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Anisotropic Swelling Rock Behaviour in Tunnels: Effect of Bedding Plane Orientation

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Abstract

The time-dependent behaviour of swelling rock formations poses significant challenges in geotechnical engineering, particularly in tunnelling and underground construction. Despite decades of practical experience, tunnel design in swelling rock remains highly complex, with considerable uncertainties arising from the interplay between anisotropy and swelling mechanisms. In Ontario, Canada, where swelling-prone shale formations have been reported, these challenges are especially pronounced.

In this paper, the time- and stress-dependent swelling behaviour of shaley rocks and their effects on underground structures are assessed using the latest PLAXIS swelling rock model. First, the recently introduced logarithmic swelling law in PLAXIS is briefly described. The model input parameters are then calibrated using laboratory swelling tests on Southern Ontario shales to ensure accurate and reliable predictions of swelling effects in subsequent boundary value problem simulations under various field conditions. It is well-documented in the literature that the presence of anisotropy in rock formations influences both the elastic and swelling behaviour, with mechanical properties varying depending on the bedding plane orientation. To investigate this, a series of boundary value problem simulations are conducted for a tunnel within Ontario shales, using different bedding plane configurations to assess the influence of bedding plane orientation and anisotropic swelling behaviour on tunnel internal forces and deformations.

The findings of this study offer valuable insights into how rock swelling can affect engineering design, while the availability of the swelling material model contributes to the advancement of geotechnical practices in these challenging environments.

Keywords

finite element method, numerical modelling, PLAXIS, swelling, time-dependent behaviour, tunnel

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1 Introduction

Swelling rocks, such as claystone and anhydrite-bearing formations, pose significant challenges for tunnelling and underground construction. Despite years of practical experience, reliably predicting swelling pressures and deformations remains difficult due to the inherently anisotropic nature of these materials and the intricate mechanisms driving their swelling behaviour. Tunnelling projects, such as the Engelbergtunnel in southern Germany and the Chienbergtunnel in Switzerland, highlight the persistent challenges associated with swelling rock formations (Anagnostou et al., 2010; Schädlich et al., 2013).

Although the anisotropic behaviour of swelling soils and rock formations is well recognized, field characterization of their properties remains a complex task. Even with extensive field investigations, numerical simulations are challenged by the limited availability of advanced geotechnical modelling tools capable of fully addressing these complexities. Among the few commercially available finite element software solutions, the PLAXIS Swelling Rock Model stands out for its ability to incorporate an anisotropic elasto-plasticity framework with swelling formulations, offering a more comprehensive analysis of swelling behaviour in these materials (Bentley Systems Inc., 2024).

Tunnelling in swelling rocks can lead to significant challenges, such as invert heave or high swelling pressures acting on tunnel linings, depending on the selected support method. These challenges are further compounded by the time-dependent and stress-dependent nature of swelling behaviour, which affects both construction and long-term tunnel stability. This paper evaluates the influence of swelling properties in shales on tunnel design, focusing on the primary lining stage of the New Austrian Tunnelling Method (NATM). Initially, the excavation will be supported by a primary lining, followed by the application of a secondary lining. This study specifically examines the effects of swelling on the primary lining and the activation of swelling pressures. A comprehensive examination of swelling characteristics is presented, along with practical recommendations for tunnelling projects in swelling rock conditions. Results from laboratory swelling tests are included, and real project experiences are discussed.

2 PLAXIS Swelling Rock Model

2.1 Model description

The Swelling Rock Model (SRM) was initially implemented as a PLAXIS User-Defined Soil Model (UDSM) to simulate the stress and time-dependent swelling behaviour of rocks (Plaxis, 2014). Recent enhancements in the SRM UDSM have significantly improved its capabilities. Firstly, the UDSM, previously limited to two-dimensional (2D) analyses, has been extended to three-dimensional (3D) compatibility, making it applicable to both PLAXIS 2D and 3D. This extension enables the simulation of complex scenarios where 2D simplifications are inadequate. The second major enhancement is the introduction of an alternative time-dependent swelling formulation, allowing users to simulate linear swelling behaviour over a logarithmic time scale, i.e., log(t)-scale.

Unlike classic elastoplastic models, where the total strain increment is decomposed solely into elastic ($\Delta\boldsymbol{\varepsilon}^{el}$) and plastic ($\Delta\boldsymbol{\varepsilon}^{pl}$) components, in the SRM, an additional swelling component ($\Delta\boldsymbol{\varepsilon}^{q}$) is introduced, as expressed in Eq. 1.

$$\Delta\boldsymbol{\varepsilon} = \Delta\boldsymbol{\varepsilon}^{el} + \Delta\boldsymbol{\varepsilon}^{pl} + \Delta\boldsymbol{\varepsilon}^{q} \qquad 1$$

Both the exponential and log(t)-based SRM formulations, referred to as MAS and MAS-Logt in PLAXIS, employ a transversely anisotropic formulation for the elastic component and the Mohr-Coulomb failure criterion for the plastic component. In this paper, in accordance with experimental observations, the recently released MAS-Logt model has been utilized. The MAS-Logt formulation's ability to capture swelling behaviour as linear in a logarithmic time scale (log(t)) makes it particularly well-suited for the conditions investigated.

The swelling rate in the MAS-Logt model is expressed as:

$$\tilde{\dot{\varepsilon}}_i^q = -k_{q,i} \cdot \log\left(\frac{-\sigma_i}{\sigma_{q0,i}}\right) \text{ and } \tilde{\dot{\varepsilon}}^q = \frac{\mathrm{d}\varepsilon^q}{\mathrm{d}\log(t)} \quad (2)$$

where $k_{q,i}$ is the swelling potential, and $\sigma_{q0,i}$ is the suppression stress in a particular direction i. Comparing the exponential and log(t)-based swelling models, it is important to note that while the MAS-Logt model depicts a continuous linear increase in swelling strains on a logarithmic time scale, the swelling rate decreases linearly with time. In contrast, the MAS model exhibits an exponential decrease in the swelling rate, as illustrated in Fig. 1.

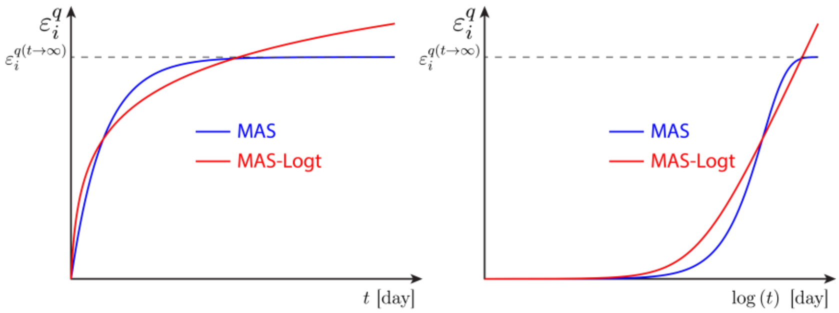

Fig. 1 Comparison of the swelling response of the MAS and MAS-Logt

2.2 Anisotropy

Rocks in nature are subjected to complex geological processes that frequently result in transverse isotropy, a form of anisotropy where mechanical properties vary perpendicular to a plane of symmetry but remain consistent within the plane. Within the SRM, this phenomenon is captured not only through a transversely isotropic elasticity formulation but also by accounting for the anisotropic swelling response.

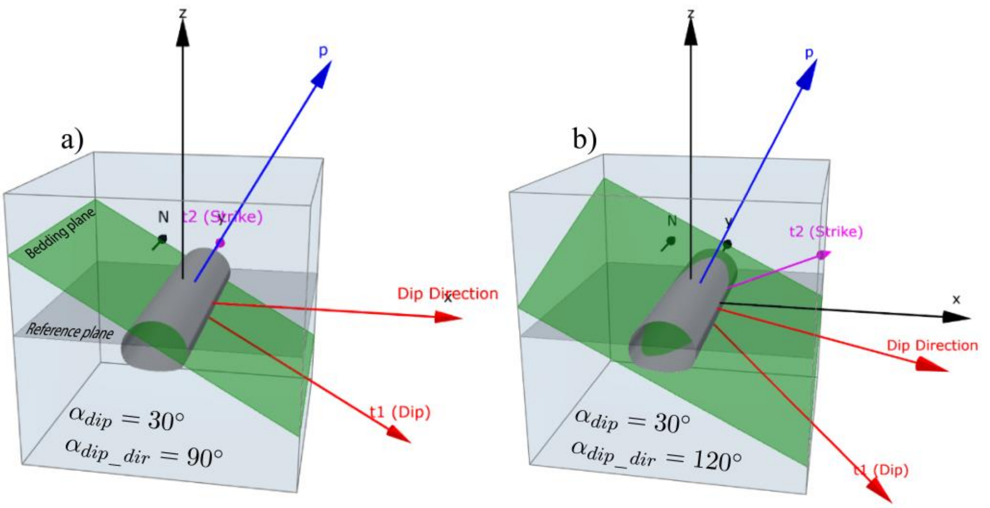

Fig. 2 The orientation of bedding planes: (a) with $\alpha_{dip} = 30^\circ$ and $\alpha_{dip\_dir} = 90^\circ$ (b) rotated configuration with $\alpha_{dip} = 30^\circ$ and $\alpha_{dip\_dir} = 120^\circ$

Two critical factors must be defined to characterize anisotropy: (1) the degree of anisotropy, which quantifies the difference in properties within the bedding plane versus perpendicular to it, and (2) the orientation of the anisotropy, which specifies the spatial alignment of the bedding plane. In the SRM, the degree of anisotropy for both elastic and swelling behaviours is defined independently through input parameters. This allows users to specify, for instance, an isotropic elasticity formulation combined with an anisotropic swelling mechanism, or vice versa.

The orientation of the bedding planes is controlled via the dip and dip direction angles, as illustrated in Fig. 2. Notably, the anisotropy orientation influences whether a problem can be simplified to a 2D analysis or requires a comprehensive 3D evaluation. For example, anisotropic rock formations with bedding planes that are not orthogonal to a tunnel cross-section, as depicted in Fig. 2 (b), often necessitate a 3D approach to realistically capture the complexity of the deformation and swelling behaviour.

3 Numerical Analysis

3.1 Boundary Value Problem

The problem analysed in this paper involves the excavation of a tunnel in a swelling rock formation, serving as a representative case to investigate both the mechanical and swelling responses of anisotropic rocks. The numerical model is designed to simulate the influence of time-dependent anisotropic swelling behaviour on the tunnel at different bedding plane orientations.

Mesh discretization and model dimensions are depicted in Fig. 3. The model represents a non-circular tunnel with a height of 18 m and a width of 23 m. The in-situ stresses are generated using an isotropic field stress of 3 MPa. To minimize the influence of boundary effects on the excavation zone, the model domain extends sufficiently in all directions. All model boundaries are normally fixed to prevent shear stresses along the model boundaries.

The numerical simulation is divided into three distinct phases (as detailed below) to simplify the tunnel excavation process and capture the subsequent swelling behaviour:

1. **Initial Phase**: The initial stress state of the rock mass is determined using the ***field stress*** option in Plaxis, establishing the in-situ conditions prior to excavation.

2. **Excavation Phase**: The complete tunnel excavation is simulated. During this phase, time is set to zero to suppress swelling effects, ensuring that the redistribution of stresses is driven solely by plastic deformations. For simplicity, no deconfinement option or method of partial staged construction is employed, and the tunnel lining is assumed to be in place immediately after excavation. Relaxation effects are not considered, as they fall outside the scope of this study.

3. **Time-Dependent Swelling Phase**: Post-excavation, swelling behaviour is modelled over a period of 2000 days. This phase utilizes the time-dependent MAS-Logt formulation to simulate the swelling response of the rock mass and its impact on the tunnel.

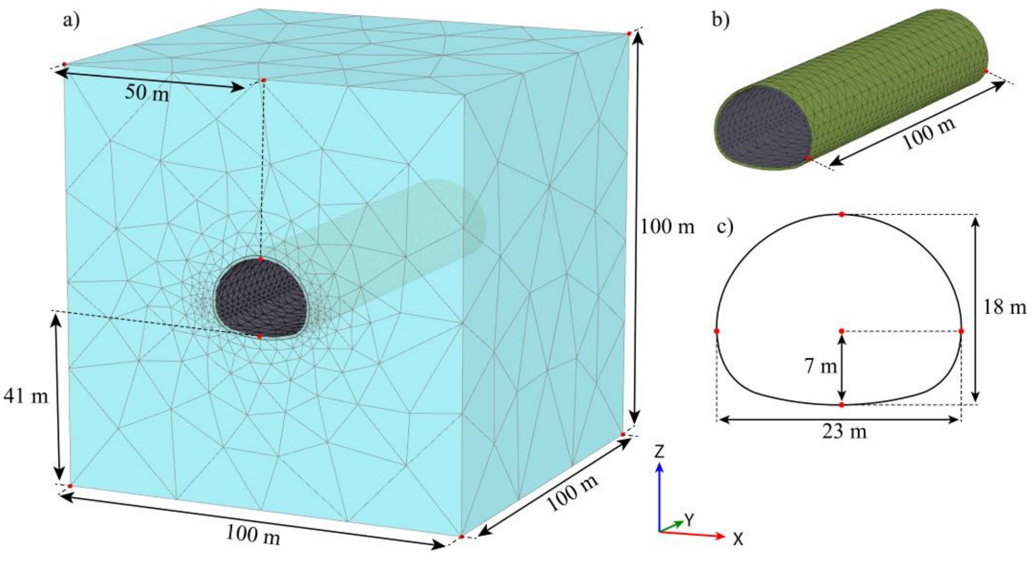

Fig. 3 Finite element model: (a) mesh discretization and dimensions, (b) tunnel structure, (c) tunnel cross section

The model dimensions and overburden height are based on a real tunnel project in Ontario. The analysis presented in this paper focuses on anisotropy effect on the primary lining. In the design, the secondary lining is modelled for a 100-year period, with swelling effects applied over an extended duration. To isolate the effect of anisotropy, additional support elements such as rock bolts are not included in the analysis.

The model input parameters for Southern Ontario shales are provided in Table 3.1. The calibration procedure followed is detailed in the PLAXIS Swelling Rock Model Manual, with additional information available in Bentley Systems Inc. (2024).

Table 3-1 MAS-Logt input parameters for Southern Ontario shales

ϕ'	c'	ψ	σ_{tens}	E_p	E_t	ν_{pt}	ν_{tt}	$k_{q,p}$	$k_{q,t}$	$\sigma_{q0,p}$	$\sigma_{q0,t}$	Swell_ID
°	kPa	°	kPa	kPa	kPa	[-]	[-]	[-]	[-]	kPa	kPa	[-]
47	291	5	60	2850000	7000000	0.25	0.25	0.0039	0.0015	2090	800	3

3.2 Effect of bedding plane orientation on tunnel behaviour

A sensitivity analysis has been conducted to assess the influence of the bedding plane orientation on the tunnel and the surrounding rock mass. Initially, the dip direction angle is fixed at 90°, while the effect of varying dip angles (0°, 30° and 60°) on the tunnel is analysed. These simulations aim to explore the relationship between the bedding plane inclination and the overall response of the tunnel. Subsequently, the effect of rotating the dip direction angle is evaluated through an additional simulation with a dip angle of 30° and a dip direction angle of 120°. All comparisons are carried out for the cross-section at y = 50 m (see Fig. 3) of the tunnel to minimize boundary effects.

The predictions in the following sections incorporate elastic, plastic, and swelling deformations. However, for the scenario modelled in this paper, the primary source of the deviations in the predictions arises from the swelling mechanism. For instance, the comparison of tunnel deformations at different dip angles in Fig. 4 and the axial force distributions in Fig. 5 at the end of Phase 2 (just before the swelling mechanism is activated) shows quite similar results. This observation suggests that the influence of anisotropic elasticity on tunnel behaviour is limited for the selected set of anisotropy parameters and the given tunnel geometry. The influence of the anisotropic characteristics of the swelling response will, however, be investigated in more detail in the following sections.

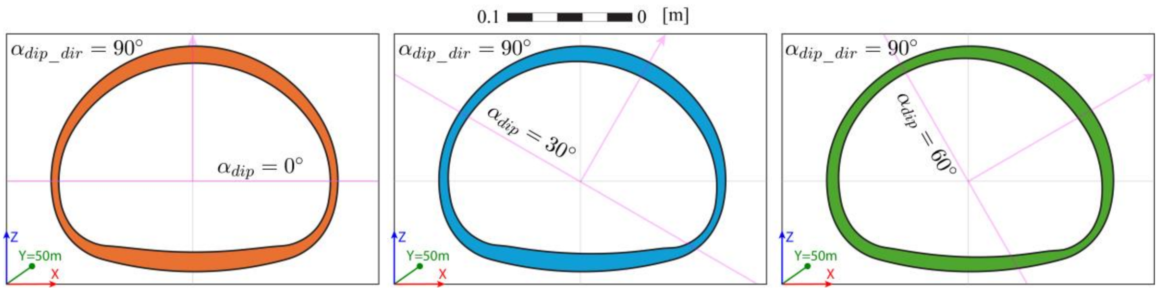

Fig. 4 Total displacements |u| of the tunnel lining (plate element) for dip angles of 0°, 30°, and 60°, with a constant dip direction angle of 90° at the end of Phase-2

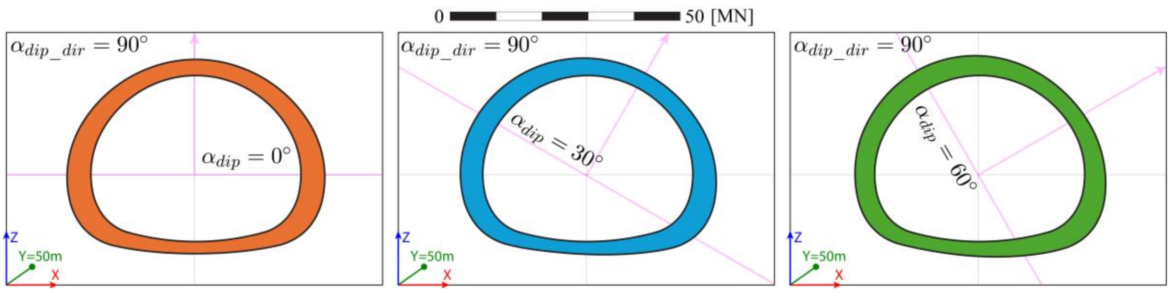

Fig. 5 Axial forces N of the tunnel lining (plate element) for dip angles of 0°, 30°, and 60°, with a constant dip direction angle of 90° at the end of Phase-2

The illustrations in Fig. 4 and Fig. 5 are qualitative and are intended solely to demonstrate the limited correlation observed with variations in the dip angle.

3.2.1 Influence of dip angle

In this section, the overall behaviour of the tunnel and surrounding rock mass at different dip angles will be discussed. The analysis begins by presenting the swelling points, which represent the stress points where swelling strains develop over a 2000-day period.

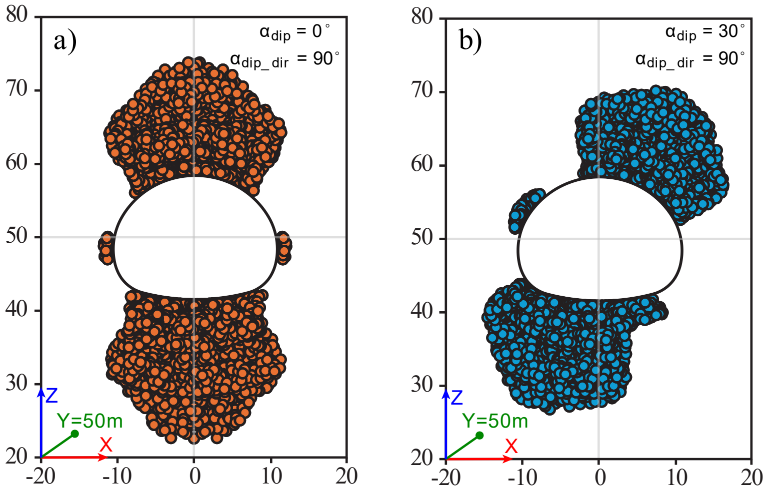

Fig. 6 Swelling point history for dip angles of 0°, 30°, and 60°, with a constant dip direction angle of 90°

As shown in Fig. 6, the locus of swelling points—representing the portions of the rock mass around the tunnel expected to swell—strongly depend on the orientation of the bedding plane, offering insights into the temporal evolution of swelling-induced deformation at varying dip angles.

Following the determination of swelling points, Fig. 7 illustrates the total displacements of the tunnel lining relative to its undeformed shape at varying dip angles (0°, 30° and 60°), providing a detailed comparison of how the tunnel's structural response evolves as the dip angle changes. The deformation patterns reflect the influence of the bedding plane orientation on the stress distribution and the resulting displacements within the tunnel.

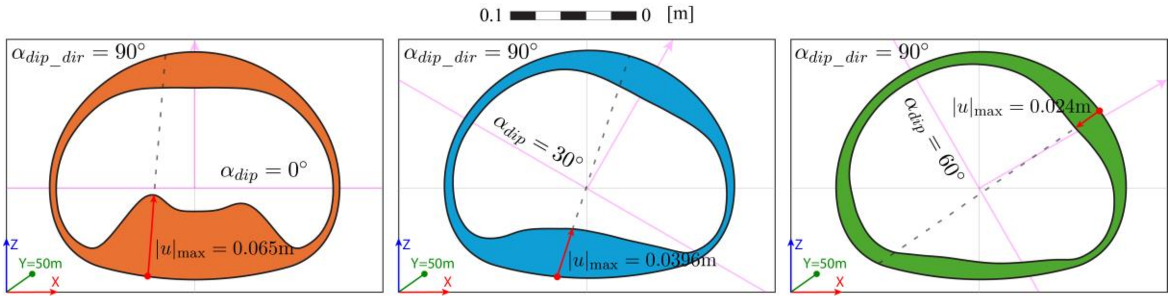

Fig. 7 Total displacements |u| of the tunnel lining (plate element) for dip angles of 0°, 30°, and 60°, with a constant dip direction angle of 90° at the end of 2000 days

At a dip direction of 0° (horizontal bedding plane), the axis of symmetry of the tunnel cross-section aligns with the normal of the bedding plane, resulting in a more symmetric deformation profile. This symmetry suggests that the swelling in the surrounding rock mass acts uniformly around the tunnel, see swelling points in Fig. 6 (a), leading to symmetric stress redistribution and deformation along the tunnel centerline. As the dip angle increases from 0° to 60°, notable changes occur in the deformation patterns. As anticipated, the axis of the maximum deformation, illustrated with the dashed line in Fig 7, begins to align with the dip angle. As a result, the total displacement at the tunnel crown and invert appears to decrease with increasing dip angle.

Following the analysis of deformation profiles, Fig. 8 presents the normal force distributions of the tunnel lining (plate element) for three different dip angles. The displacement of the tunnel and the distribution of normal forces are interconnected phenomena, as the deformation patterns directly influence the stress redistribution within the tunnel structure. Additionally, these forces are strongly related to the geometry of the tunnel, further emphasizing the complex relationship between the orientation of the bedding plane, the tunnel shape, and the resulting mechanical behavior.

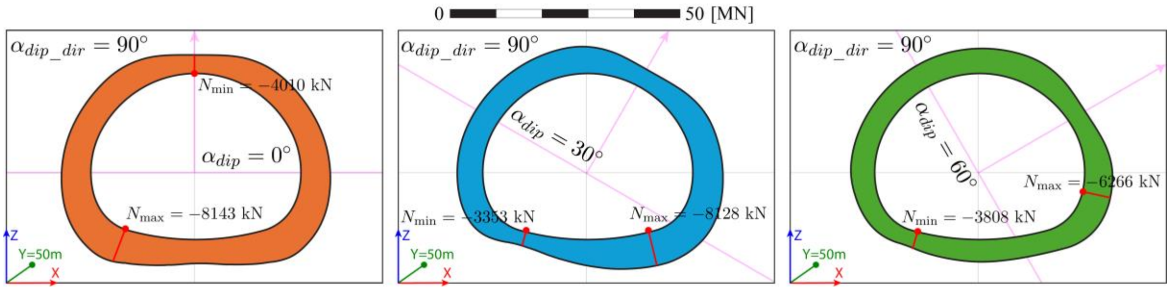

Fig. 8 Axial forces N at tunnel plate elements for dip angles of 0°, 30°, and 60°, with a constant dip direction angle of 90° at the end of 2000 days

Fig. 8 shows that the dip angle of bedding planes significantly influences the distribution of the normal forces on the tunnel lining. At smaller dip angles, when the axis of symmetry of the tunnel cross-section aligns with the normal of the bedding plane, the normal force distribution is relatively uniform. As the dip angle increases, asymmetry effects start to emerge, with higher forces concentrated in specific regions due to changing direction of the swelling tendency. This highlights the importance of considering the bedding plane orientation when designing tunnel support systems, as it can affect the required level of reinforcement and the risk of localized failure.

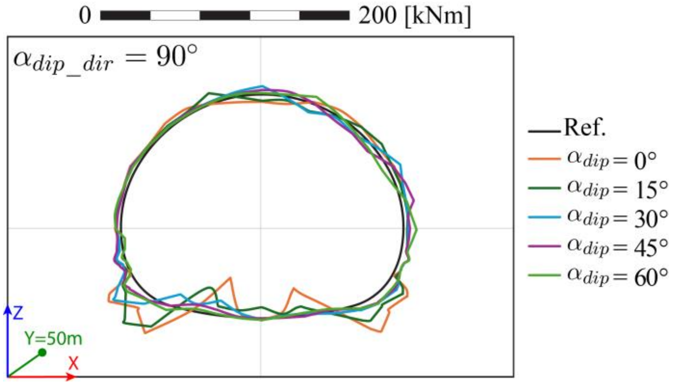

Fig. 9 Bending moments M at tunnel plate elements for dip angles of 0°, 15°, 30°, 45° and 60°, with a constant dip direction angle of 90° at the end of 2000 days

As shown in Fig. 9, the influence of bedding plane rotation on the bending moment (BM) distribution is significant across various dip angles. At 0° (horizontal bedding), the BM distribution is uneven, with distinct peaks, highlighting concentrated stress areas caused by the lack of alignment with primary stress redistribution paths. This misalignment results in higher BMs. As the bedding plane dip angle increases to 15° and 30°, the BM distribution begins to smoothen, indicating that the bedding planes start aligning with the stress redistribution pathways, thereby reducing stress concentrations and lowering the BMs around the tunnel. At 45°, the BM distribution becomes the most uniform, showing reduced peaks compared to lower dip angles. This is the critical angle at which bedding planes effectively align with the induced stresses, resulting in better load dissipation and reducing bending effects. Finally, at 60°, the BM distribution smoothens further, with additional reductions in peak moments, suggesting that at high dip angles, the bedding planes function as sliding or stress-relief zones, further diminishing the overall bending moment acting on the tunnel.

The angle of bedding planes significantly impacts how stress is redistributed around tunnels. At higher dip angles, stresses disperse more uniformly along the bedding planes, reducing concentrated stress zones. This smoother redistribution also reduces bending effects, as the rock offers less resistance to deformation when bedding planes align with the direction of stress. Sliding along these planes further relieves stress, lowering bending moments. At lower dip angles, such as horizontal orientations (e.g., 0°), the bedding planes resist deformation more effectively. This resistance leads to higher bending stresses and moments, making the rock mass stiffer but more prone to localized structural instability. On the other hand, as dip angles increase, the bedding planes act as natural paths for stresses to "flow," reducing bending stresses while making the rock more flexible. The lower dip angles concentrate stresses and bending moments, increasing the risk of structural damage at the tunnel linings, while higher dip angles result in smoother stress redistribution and lower bending moments. However, steeper angles can introduce new challenges, such as sliding and shear-related instabilities, which require careful attention.

3.2.2 Influence of dip direction angle

In this section, the influence of the dip direction angle on the tunnel behaviour is investigated. Two simulations are compared: one with a dip and dip direction angle of 30° and 90°, and another with the same dip angle but a dip direction angle of 120°. The orientation of the bedding planes for these two cases is illustrated in Fig. 2.

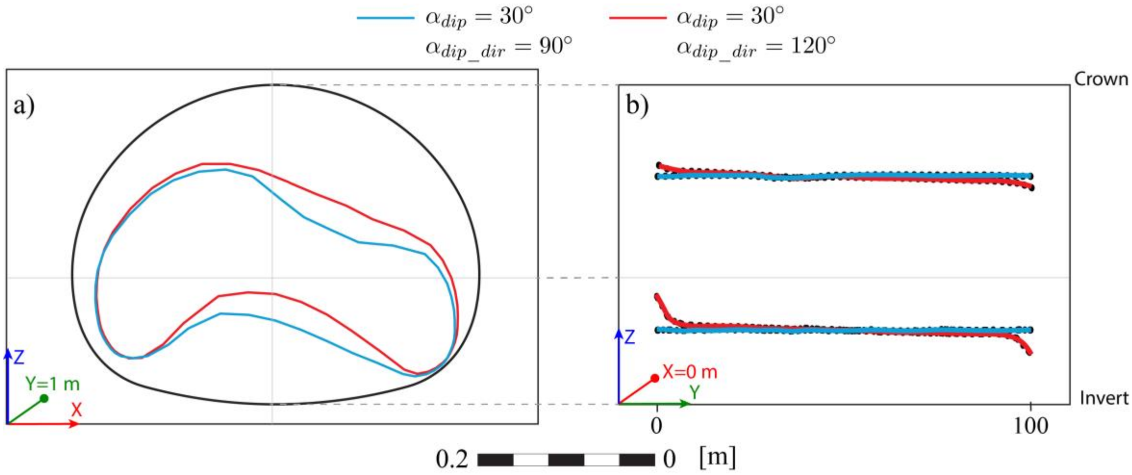

Fig. 10 Influence of dip direction angle change on: (a) total deformation |u| within the tunnel cross-section at y=1 m, and (b) vertical deformation u_z along the tunnel length

Although the two different bedding plane configurations result in quite similar tunnel deformations, maximum differences are observed at the boundaries at y=0 m and y=100 m, leading to a slight tilt of the entire tunnel across the tunnel's central axis as shown in Fig. 10.

4 Discussions

The geotechnical challenges associated with swelling in tunnelling, particularly when they are coupled with anisotropic rock formations, are significant and complex. One of the key difficulties is to accurately characterize the anisotropic properties of soils and rocks. Despite the well-established nature of anisotropic behaviour in these materials, quantifying and modelling this in the field remains a challenge. Factors such as bedding plane orientations and the varying mechanical properties perpendicular and parallel to these planes complicate the understanding of swelling and deformation behaviour.

The use of the PLAXIS swelling rock model, particularly with the MAS-Logt formulation, has proven to be an effective tool in addressing some of these challenges. The extension of the SRM to 3D simulations and its incorporation of time-dependent swelling mechanisms allow for more realistic modelling of swelling behaviour under tunnel excavation conditions.

Furthermore, the anisotropic nature of rock formations adds further complexities. The orientation and degree of anisotropy—specifically the bedding plane angle—greatly affect the mechanical response of the rock mass surrounding a tunnel. As the sensitivity analysis has demonstrated herein, varying the dip angle of the bedding planes alters the swelling response and the resulting deformation patterns. The numerical analysis predictions indicate that bedding plane orientations impact the magnitude of the tunnel lining deflections, axial forces, and bending moment distributions. In particular, smaller dip angles lead to more concentrated deflections, while higher angles enable smoother stress redistribution. This underlines the importance of considering bedding plane orientations in tunnel design to mitigate risks of localized failure and ensure structural stability.

5 Conclusions

In conclusion, the swelling of rock masses, particularly in anisotropic formations, presents a challenging aspect of tunnel design and construction. Accurate characterisation of anisotropic swelling behaviour and the availability of advanced modelling tools like the SRM (available with PLAXIS) are crucial in overcoming these challenges. The sensitivity analysis and numerical simulations demonstrate that bedding plane orientation significantly influences the mechanical behaviour of the tunnel, including deformations and force distributions. By carefully considering these factors and leveraging advanced models such as the MAS-Logt, engineers can better predict and mitigate the risks associated with swelling rocks in tunnelling projects.

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