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Effect of Moving Train Load on Tunnel Deformation and Track-Tunnel Interaction

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ABSTRACT: Underground railway transportation systems offer a sustainable solution to urban space constraints. However, the construction of such structures presents significant challenges, including ensuring a stable environment for a smooth train transition and balanced interaction between the tunnel and the surrounding soil. This study investigates the influence of moving train load on the concrete inlay and soft rock formations adjacent to the tunnel. A viscoelastoplastic model is developed considering Hooke's, Newton's and St. Venant's elements. An integrated interaction of track and tunnel systems is considered to assess the behaviour of the integrated track-tunnel system and to understand the long-term stability of tunnels in soft rock formations.

1 INTRODUCTION

In view of the ever-growing demand for space in urban environments, constructing underground railway systems offers a practical and sustainable solution. This approach not only saves land use but also contributes to sustainability by minimising noise pollution, reducing disruption to the natural landscape, and ultimately improving the quality of life. Nevertheless, building underground transport networks is complex and requires careful design, which considers all factors essential for feasibility and long-term performance. While modern tunnel construction increasingly favours non-ballasted systems such as fixed or floating slab tracks due to their lower maintenance demands and geometric stability (Gala et al., 2020), a significant number of existing and new railway tunnels still utilise conventional ballasted tracks. These ballasted systems present unique and complex challenges, particularly concerning the time-dependent deformation of the granular ballast and the long-term creep settlement of the surrounding ground, which is the specific focus of this investigation.

The engineering challenges and dominant deformation mechanisms in tunnelling are fundamentally dictated by the geological setting. In hard rock, stability is primarily governed by structural discontinuities, and time-dependent deformation is often negligible, with design focused on controlling block falls or rock bursts (Hoek & Marinos, 2000). Conversely, in soft ground, the critical challenges are low strength and high compressibility, where long-term settlement is mainly driven by consolidation processes (Zhang et al., 2021b). However, soft rock formations are prone to significant time-dependent creep settlement under sustained train (Kovačević et al., 2021).

Effective design and maintenance planning for underground railways necessitate a comprehensive understanding of the railway track, the tunnel structure, and the surrounding ground. Several methods exist for analysing such systems, including empirical approaches, numerical simulations, and rheological modelling. Empirical equations rely on experience and have a limited scope for complex designs, and numerical simulations are time-consuming and expensive. In contrast, rheological modelling provides a more robust way to assess underground responses (Zhang et al., 2021b).

Previous research has primarily focused on evaluating ground movements under instantaneous conditions. However, assessing the time-dependent stability is crucial for ensuring the safety and stability of underground structures (Zhang et al., 2021a). Time-dependent stability issues include deformations of the tunnel lining and the surrounding soil (Hu et al., 2024). Some researchers, such as Hu et al. (2024), employed the rheological model following the Kelvin-Voigt theory to address these issues in the ground surrounding the tunnels. Zhang et al. (2021a) investigated the time-dependent behaviour of ground movements in tunnel soil using a Boltzmann viscoelastic model.

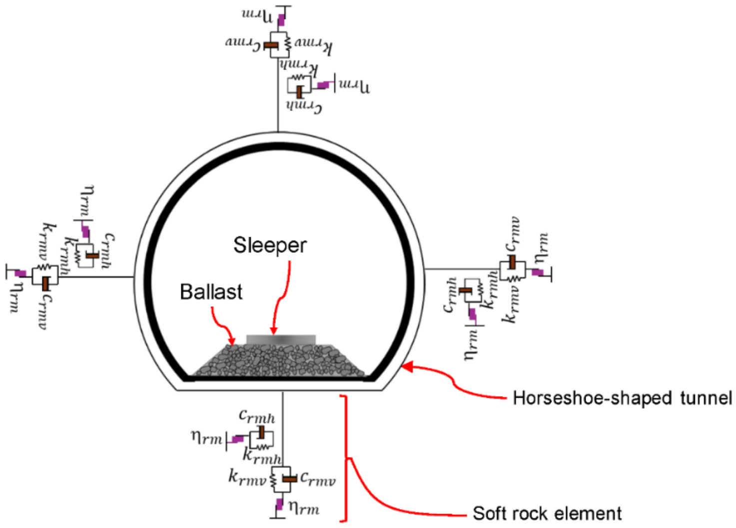
For a well-designed railway tunnel, the surrounding ground must be stable, ensuring minimal deformation occurs during train operations. For such complex structures, ground settlements are often overlooked in their design. However, this assumption is fallacious when the tunnel is situated in soft rock, as these rocks are prone to time-dependent creep settlement (Kovačević et al., 2021). Past studies have also focused on the assessment of time-dependent behaviour using viscoelastic and viscoplastic approaches. For example, Yang et al. (2020) evaluated tunnel safety in argillaceous sandstone by studying its permeability characteristics, Kovačević et al. (2021) and Li et al. (2023) studied the soft rock surrounding the tunnel using Burger's model, while Zaheri and Ranjbarnia (2024) analysed the time-dependent behaviour of pressurised circular tunnels. These studies evaluate the time-dependent response due to overburden and surcharge pressures, using viscoelastic or viscoplastic models. A more complete understanding requires investigating the integrated interaction of track and tunnel systems, encompassing both elastic and plastic responses. This can be achieved using a viscoelastoplastic model, by incorporating both immediate elastic deformation and time-dependent plastic flow, allowing for a more accurate assessment of overall tunnel stability. In addition, most prior research using rheological models has focused on circular tunnels, while the horseshoe shape is more commonly used in practice.

To address these limitations, this study presents a computational methodology for analysing the dynamic effects of moving train loads on an integrated tunnel-track system. The approach employs a novel viscoelastoplastic model that simulates the behaviour using a combination of Hooke's, Newton's, and St. Venant's elements. The model represents a ballasted track with a ballast layer resting on a concrete inlay, treated as a rigid base behaving like a continuous beam. The tunnel is horseshoe-shaped. To simulate the interaction with the surrounding weak rock in the rheological model, Hooke's and Newton's elements are integrated at the concrete inlay interface to represent stiffness and damping, while St. Venant's elements are included to specifically model the plasticity of the soft rock. The accuracy and reliability of the model have been demonstrated by validating against results from past investigations.

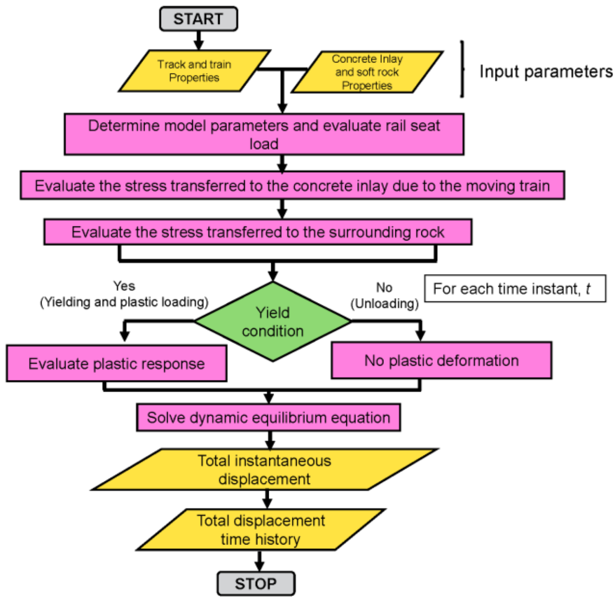
2 MODEL DEVELOPMENT

This study proposes a viscoelastoplastic rheological model for an integrated tunnel-track system. The system consists of a ballasted railway track positioned on a concrete inlay, which is treated as a rigid beam, surrounded by soft rock. The soft rock is the karstic rock, which is prone to creep and settlement. Figure 1 (a) shows the viscoelastoplastic model of the integrated tunnel track surrounded by karstic rock and Figure 1 (b) includes a flowchart to represent the plastic strain accumulation process for each time step. The model incorporates Hooke's (elastic), Newton's (viscous), and St. Venant's (plastic) elements for both the ballasted track and the surrounding rock mass.

For determining the response of the tunnel and the surrounding rock under a moving train load, the dynamic response is first evaluated. The resulting stresses transferred from the track to the inlay are then treated as internal pressure to predict the deformation of the surrounding weak rock. Plasticity in the ballast is based on the Nor-Sand model (Jefferies, 1993), employing a non-associated flow rule (Oka and Kimoto, 2017). For the weak rock, the Hoek-Brown strength criterion is utilised to define its yield behaviour, capturing the time-dependent deformations (Hoek & Brown, 2019).



(a)



(b)

Figure 1 (a) Viscoelastoplastic model of a horseshoe-shaped tunnel surrounded by soft rock (b) flowchart for determining response

The Nor-Sand model developed is based on critical state theory and captures the track response under various conditions. A non-associated flow rule is applied to the granular ballast to depict the realistic material behaviour. The yield surface (*f*) was defined by Jefferies and Been (2015) using the following equation:

$$f = {}^{\eta}/_{M_i} + ln({}^{p}/_{p_i}) - 1 \quad (1)$$

where M is the critical stress ratio; subscript i represents image state condition; η is the ratio of deviatoric (q) to mean effective stress (p), defined using the following equations:

$$p = \sigma_{kk}/3 \quad (2)$$

$$q = \sqrt{\frac{3}{2}\sigma_{ij} - p\delta_{ij}} \tag{3}$$

where σ_{ij} is the stress tensor and δ_{ij} is the Kronecker delta.

The non-associated flow rule accounts for both the yield function (*f*) and plastic potential function (g) as distinct terms in this study. The plastic potential function is defined using the following equation:

$$g = \frac{\eta}{M_g} + \ln\left(\frac{p}{p_i}\right) - 1 \tag{4}$$

where M_g is the dilatancy-modified stress ratio; p_i is the mean effective stress in the image state condition. The stress-dilatancy relationship for the non-associated was given by Oka and Kimoto (2017) and is expressed as:

$$D_{ij} = \frac{1}{N} \times \frac{d\varepsilon_v^p}{d\varepsilon_q^p} \tag{5}$$

where D_{ij} is the plastic dilatancy; $d\varepsilon_v^p$ and $d\varepsilon_q^p$ are the plastic volumetric and deviatoric strain increments; N is the non-associativity parameter ($0 < N < 1$). Table 1 includes the input parameters used in this study for evaluation of elastic and plastic deformation of the track.

For evaluating the plasticity of the surrounding rock, the Hoek-Brown criterion is utilised, which is based on three essential parameters: uniaxial compressive strength (σ_c), a constant m_i and geological strength index (GSI) (Hoek & Marinos, 2000). In this study, σ_c values were adopted from the triaxial tests utilised in the study of Kovačević et al. (2021), m_i and GSI were determined either from qualitative rock description outlined by Hoek and Brown (1997). The generalised expression for this criterion is defined using the following equation:

$$\sigma'_1 = \sigma'_3 + \sigma_c\left(m_b{}^r \frac{\sigma'_3}{\sigma_c} + s^r\right)^a \tag{6}$$

where σ'_1 and σ'_3 are the major and minor principal stresses (MPa); σ_c is uniaxial compressive strength; $m_b{}^r$, s^r and a are rock mass constants, expressed as follows:

$$m_b{}^r = m_i \times e^{\left[\frac{GSI-100}{28-14D_f}\right]} \tag{7}$$

$$s^r = e^{\left[\frac{GSI-100}{9-3D_f}\right]} \tag{8}$$

$$a = 0.5 + 0.17\left(e^{-GSI/15} - e^{-20/3}\right) \tag{9}$$

where m_i is a material constant; D_f is the disturbance factor signifying damage, which is influenced by the dilation caused in the rocks due to excavations in the surroundings. The various input parameters used in this study are included in Tables 1, 2 and 3.

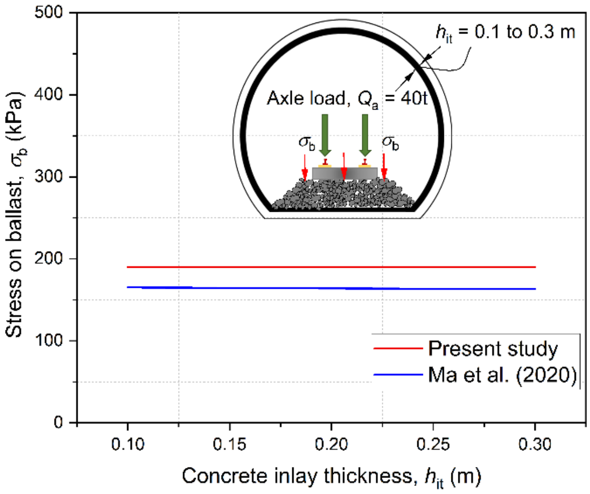


Figure 2 Comparison of stress on ballast calculated using present study and results of Ma et al. (2020)

Table 1 Input parameters for the railway ballast

Parameters	Symbol	Unit	Value
Young's modulus of ballast	E_b	MPa	276
Poisson's ratio of ballast	ν_b	-	0.3
Density of ballast	ρ_b	kg/m^3	1760
Thickness of ballast	h_b	m	0.3
Shear stiffness of ballast	k_b^s	MN/m	78.4
Shear damping of ballast	c_b^s	kNs/m	80
Critical stress ratio	M_{tc}	-	1.25
Slope of critical state line	λ	-	0.05
Hardening parameter	H	-	50-250
Cyclic hardening parameter	a_h	-	0.9
Volumetric coupling coefficient	N_v	-	0.2
Non-associativity parameter	N	-	0.5
Maximum dilatancy	χ_i	-	3

3 MODEL VALIDATION

To validate the model, results were compared against a previous study by Ma et al. (2020), who developed a model of a single-track ballasted tunnel in rock to investigate damage and fatigue under a heavy 40t axle load simulated with an excitation force function. Figure 2 presents this comparison, specifically showing the vertical stress on the ballast top as the thickness of the inlay varies, as calculated by both Ma et al. (2020) and the present study. The close agreement between the results suggests that the present model is capable of accurately simulating track-tunnel behaviour. This comparison demonstrates the ability of the model to capture and predict key stress distributions within the tunnel structure, highlighting its potential value for assessing and reducing damage risks associated with ballasted tunnel operations.

Table 2 Input parameter values for concrete inlay and sleeper

Parameters	Symbol	Unit	Value
Concrete inlay:			
Young's modulus	E_{it}	MPa	0.0033
Poisson's ratio	v_{it}	-	0.3
Thickness	h_{it}	m	0.02
Damping	c_{it}	kNs/m	100
Stiffness	k_{it}	kN/m	1.7×104
Density of sleeper	ρ_s	kg/m^3	2500
Width of sleeper	b_s	m	0.3
Length of sleeper	l_s	m	2.6
Sleeper spacing	s	m	6.5

Table 3 Input parameter values for soft rock

Parameters	Symbol	Unit	Value
Poisson's ratio	v_{rm}	-	0.25
Internal friction angle	φ	°	25
Density	ρ_{rm}	kg/m3	2450
Geological strength index	GSI	-	29
Material constant	m_i	-	7
Young's modulus	E_r	MPa	20000
Rock mass constants	s^r	-	0.001
	a	-	0.5
Disturbance constant	D_f	-	0.1

4 RESULTS AND DISCUSSION

In an integrated tunnel-track system, concrete inlay thickness, h_{it} is a critical factor that influences the structural behaviour and load capacity of the system. To assess its impact, h_{it} was systematically increased from 0.02 to 0.1 m. This investigation revealed that increasing the inlay led to a roughly proportional increase of approximately 50% in both inlay deflection, d_{it} and reaction force, f_{it}. However, the rate of this increase was highest for smaller thickness increments, i.e., a 25.9% rise between 0.02 and 0.05m, and decreased significantly for greater thicknesses, i.e., only 6.3% from 0.075 to 0.1m. This indicates that the effectiveness of increasing inlay thickness diminishes at higher values. This behaviour is consistent with findings from Ma et al. (2020), who noted that increased h_{it} improved stress distribution on the inlay, likely due to enhanced stiffness and reduced stress concentration. Figure 3 demonstrates how h_{it} affects the overall structural response.

Evaluating the impact of repetitive train loads on soft rock settlement, S_r was conducted for the tunnel embankment for a depth of 30 m. The tunnel is located at 20 m depth from the ground surface, z. Figure 4 presents these findings, showing that S_r varied non-linearly with z. For a 25t axle load at 150 km/h, the highest S_r of 1.3 mm was recorded at the tunnel base, decreasing sharply to become almost negligible (99% reduction) at the ground surface. This pattern indicates that the influence of train loads on rock settlement is concentrated near the tunnel, having minimal impact closer to the surface.

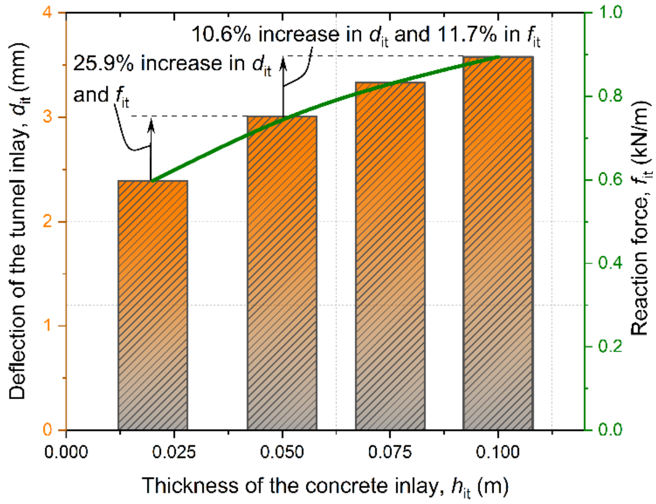


Figure 3 Deflection and reaction force on the concrete inlay due to increasing thickness of the concrete inlay

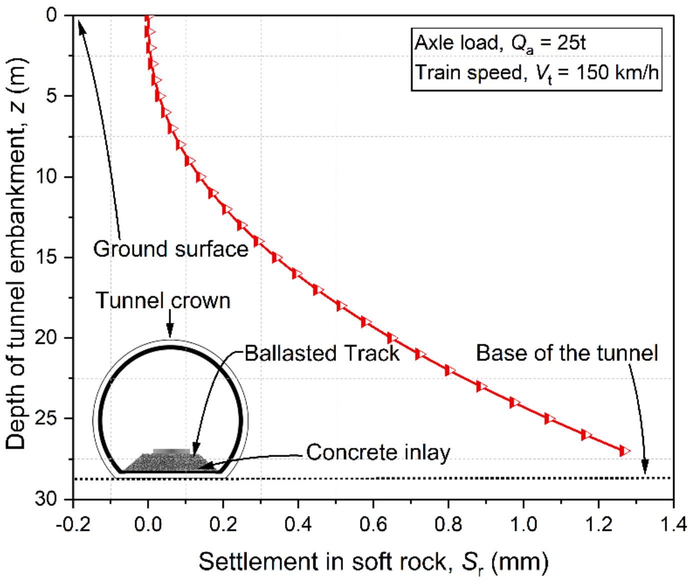


Figure 4 Settlement in the soft rock due to train passage

5 CONCLUSIONS

Construction of underground railways in soft rock poses severe challenges, particularly concerning time-dependent stability under dynamic train loads. In order to address gaps in previous literature, this study presents a novel viscoelastoplastic model for the integrated tunnel-track and the surrounding soft rock. The model is validated against past studies. The model simulates complex material behaviour using Hooke's, Newton's, and St. Venant's elements, incorporating the Nor-Sand and Hoek-Brown criteria. The dynamic track-inlay response and resulting ground (soft rock) settlement are evaluated. Key findings illustrate the increased deflection of the concrete inlay with an increase in concrete inlay thickness. The results from the present study reveal that train-induced rock settlement is primarily localised near the tunnel base. This research provides practising engineers with a valuable computational tool for assessing the long-term structural response of integrated tunnel-track systems in challenging soft rock formations.

While the presented viscoelastoplastic model effectively captures the cumulative ground settlement resulting from repeated train loads through a time-dependent creep mechanism, it does not explicitly account for the potential fatigue degradation of the rock intrinsic strength and stiffness. Incorporating this represents a valuable and complex avenue for future work, which would allow for an even more comprehensive assessment of the long-term integrity and service life of the integrated tunnel-track system under operational loading.

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