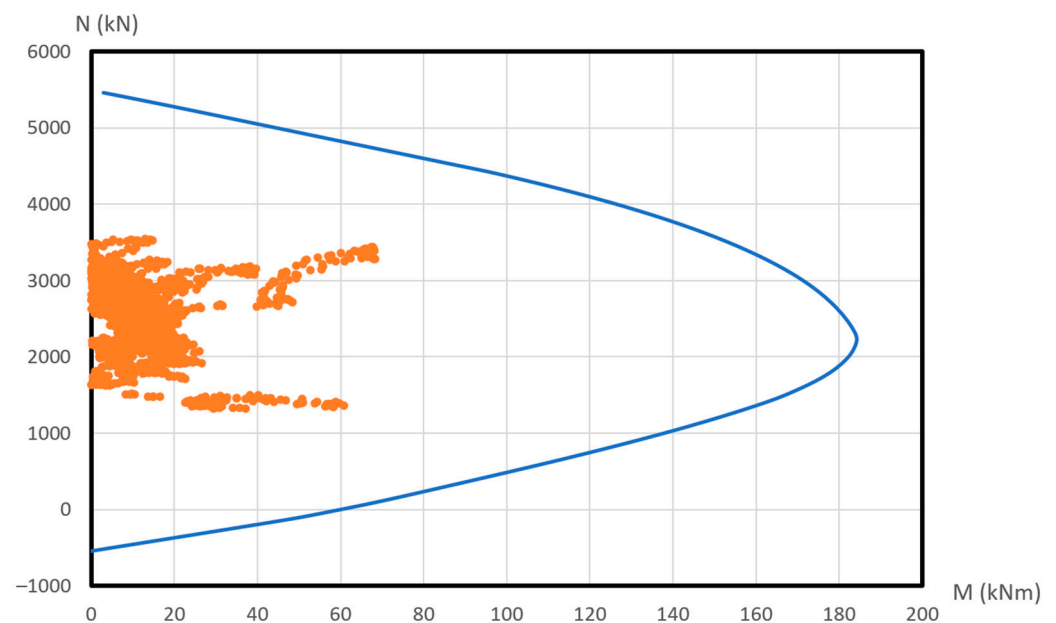


Figure 12. N-M curve of segmental lining between the first and second ring row of Model 3. The orange points represent the combined axial force (N) and bending moment (M) values acting on the segment cross section, while the blue line indicates the capacity limit boundary.

4. Discussion

4.1. Deformational Behavior and Structural Stability

The analysis shows that steel rings slightly reduce overall displacements compared to the lining without steel rings. While the steel-ring-reinforced model exhibits lower deformations, the limited difference in global displacement magnitude between the two configurations reveals a critical geomechanical mechanism. This behavior confirms that in high-pressure deep tunnels, global boundary convergence is primarily governed by the overall ground–structure stiffness rather than localized lining alterations. This outcome critically aligns with the numerical observations [8,12,17], where secondary stiffness-enhancing

measures primarily optimize localized stress trajectories and structural deformation control rather than forcing substantial drops in macroscopic tunnel convergence.

The presence of supplementary support elements contributes positively to the structural stability of TBM tunnel linings by increasing confinement and overall system stiffness [13,18,32]. In particular, steel rings can act as a stabilizing structural component that limits localized deformations and improves the lining's resilience against unfavorable ground conditions or construction-related irregularities. This effect is especially relevant when reduced segment thickness is adopted for material and cost optimization, as thinner linings are generally more sensitive to stress concentrations and joint behavior [29].

4.2. Internal Forces and Stress Redistribution

The numerical results reveal distinct patterns of load redistribution associated with the presence of steel rings. The marginal variance observed in the maximum shear force (Q) values between the unreinforced and ring-reinforced configurations provides a critical validation of lining kinematics. This confirms that the dominant structural flexibility of segmental longitudinal joints intrinsically governs the overarching macro-level shear transfer across the ring architecture, a structural phenomenon heavily evaluated by [20,36]. However, we found that localized stress concentrations around the steel rings successfully de-escalate the net shear demand within the concrete block core expands upon the classical framework of [32], demonstrating that the hybrid setup induces a highly favorable, decoupled stress state within the concrete matrix without altering joint configurations.

Regarding axial forces, the longitudinal component (N_1) reflects the contribution of steel rings along the tunnel axis, while the circumferential axial force (N_2) provides clearer evidence of their structural efficiency [18,43]. Since N_2 forces are primarily responsible for resisting overburden loads and maintaining ring stability, the ability of steel rings to absorb a significant portion of these forces is structurally advantageous.

We observed a similar trend for the bending moments. Among the evaluated components, the transverse bending moment M_{11} shows the most pronounced reduction in the concrete segments due to the presence of steel rings. This indicates that the steel rings effectively attract a higher share of bending demand, allowing the thinner concrete segments to safely resist the remaining loads.

The N–M interaction analysis further supports these findings. All N_2 – M_{11} load combinations obtained from the numerical model fall within the safe capacity domain of the interaction diagrams for the adopted cross-sections, confirming the structural adequacy of both the conventional and optimized lining configurations.

4.3. Implications for Design Optimization and Sustainability

The results indicate that the use of steel rings enables a performance-based optimization of TBM tunnel linings. The analyses demonstrate that 25 cm thick segments reinforced with steel rings can achieve structural performance comparable to that of conventional 40 cm thick unreinforced segments. Similar optimization approaches have been discussed in the literature as effective strategies for improving structural efficiency without compromising safety [13,17,29].

The 37.5% reduction in concrete segment thickness yields high geometric efficiency by optimizing the tunnel's outer excavation diameter from 8.80 m to 8.50 m. This structural trade-off introduces an additional steel demand of 2.83 tons per meter but results in a significant concrete volume saving of approximately 5.2 m³ per linear meter, corresponding to a 43.7% decrease in concrete consumption. Consequently, this geometric optimization simultaneously minimizes excavation volumes and simplifies downstream underground construction logistics within deep formations [2,13,29,51].

Beyond construction efficiency, the improved deformation control and reduced bending moments observed in the reinforced lining contribute to enhanced structural robustness and may support a longer service life with reduced maintenance requirements [15,22,52]. Furthermore, the significant reduction in concrete consumption aligns with sustainability objectives of the tunnel lining system [28,29,51].

These findings contribute directly to alternative design methodologies for deep underground structural support systems and tunneling standards. Currently, most standards suggest increasing segment thickness for deep tunnels, which uses too much material. Our study shows that using thinner segments with steel rings is a more efficient and sustainable alternative. This approach could encourage new design codes that focus on structural performance and resource efficiency instead of just using thicker concrete.

However, there are some practical trade-offs when using steel rings. While they save a large amount of concrete, the cost of steel and the extra steps during installation must be managed. Installing these rings inside the TBM requires careful planning and may take extra time. To solve these issues, contractors can use automated systems and pre-made steel parts that fit together quickly. These solutions make the hybrid system more practical and help balance the higher cost of steel with the savings from using less concrete and smaller excavation areas.

5. Conclusions

This study compared different lining configurations using a numerical analysis utilizing the PLAXIS 3D Finite Element Method to rigorously investigate the structural efficiency of integrating steel rings as a novel strategy for optimizing TBM segmental linings. The immediate evidence-based findings confirm that the 25 cm thin segments, when reinforced with strategically placed steel rings, achieve structural performance levels comparable to conventional 40 cm thick unsupported segments under high-overburden conditions. This primary structural benefit stems from a superior load redistribution mechanism, where the steel rings effectively manage and absorb substantial N_2 axial forces, consequently reducing the critical M_{11} bending moments and flexural demands on the concrete elements. This enhancement in load transfer is systematically evaluated within the specified numerical framework by the N-M interaction analysis, which confirms that the loading points for the thin, reinforced segments fall well within the ultimate capacity curve, thereby maintaining a significant structural safety margin. Ultimately, as highlighted during the text conciseness consolidation, the design innovation enables performance-based optimization by achieving a 43.7% concrete volume reduction per linear meter, thereby lowering initial material baselines and optimizing the necessary excavation profile. While these numerical outcomes provide valuable structural insights, it is important to acknowledge certain boundaries and operational trade-offs. The overall long-term economic benefit depends on the balance between concrete production savings and increased steel or specialized installation expenditures. Additionally, since our findings are mapped to a specific Claystone profile under high geostatic pressure, these behavioral dynamics may vary across softer soils, sands, or highly fractured rock masses with complex groundwater configurations. To bridge these numerical baselines with real-world construction execution, future engineering expectations prioritize the parametric design optimization of ring layouts, long-term creep or shrinkage evaluations, full-scale experimental testing, and field sensor tracking during pilot deep tunnel drives.

6. Patents

The structural design concept, geometric layout, and proactive reinforcement mechanisms of the steel ring system for TBM tunnel segmental linings reported in this manuscript

are currently subject to preparation for a formal patent application. The authors intend to initiate the official patent filing and intellectual property protection registration procedures following the formal publication of this research work.

Author Contributions: Conceptualization, C.Ç., B.U. and C.G.; methodology, C.Ç. and B.U.; software, C.Ç.; validation, C.Ç. and C.G.; formal analysis, C.Ç.; investigation, C.Ç. and C.G.; resources, B.U.; data curation, C.Ç.; writing—original draft preparation, C.Ç.; writing—review and editing, C.Ç., B.U. and C.G.; visualization, C.Ç.; supervision, B.U.; project administration, B.U. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The datasets generated and analyzed during the current study (specifically the PLAXIS 3D numerical models and extracted structural force data) are available from the corresponding author on reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

D	Disturbance Factor
E	Young's Modulus/Modulus of Elasticity
E_{rm}	Rock Mass Deformation Modulus
FEM	Finite Element Method
GSI	Geological Strength Index
GWT	Groundwater Table
ISO	International Organization for Standardization
K_0	Coefficient of Earth Pressure at Rest
KPI	Key Performance Indicator
M_{11}	Transverse Bending Moment
M_{12}	Torsion Moment
M_{22}	Longitudinal Bending Moment
m_i	Intact Rock Material Constant
N_1	Longitudinal Axial Force
N_2	Circumferential/Cross Sectional Axial Force
NATM	New Austrian Tunnelling Method
PFP	Passive Fire Protection
Q_{12}	Primary In-Plane Shear Force
Q_{13}	Out-of-Plane/Transverse Shear Force in 1–3 local plane
Q_{23}	Out-of-Plane/Transverse Shear Force in 2–3 local plane
RWS	Rijkswaterstaat (Standard Thermal Fire Curve for Tunnels)
S355	Structural Steel Grade (with a minimum yield strength of 355 MPa)
TBM	Tunnel Boring Machine
u_{total}	Total Displacement
ν	Poisson's Ratio
σ_{ci}	Uniaxial Compressive Strength of Intact Rock
γ	Unit Weight

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