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Numerical Modeling for Excavation Stability: Comparing 2D and 3D Approaches in Underground Mining

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Abstract - Development headings such as tunnels, ramps, and access are crucial infrastructure components for efficient ore extraction in underground mining operations. Creating these openings, governed by various geological and operational parameters, necessitates careful planning and assessment to ensure the stability and integrity of the excavations. The stability of underground structures is primarily influenced by several factors, including rock mass quality, inducing stress, the depth of the excavation, and the excavation methods applied. These factors are critical in determining the risk of collapse, deformation, or failure, which can significantly impact safety and operational efficiency. To enhance the stability of this excavation, 2D and 3D numerical models (FEM) and field investigations were compared to highlight the deformation around the excavation at varying depths. The numerical results revealed that 3D geomechanical modelling is required to create realistic models in complex geological conditions and under varying depths. However, the 2D geomechanical model can be used in very shallow areas.

Keywords**:** Tunnel stability, Rock mass quality, Induced stress, Deformation, Depth.

1. Introduction

The stability of underground tunnel openings is affected by various geological and geomechanical factors, including rock mass quality, discontinuities, blasting effects, groundwater inrush, and stratification orientation [1, 2]. Excavation activities can cause stress redistribution and deformation, leading to risks for worker safety, project sustainability, and economic viability. The natural rock mass is heterogeneous and characterized by various discontinuities, making it essential to consider these factors when determining the appropriate support specifications for a horseshoe tunnel to ensure it can endure complex geological conditions.

previous studies discuss the impact of rock mass quality on underground excavation, emphasizing its importance for geotechnical design [3-5]. It highlights how discontinuities like faults and joints affect tunnel stability, with specific failure modes depending on the orientation of these joints [4]. The presence of fractured rock masses and the characteristics of joints are crucial, as they influence the fragmentation process post-blasting. The underground mining industry has made enormous technical advances, allowing for deep mining and advancement. The variation in the rock mass quality as a function of depth influences the rate of extraction of the ore and the progress of the tunnel. However, when creating an underground opening, the initial stress conditions of the rock are modified, producing the phenomenon of stress redistribution; this can cause a deformation surrounding rock mass or induced rock instabilities, such as rock bursts around the opening [6]. Additionally, the phenomenon of stress redistribution during excavation was addressed in the literature, which can lead to rock instabilities and the formation of a blasting damage zone (BDZ) characterized by fractures and displacements [7-9]. Tunnel stability is further influenced by factors such as block geometry and stress levels in stratified rock [10].

In light of the above research results, analytical and numerical methods are used to assess the stability of rock masses surrounding openings. In their study, a finite element simulation was applied to study the influence of bedding joints on rock mass behavior [11-13]. Furthermore, several investigations are focused on evaluating the behavior of circular tunnels [14] as well as noncircular tunnels in horizontal and inclined stratification [12, 15]. Thus far, the literature has not addressed the effect of multiple joint sets, layer dip angle, and depth variation on rock mass stability for tunnel horseshoes.

The present study investigates an underground mine in Morocco with complex geological conditions. The deposits are veins and irregular mineralized masses, with sub-vertical dip and moderate-quality rock mass. The stratigraphy includes limestone, marl, and mudstones. The study uses a finite element method to examine the stability of horseshoe tunnels in varied depths, considering geological and geomechanical properties. This study uses the finite element method (FEM) to effectively illustrate the differences between two-dimensional and three-dimensional simulations under various ground conditions. By carefully analyzing these variations, the research aims to clarify how different dimensional models react to their complex environments, offering valuable insights into their respective performances and limitations.

2. Materials and methods

The study was carried out at an Ouansimi underground mine (Morocco). The geological formations encountered date from the Terminal Neoproterozoic. Fig. 1 shows a synthetic stratigraphic log of the study work. Alternating violet-chlorite facies (Mudstone), weathered marls, and limestone characterize the study area. In addition, the stratification of heterogeneous terrain changes throughout the tunnel with various ground conditions.

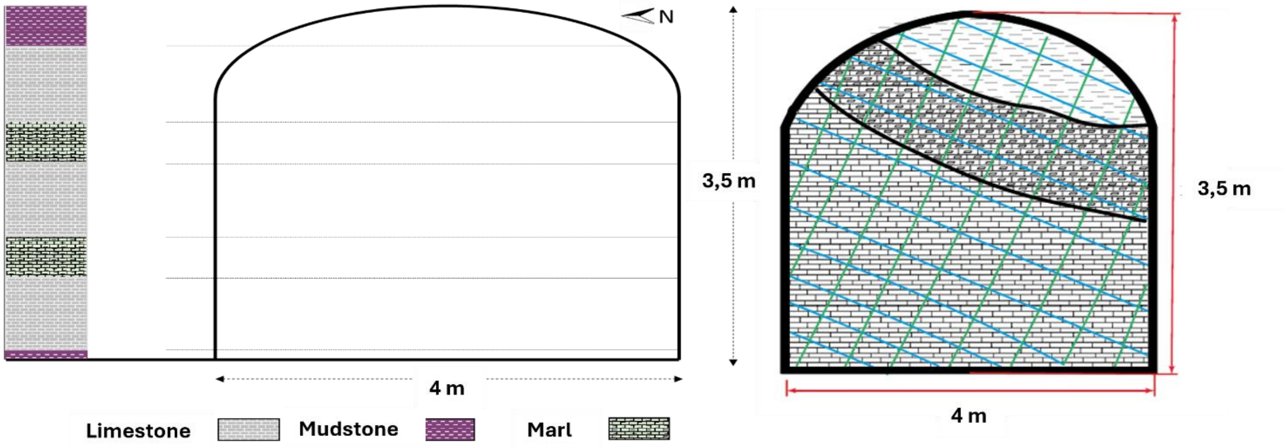


Fig. 1: synthetic stratigraphic log of the study work

They are many parameters that can significantly influence stability in underground mine. Some are controllable (blast design, explosive charge, deviation factor) and uncontrollable geological-geomechanical parameters (presence of fractures, rock quality, uniaxial compressive strength, and tensile strength). Solving this type of problem in geomechanical engineering requires a reliable model based on the following steps:

- Characterization of intact rock;
- Fracture characterization;
- Characterization of initial stresses
- Selection of the correct model
- Select a prediction model that considers the shear behavior of jointed rock
- Selection of the appropriate failure criterion
- Determining boundary conditions for numerical geomechanical modelling
- **Comparing 2D and 3D Approaches**

This research integrates experimental and numerical modeling with an approach for quantifying rock mass properties to assess the critical factors influencing the stability of horseshoe tunnels (Fig. 2). It then focuses specifically on rock mass behavior, multiple joint sets, and variation of strata orientation, as well as comparing 2D and 3D approaches.

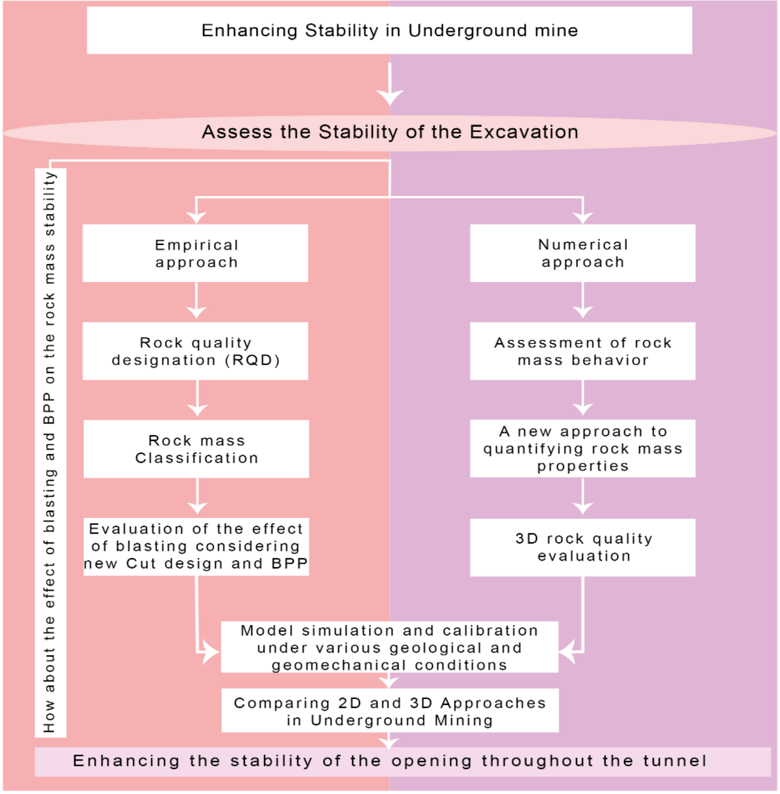


Fig. 2: Methodology adopted

3. Results and discussion

Several simulations were carried out to evaluate the differences between 2D and 3D models and their respective impacts. Both models were compared at depths of -100 m and -400 m, considering the dominant fractures and varying orientations of stratification within the heterogeneous rock mass. Additionally, the softening method was applied in this geomechanical simulation to describe the mechanical behavior of the rock mass.

3.1. Comparison of the plasticity zone between 2D and 3D -Rock mass without joints

The plasticity zones in both the 2D and 3D models are similar for a rock mass without fractures at a depth of -100 meters (Fig. 3). Furthermore, deformation is observed only in mudstone and marls. At a depth of -400 meters, both models exhibit symmetry across all three scenarios, with significant deformation occurring around the excavation site. However, at this depth and without joints, both models can be used.

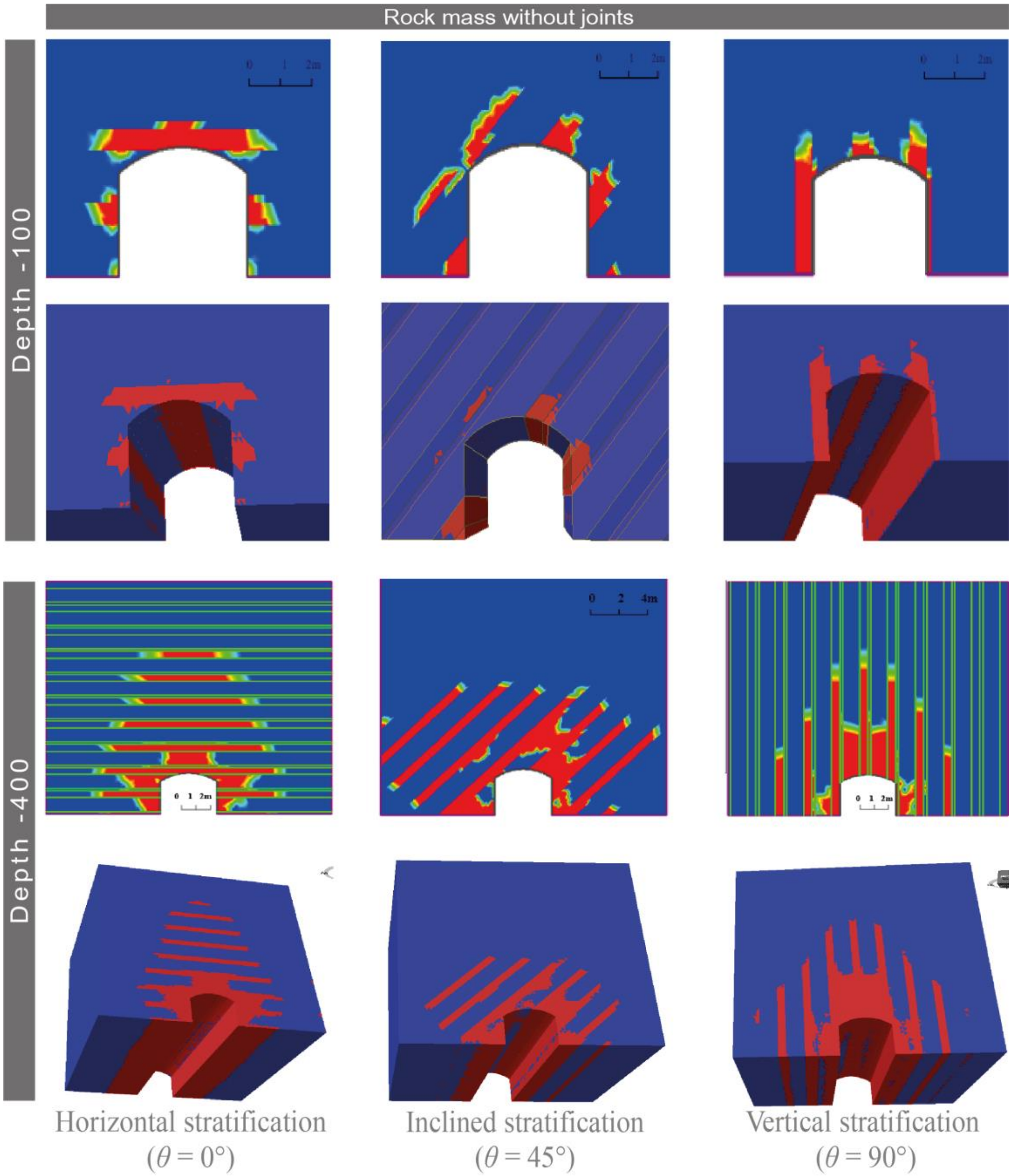


Fig. 3: The 2D and 3D numerical models in cases without joints at varying depths and strata orientations

3.2 Comparison of the plasticity zone between 2D and 3D - Rock mass with joints:

In simulations of a fractured rock mass at a depth of 100 meters, both the two-dimensional and three-dimensional models reveal distinct asymmetrical behaviors influenced by substantial discontinuities within the geological structure (Fig. 4). The two models can be effectively employed under the same field conditions, providing valuable insights into the complex dynamics of rock mass behavior in fractured environments under low stress. On the other hand, as the overestimation of the plasticity zone increases with depth in the 2D model, it becomes quite pronounced throughout the mudstone lithology. However, the results from the 3D model are realistic and consistent, showing evident plasticity around the excavation site and at the intersection points between the different joints.

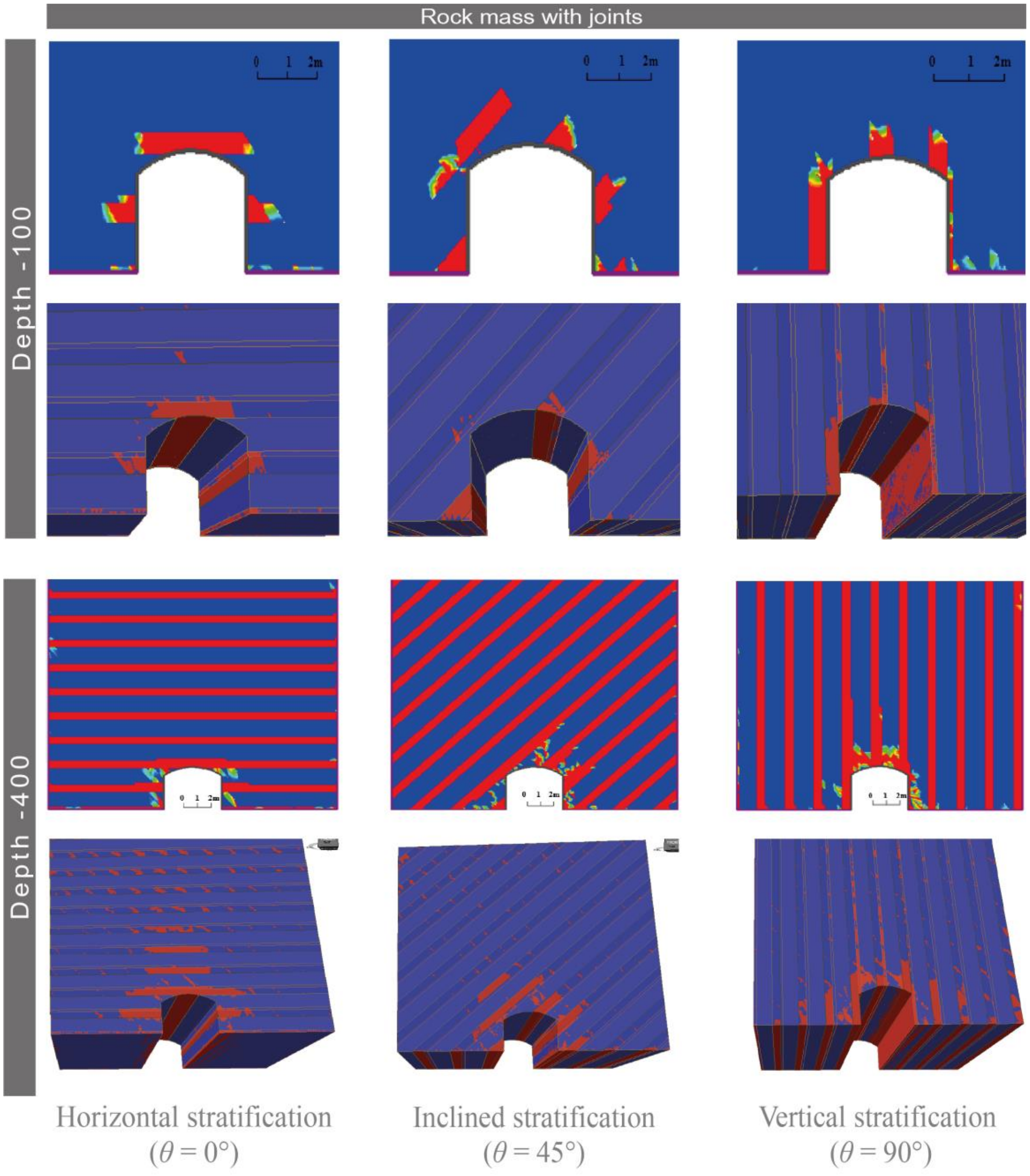


Fig. 4: The 2D and 3D numerical models in cases with joints at varying depths and strata orientations

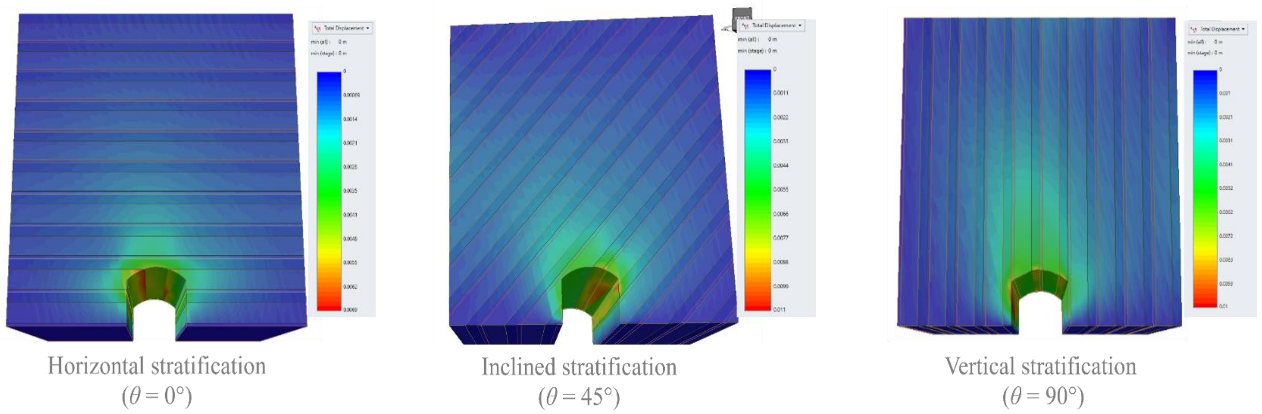
3.3 Comparison of 2D and 3D model displacements

Based on the Table 1, the displacement differences are 0.628 mm for the upstream scenario at -100 m and 1.784 mm for the downstream scenario at -400 m. Notably, the most significant discrepancies between the numerical model results occur in the vertical and inclined scenarios. This may be attributed to the geometric complexity and high node intersections in these two models, which exacerbate the differences between the 2D and 3D model results. Most of the displacement values are negative, indicating that the 2D model tends to overestimate displacements compared to the 3D model. This overestimation can be explained by the 2D model's inability to account for interactions in the third dimension. However, the displacements observed are not particularly significant when considering field observations and the record of incidents in the mine over the past six months.

Additionally, the 3D model's boundary conditions provide greater precision and flexibility for adjustments in all three dimensions, whereas the 2D model's boundary conditions are restricted to two planes. As a result, the displacements predicted by the 3D model are more realistic and accurately represent actual conditions than those predicted by the 2D model. Thus, Fig. 5 offers a detailed illustration of how the displacement ratio affects the ribs and roofs at a depth of -400 m in different scenarios. In addition, wedge and sliding failure zones developed on the roofs and left rib, respectively. Among these scenarios, the vertical configuration is the safest for development work, while the horizontal configuration is the least favorable.

Table 1: Comparison of 2D and 3D model displacements

	Difference = 3D - 2D								
	S1 (Horizontal)			**S2 (Inclined)**			**S3 (Vertical)**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
Level -100	-0.628	-0.407	-0.397	-0.181	-0.106	-0.099	-0.137	-0.044	-0.095
	-0.390	-0.340	-0.310	-0.159	-0.121	-0.126	-0.118	-0.056	-0.019
	-0.354	-0.290	-0.232	-0.153	-0.088	-0.112	-0.132	-0.068	-0.116
	-0.266	-0.243	-0.181	-0.122	-0.125	-0.083	-0.088	-0.053	-0.114
	-0.226	-0.207	-0.122	-0.101	-0.073	-0.054	-0.074	-0.072	-0.025
	-0.182	-0.182	-0.083	-0.086	-0.067	-0.028	-0.075	-0.056	-0.033
	-0.172	-0.150	-0.056	-0.082	-0.073	-0.055	-0.068	-0.039	-0.024
Level -400	0.198	-1.047	0.661	-0.835	1.523	0.817	-1.784	-1.616	1.492
	-0.152	-0.455	1.368	-0.899	1.657	0.296	-1.160	-0.799	0.280
	-0.655	-0.383	0.004	-0.957	1.137	0.139	-1.242	-0.782	-0.478
	-0.378	-0.172	-0.137	-1.254	0.641	-0.116	-0.965	-0.584	-1.177
	-0.352	-0.135	0.099	-0.797	0.708	0.021	-0.827	-0.498	-0.550
	-0.603	-0.109	0.246	-0.605	0.486	0.261	-0.766	-0.462	-0.227
	-0.647	-0.053	0.253	-0.650	0.152	0.161	-0.670	-0.360	-0.244


Horizontal stratification
$(\theta = 0°)$

Inclined stratification
$(\theta = 45°)$

Vertical stratification
$(\theta = 90°)$

Fig. 5: Distribution of the displacement in a 3D geomechanical model in the case of dominant joints

This research project evaluates tunnel stability in sedimentary rock masses by comparing 2D and 3D models. Both models consider rock mass conditions, varying rock properties with depth, and changes in stratification orientation. Natural discontinuities are explicitly represented, and the behavior of the rock mass is described using appropriate constitutive models. This approach allows for significant block displacements and rotations, which include sliding along discontinuities and block detachment. Numerous applications of discontinuity modeling have been successfully implemented in practical scenarios [16-18]. Understanding the orientations and complexities of rock formations can enhance excavation stability. Hooghvorst, Harrold, Nikolinakou, Fernandez and Marcuello [19] demonstrated that the 2D model predicts stress reduction comparable to that of the 3D model in sedimentary conditions. However, this finding applies only to little disturbed and low-stress rock masses. Studies conducted by Do, Dias, Tran, Dao and Nguyen [15] and Fortsakis, Nikas, Marinos and Marinos [20] indicate that the behavior of stratified rock masses surrounding tunnels is influenced by the properties of the intact rock and the characteristics of the rock mass between the layers. The results from a 2D numerical model reveal displacements generally similar to those produced by a 3D model, with both models correlating reasonably well with monitored data. Our study demonstrates that both models are effective in less complex conditions, such as those involving a single family of fractures, like bedding joints.

4. Conclusion

the present study compared the 2D and 3D models and their impact on rock mass behavior throughout tunnelling. The main results and conclusions of this study are summarized as follows:

- The 3D model is more realistic and is recommended for fractured rock mass with high stresses and complex geology.
- At a depth of -100 m, the yielded area is smaller than that observed at -400 m, with significant deformation in the case of horizontal stratification. In addition, the results are asymmetric for rock masses with dominant joints and heterogeneous lithology under minimum to medium stress.
- The highest displacement ratio is concentrated at the intersection of bedding and cross-joints with dip angles ranging from 0° to 45°,
- Wedge and sliding failure zones developed on the roofs and left rib in both inclined and horizontal scenarios.
- The vertical scenario is the most secure for work on underground advances.

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