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Investigation into the influence of macro-scale geometry on the stability of underground excavations in layered rock masses

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Abstract. Underground excavations for the development of infrastructure, mining operations, waste management etc. require support measures to ensure stability both during their construction and operational phases, which highly depends on the rock mass strength and deformability. Discontinuities within the rock mass are intrinsic features which determine said strength and deformability and affect the excavation stability. Several defining parameters demonstrate that rock mass variability has significant control in the material response during an excavation, especially in sedimentary rocks. In this paper, the Thornhill Sandstone is examined by applying numerical analysis and its mechanical response is investigated under several scenarios with varying excavation geometries, stress conditions while incorporating the influence of discontinuities explicitly within the numerical model. A two-dimensional parametric analysis is performed by applying the Finite Element Method (FEM) and integrating Discrete Fracture Networks (DFNs). More specifically, four different excavation geometries and three different in situ stress regimes are investigated. Drawing on the results, this paper provides insights for tunnel design optimisation when layered rock masses are encountered during an excavation in various underground stress environments with different opening geometries.

1. Introduction

The ever-increasing urban population across the globe, the requirement to reach greater depths for mining operations, the development of waste management or storage facilities etc. require implementing underground excavations to solve complex engineering problems and promote sustainable development. Underground excavations, however, are structures requiring support measures in most cases to ensure the excavation stability both in short- and long-term conditions. The opening stability is influenced by various aspects, including the properties of the host rock mass, the excavation geometry, the depth of the overburden etc. Underground structures aid in furthering a community's long-term sustainability and resilience when a holistic approach and smart planning is incorporated in the design, obtaining positive results in both socio-economic and environmental aspects of development [1]. However, it is important to understand what the ground response as well as the ground/support interaction is going to be to ensure the stability of the underground opening. For the purposes of this research, we are investigating the influence of macro-scale rock discontinuities to assess potential excavation instabilities across a range of different discontinuity patterns that may be encountered when excavating within layered rock masses with an emphasis on sedimentary rocks.



We primarily investigate the influence of the geometry on excavations' stability within the Thornhill Sandstone by applying two-dimensional (2D) Finite Element Method (FEM) analysis using the software package RS2 (Rocscience) and the use of Discrete Fracture Networks (DFNs). This research aspires to provide future developments with knowledge of the macro-scale structure's optimum design to ensure opening stability looking at the excavation geometry, structural geology, and stress conditions. The latter contributes in design optimisation and potentially decreasing support requirements and associated construction costs [2].

2. Background

The ambient stresses within the ground, the rock mass properties, and the excavation geometry play a critical role on underground opening stability. When considering underground excavations, there are two types of stress states, present over time: i. initial in situ geostatic stresses and ii. excavation induced stresses upon removal of material during construction. In situ stresses act on the rock mass prior to carrying out the excavation, and these derive from ambient gravitational and tectonic forces, topography, glaciation and other geological factors. Induced stresses are exerted due to the redistribution of in situ stresses as a result of excavation processes and changes across the different construction stages. The excavation geometry can significantly influence these redistributed stresses and their flow around the opening. As an initial step, it is crucial to assess the magnitude and direction of the in situ principal stresses, which are obtained from various methods including empirical predictions and in situ measurements [3].

2.1. Stress-controlled damage

The creation of an underground opening causes stress redistribution, and the magnitude and direction of these induced stresses are a function of the in situ stress and the excavation's geometry. These are critical factors which could result in generating unfavourable conditions resulting in material instabilities during construction. The development of stress induced fractures forming around the excavation results from re-distributed stresses exceeding the strength of the rock mass, hence creating a disturbed zone around the opening known as the excavation damaged zone (EDZ_{SI}). EDZ_{SI} exists regardless of the construction method and is divided into categories based on the extent and damage accumulation

2.2. Structural controlled failure

The presence of discontinuities affects directly the re-distributed stress direction and magnitude, and plays a critical role in the behaviour of the material, especially in massive and blocky rock masses in which explicit discontinuities can trigger instabilities. When the excavation intersects these planes of weakness, rock blocks form and depending on the orientation of the discontinuities and their intersection can generate unfavourable stability conditions. Kinematic stabilities analysis is performed to identify structural-controlled instability.

2.2.1. Slip within stratified rocks

Slip on pre-existing discontinuities can lead to the development of discrete blocks falling within the excavation. This process is commonly associated with stratified jointed rocks having discontinuities at relatively steep angles as the induced stresses can result in slip along critically orientated discontinuities. Joints begin to open, enabling the detachment or slip of blocks. Slip predominantly occurs in the corners of excavation. This is the location where the discontinuities are critically orientated to promote slippage given the generation of specific stress trajectories.

2.3. Underground excavations in sedimentary rocks

Sedimentary rocks, including sandstones, limestones, siltstones, mudstones, and shales, are mostly formed from the deposition of organic, siliceous, and/or calcareous sediments. These sediments

accumulate into a complex assembly of grains and crystals, with cement/matrix material, air and/or water within the pore spaces. The depositional process causes the formation of bedding planes, distinguishable on the macro-scale that cause the rock mass to exhibit strong anisotropy. Sedimentary rocks can form a vast variant of compositions and structures, a function of the depositional environment and processes and the deformation history [4].

2.3.1. Instability in sedimentary rocks

The structural arrangement and composition of the material composing the rock mass control the intact rock's microscopic strength and ductility. However, sedimentary rocks are commonly associated with the development of micro-fractures caused by microstructure imperfections. These can coalesce into larger fracture planes/zone. Therefore, the microscopic behaviour of these rocks is ductile. This means the inherent rock strength cannot be used to determine the failure properties; rather, it is primarily influenced by the grain contacts, intergranular bond material and porosity [5]. The development of microfractures impacts the stress-controlled instability, principally the result of fracture zones. The anisotropy and microstructure of rock largely control the fracture pattern, directly impacting the EDZ formation both in terms of extent and shape. The inherent existence of bedding planes in sedimentary rock also impacts the structural-controlled instability of the rock mass. When the rock mass is undeformed, the bedding planes will be highly pervasive. The latter implies that discrete block development by slip on the existing bedding planes or released is also more likely to occur.

3. Thornhill Sandstone

Thornhill Sandstone is a Permian aged formation and is a member of the Middle Pennine Coal Measure Group, found extensively in West Yorkshire in the UK. The Sandstone is brick-red in outcrop, whereby it is commonly found unconformably above coal layers. At the base of the unit, it is very coarse with silica-cemented, evenly laminated quartz. Grading upwards, it forms large-scale, cross-stratified, fine-grained deposits. Sandstone samples were collected at the Britannic Quarry, Morley, UK and tested in the RMEGG (Rock Mechanics, Engineering Geology and Geotechnical) lab at the University of Leeds. Unconfined Compressive Strength (UCS), Triaxial and Brazilian tests are performed to estimate the sandstone strength and deformability parameters. An average of 4.2 MPa for the tensile strength (σ_t) and a UCS of 53 MPa with Young's Modulus of 14.6 GPa and a Poisson's ratio of 0.20 is derived. Figure 1 shows a specimen before and after a UCS test, the complete stress-strain curves of the UCS testing series, the Hoek-Brown envelope, and the DISL yield derived from the testing series for the intact rock.

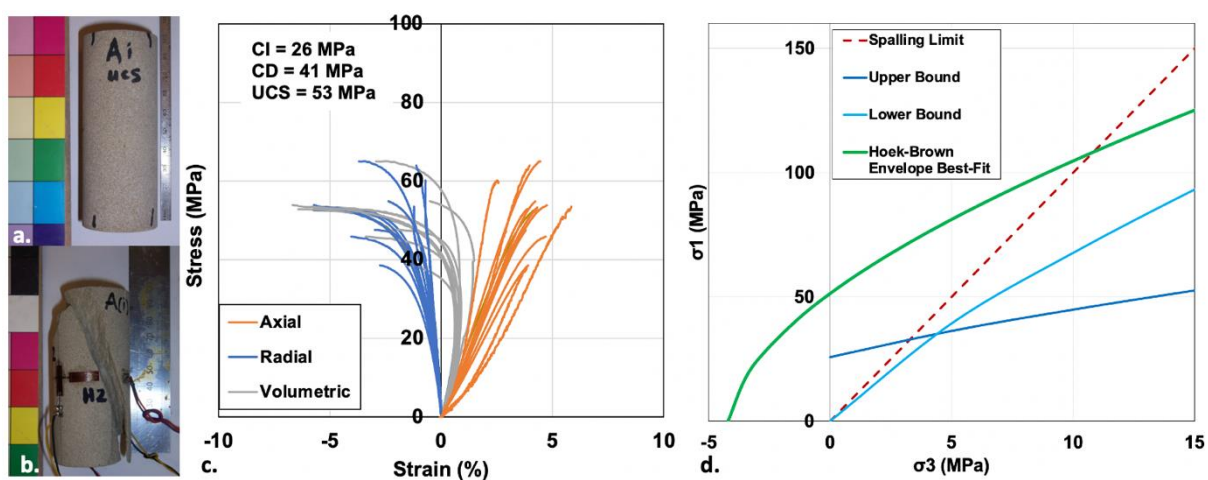


Figure 1. Thornhill Sandstone specimen a. before UCS test, b. after UCS test, c. complete stress strain curves of the UCS testing series and d. DISL yield limits and H-B failure envelope.

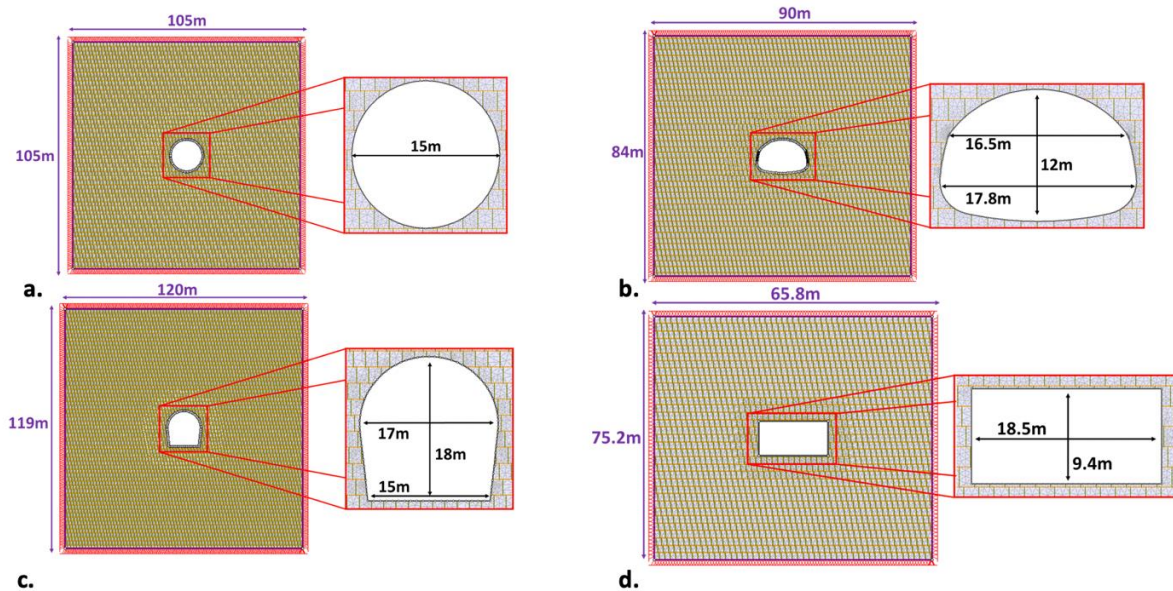


Figure 2. Tunnel geometries used in numerical analysis.

4. Numerical analysis

A 2-dimensional numerical FEM analysis has been undertaken to examine the stability conditions in stratified rock masses. Four different tunnel geometries are examined assuming an underground development in the Thornhill Sandstone. Figure 2 illustrates the different tunnel geometries with a similar cross-sectional area of 175 m^2 . The boundaries have been extended adopting a distance of approximately 3 diameters and the loading represents an excavation depth of 500 m. All the model geometries include a single material and a single joint network geometry whereas the graded-mesh of triangles with gradation factor of 0.1 (110 nodes in total). A graded mesh with 6-noded triangles is used to provide greater resolution in the region of greatest interest and variability.

A baseline model is defined based on the parameters shown in table 1 and a sensitivity analysis is performed based on the different excavation geometries. There are 3 different scenarios (baseline, scenario 1 and scenario 2) that alter one or more parameters that show large variations and/or uncertainties, with a focus on discontinuity influences, in the analysis of the Thornhill Sandstone.

This research work as previously stated investigates the impact of the geometry on the stability of an opening excavated in layered rock masses. To cover a wide range of conditions, three scenarios for the purposes of this paper have been created based on likely conditions that may arise during excavation within the Thornhill Sandstone. For this, investigations with variation in the discontinuity spacing, discontinuity orientation, discontinuity strength and stress state have been selected based on the analysis of the data. One or more parameters are altered in each series. Table 2 illustrates the changes for each analysis scenario.

5. Numerical Results and Discussion

The numerical analysis results are presented and discussed in this section. There is also the existence of a localised wedge-shaped region of stress intensities where the excavation periphery intersects discontinuities at an acute angle. During the analysis of stress-controlled stability, these are classified as outliers as they indicate highly unfavourable condition, not represent the overall stability of the excavation. In practice, these are easily mitigated by scaling or bolting.

Table 1. Input parameters used in the baseline model.

Data Type	Parameter	Reading	
Intact Rock	Elastic Parameters	Youngs' Modulus (GPa)	14.6
		Poisson's Ratio	0.2
		Uniaxial Compressive Strength (MPa)	53.1
	Hoek-Brown Parameters	mi	12.3
		a	0.5
		s	0.0623
	Tensile Cut-off (MPa)	-4.2	
Discontinuities	Structure of the Bedding	Orientation – Dip (°)	0*
		Spacing (m)	2*
		Persistence (m)	Full Extent
	Structure of the Joints	Orientation – Dip (°)	90*
		Spacing (m)	1.5*
		Persistence (m)	Full Extent
	Conditions of the Bedding	Dilation Angle (°)	0
		Joint Roughness Coefficient	6*
		Joint Wall Compressive Strength (MPa)	77.5*
		Residual Friction Angle (°)	32
		Dilation Angle (°)	0
	Conditions of the Joints	Joint Roughness Coefficient	2.75*
		Joint Wall Compressive Strength (MPa)	77.5*
		Residual Friction Angle (°)	32
Stress State	Vertical Stress (MPa)	13.5*	
	Horizontal Stress (MPa)	13.5*	

Table 2. Model registry with the different scenarios used parametric analysis.

Analysis	Parameters	Baseline Value	Scenario 1	Scenario 2
Discontinuity Spacing	Spacing of Bedding (m)	2	0.5	1.25
	Spacing of Joints (m)	1.5	0.5	1
Bedding Orientation	Bedding Dip (°)	0	15	30
Joint Orientation	Joint Dip (°)	90	75	60
Discontinuity Strength	JRC of Bedding	6	2	4
	JRC of Joints	2.75	0.75	1.75
	JCS of Bedding and Joints (MPa)	77.5	57.5	67.5
Stress State	K-ratio	1	0.5	2

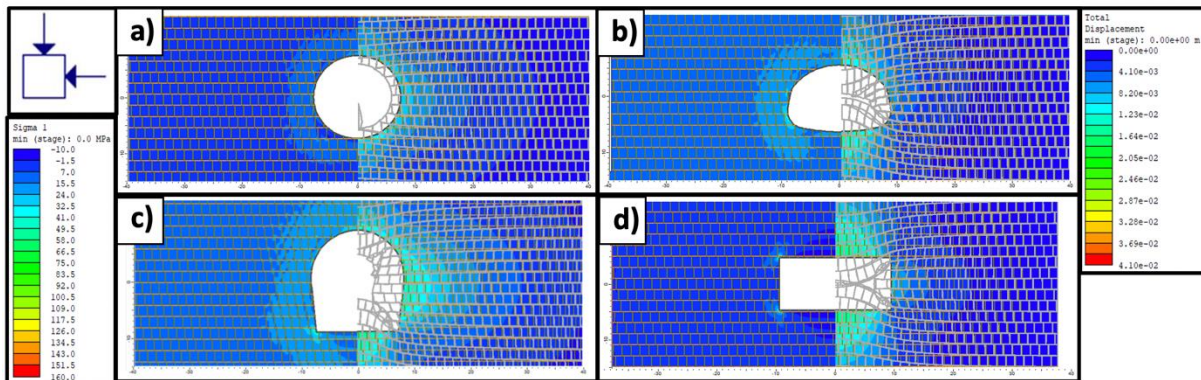


Figure 3. The distribution of major principal stress σ_1 (left) and total displacement (right) within the rock mass surrounding the excavation for the baseline scenario. a) Circular, b) circular Arc, c) horseshoe, and d) rectangular. Exaggerated deformed shapes are used for illustration purposes.

5.1. Baseline Model

The baseline condition represents the most likely condition that is encountered in an excavation of Thornhill Sandstone, based on the compilation of data obtained for this investigation. Figure 3 shows the modelling results in stress and total displacements.

For all excavation geometries redistributed stresses around the tunnel periphery are more profound extending to 1 to 2m into the excavation. Circular excavation performs better, due to the even distribution of the relatively low stresses across the excavation periphery. Although the rectangular appears to have less stress variation, stress concentration at the sharp corners. Additionally, large displacements can be observed as a result of bending moments generated due the vertical stress imposed to the “beams” forming due to the bedding. Higher damage could be associated in these areas, especially on the roof and invert which are spanning larger extents in this particular case. This means the rectangular geometry is likely the least favourable geometry under such rock mass conditions. The rest of the geometries perform well showing good stability, but either demonstrating minor damage (circular arc and horseshoe).

5.2. Stress State Scenarios 1 and 2

The influence of the stress state has been examined by altering the stress ratio K of the stresses with Scenario 1 (S1) representing lower and Scenario 2 (S2) higher horizontal stresses. The change in K -ratio for both scenarios results in larger σ_1 but lower displacements on the peripheries and of the surrounding rock mass in the plane of the far-field σ_3 . For S1, (figure 4) the region is aligned with the vertical plane and S2 (figure 5) is with the horizontal plane.

The largest concentration of σ_1 is usually spread across the excavation boundary and diminish within a short distance into the rock mass. In turn, the peripheries and surrounding rock mass in the plane of σ_1 of the far-field regime experience tension and large displacements. High tension extends within a narrow area but is persistent into the rock mass. The division between regions of the larger and smaller stresses is very sharp. Overall, the distribution of σ_1 forms a ‘butterfly’ pattern, however, the positioning of the division is controlled by the geometries.

5.3. Discussion

Figure 6 summarises the results of this analysis. More specifically, figure 6 presents the strain distribution around the excavation. Figure 6a indicates the strains range from 1.4% to 3.5% for the baseline scenario. Most excavations show similar strain magnitudes across the peripheries with the circular excavation having the lowest average strains. Excavations with elongate roofs and inverts (rectangular and circular arc) are exceptions to this, strains are greater at the roof.

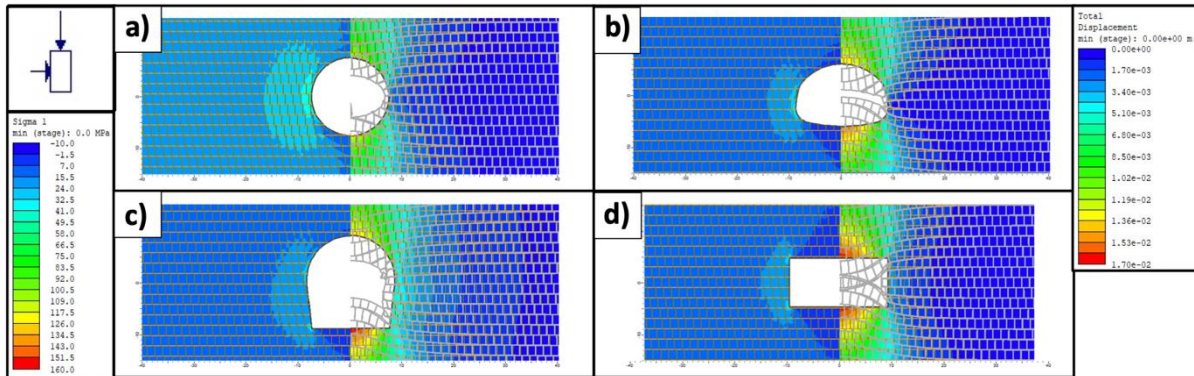


Figure 4. The distribution of σ_1 (left) and total displacement (right) within the rock mass surrounding the excavation for Scenario 1, K -ratio=0.5. a) Circular, b) circular arc, c) horseshoe, and d) rectangular.

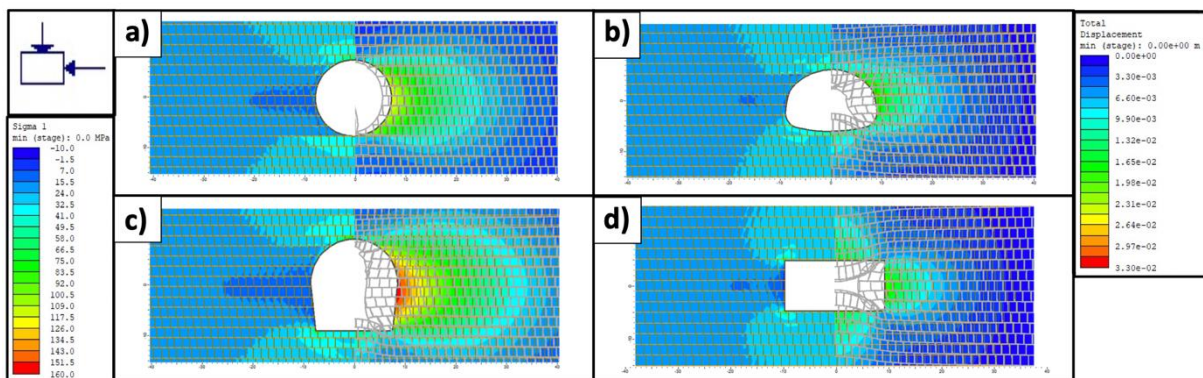


Figure 5. The distribution of σ_1 (left) and total displacement (right) within the rock mass surrounding the excavation for Scenario 2, K -ratio=2. a) Circular, b) circular arc, c) horseshoe, and d) rectangular.

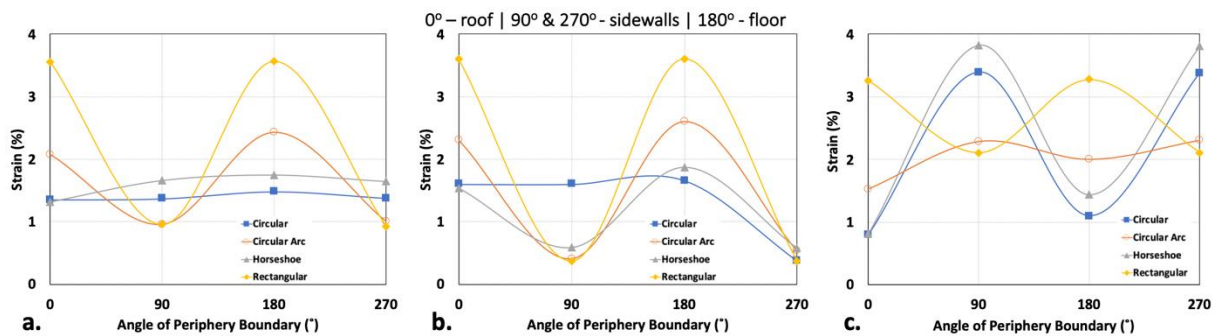


Figure 6. Strain distribution around the excavation: a) for the Baseline Scenario, b) Scenario 1, K -ratio=0.5 and c) Scenario 2, K -ratio=2 for the different tunnel geometries.

All excavations (excluding the right sidewall of the circular and squared arc) follow the same trend for low K -ratio for scenario 1 (figure 6b), whereby the roofs and inverts on the plane of the far-field σ_1) experience more strain as the sidewalls. The difference is more prevalent for the circular arc and rectangular excavations, strains reaching 2.6% and 3.5% respectively, relative to 0.5% on the sidewalls. The opposite trend for the higher K -ratio for scenario 2 (figure 6c), generally the invert and roof experience approximately half the strain as that the sidewalls. However, the rectangular excavation even has a greater strain on the roofs and inverts (3.2% compared to 2.1%) and the circular arc has a very even distribution ranging from 2.3% to 1.7%.

Circular excavation performs well, due to the even distribution of the relatively low stresses and strains across the excavation periphery. Although the rectangular appears to have no excessive stresses rock mass overall, stress concentration at the sharp corners would likely have relatively large damage associated in these areas, and generation of high bending moments on the roof and invert result in higher displacements. Preliminary findings show that smoother geometries seem to be performing better.

For Scenario 1, reducing the K -ratio creates favourable conditions for the circular, horseshoe excavations. This is because the horizontal stresses are considerably less, and the overall far-field stress is lowered. However, the circular arc and rectangular arc have the far-field σ_l directed towards the roofs and inverts. These longer peripheries build-up of large displacements and for the circular arc, the rock mass adjacent could experience ravelling. All excavations have no excessive stresses at the sidewall, however, different degrees of tension build-up on the sidewall (90° from σ_l) and is more significant for the curved excavations. The significant increase in horizontal stresses in the far-field stresses creates largely unfavourable conditions for all geometries in Scenario 2. The damage initiated more severe for those geometries with curved peripheries at the roof and invert (90° from σ_l). The amount of strain is more significant on the sidewalls (0° from σ_l) on those excavations with aspect ratios of 1. The circular arc and rectangular excavations with longer roof and invert profiles distribute the induced displacement more evenly across the entire excavation boundary, making them the more favourable geometries for this condition.

6. Conclusions

In this research we demonstrated the critical influence of excavation geometry has along with the highly pervasive structures present in stratified rock masses. Initial assessments carried out through numerical modelling using the FEM method and discrete discontinuities explicitly captured in the model showed different rock mass responses for a number of scenarios. More specifically, the relative orientation of in situ stresses and rock joints have different impacts on the excavation depending on its geometry, and therefore, the optimization of a geometry becomes a complex process that requires a thorough investigation since this influences the required support measures and rock mass mobilization. Based on the numerical models, initial findings demonstrate that circular excavations appear to be performing better regardless of the in-situ stress orientation. Rectangular excavations appear to be performing adequately under specific conditions which if identified in the field can justify their selection. While this research is at its early stages, it shows the great impact that the excavation geometry plays in sedimentary rocks and future steps will address more aspects including constructability and how the construction sequence itself can affect the rock mass behaviour.

References

- [1] Paraskevopoulou, C., Cornaro, A., Admiraal, H., Paraskevopoulou, A., 2019. Underground space and urban sustainability: an integrated approach to the city of the future. *In: Changing Cities IV Spatial Design, Landscape and socioeconomic dimensions*, June 2019, Crete, Greece.
- [2] Paraskevopoulou C, Benardos A (2013) Assessing the construction cost of tunnel projects. *TUST J*, **38**(2013), 497–505. <https://doi.org/10.1016/j.tust.2013.08.005>
- [3] de Vallejo, L.G. and Ferrer, M., 2011. Geological engineering. CRC Press.
- [4] Pietruszczak, S., Lydzba, D. and Shao, J.F., 2002. Modelling of inherent anisotropy in sedimentary rocks. *International Journal of Solids and Structures*, 39(3), pp.637-648.
- [5] Bruno, M.S. and Nelson, R.B., 1991. Microstructural analysis of the inelastic behaviour of sedimentary rock. *Mechanics of Materials*, 12(2), pp.95-118.