The Redundancy of Systematic Rock Bolts in Cavern Construction

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ABSTRACT

The general design approach for the permanent supporting system of caverns and drained tunnels with more than half a span of rock cover follows a 3-Stages Approach, which is 1) deriving the initial supporting types based on the NGI Q-system (2015), 2) checking of the initial supporting types by Reinforced Rock Arch (RRA, Bischoff and Smart, 1977) theory and 3) verifying the design by finite element analyses to confirm the support requirements arrived from 1) and 2) above.

The development and use of the Q-system for the temporary and permanent design of rock bolts and shotcretes are routinely used in practice, which would not require any deliberations. For the RRA approach, the concept is to form a reinforced rock arch from the systematic rock bolts around the opening by improving the confining pressure to increase the surrounding rock mass strength, which, in theory, provides a better utilization of the rock mass strength than that of the rock bolts.

In this study, 3D and 2D finite element analyses have been carried out to investigate the soil-structure interaction and load transfer mechanism from the rock stress to the rock bolts at each stage of excavation. Typical rock mass properties commonly adopted in Hong Kong are used, and a large cavern span of 32 m and height of 36 m is used. With the use of the same material properties and geometry, finite element simulations are carried out using the 3D software RS3 to generate the ground convergence-support reaction curve and compare it with the longitudinal displacement profile (Vlachopoulos and Diederichs, 2009) for predicting the amount of ground relaxation before the supporting bolts are activated. Based on the ground convergence-support reaction curve from the RS3, another 2D finite element program, RS2, compares the load developed in the systematic rock bolts in a 2D plane strain vs a 3D stress environment.

The paper discusses the stress distribution, plastic zones, convergence in the rock mass and the development of rock bolt loads before, during and after each stage of excavation. With different ranges of Q-value tested, it can be concluded that the ground behaves nearly in an elastic behavior due to the low stress-to-strength ratio of the rock mass, and the load mobilized in the rock bolts has an insignificant contribution to the cavern convergence, stress redistribution due to the free-moving boundary conditions at the cavern walls, as demonstrated by a low mobilized working force less than 20% of the tensile strength of the working forces developed in both the 2D and 3D analyses. The systematic rock bolts in a homogeneous isotropic rock mass can be considered a redundant and prescriptive measure. Its main contribution will only be developed in a jointed rock mass by increasing the confining stresses across the rock joints and mobilizing the shearing resistance of the jointing materials.

1 INTRODUCTION

The general design approach for the permanent supporting system of caverns and drained tunnels with more than half a span of rock cover follows a 3-Stages Approach, which is 1) deriving the initial supporting types based on the NGI Q-system (2015), 2) checking of the initial supporting types by Reinforced Rock Arch (RRA, Bischoff and Smart, 1977) theory and 3) verifying the design by finite element analyses to confirm the

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The development and use of the Q-system for the temporary and permanent design of rock bolts and shotcretes are routinely used in practice, which would not require any deliberations. For the RRA approach, the concept is to form a reinforced rock arch from the systematic rock bolts around the opening by improving the confining pressure to increase the surrounding rock mass strength, which, in theory, provides a better utilization of the rock mass strength than that of the rock bolts.

Using the RRA approach has become popular in Hong Kong due to increasing cavern developments, with cost savings when a cast in-situ concrete lining is not required after the temporary supports are installed. The concept is illustrated schematically in Figure 1 that a reinforced rock arch can be developed if the rock strength can be mobilized (Points 1 to 2) by increasing the confining stresses (Points A to B) due to introducing the systematic rock bolts within the stress redistributed zone.

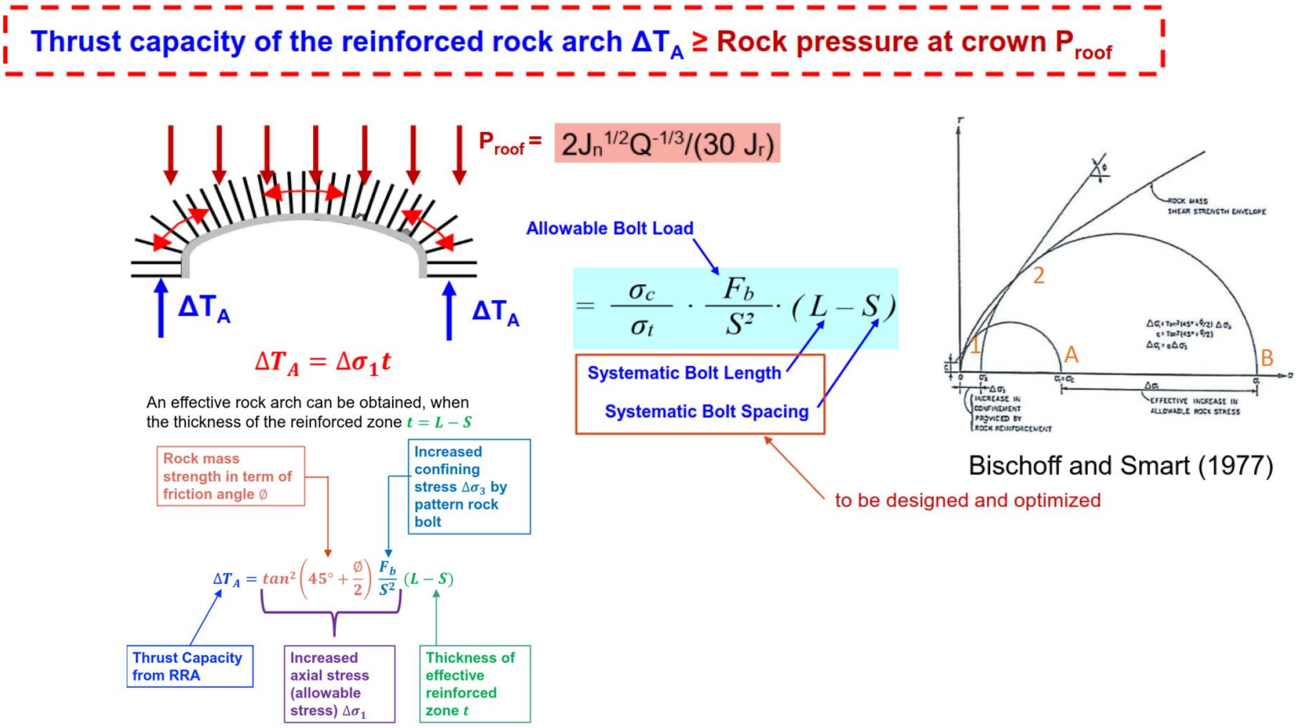
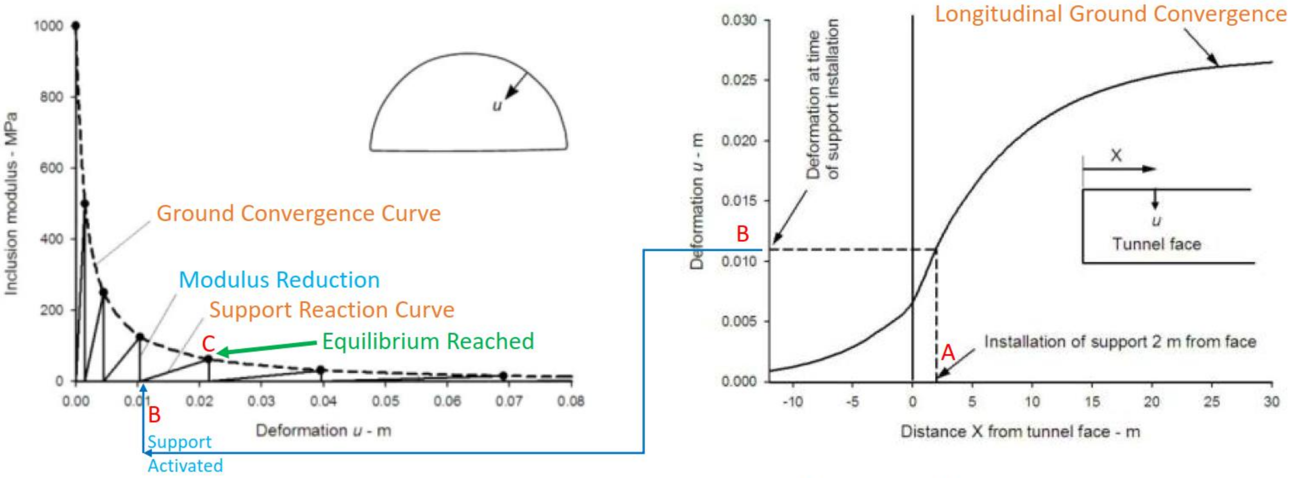


Figure 1: Concept of RRA in a Stress Redistributed Area

The theoretical basis for this concept is sound. Still, it is not evident to the author during the construction stages whether the sequence of excavations followed by bolt installation mimics the assumed boundary conditions in the numerical modeling and whether the bolts can generate a reinforced arch to increase the rock strength. We know that the contribution of the bolts is a stress-path-dependent problem in rock mechanics, which means that the outcome of the redistributed stress depends on the intended construction sequences.

The moving front of the tunnel and cavern excavation is a three-dimensional process where we know stresses and deformation will occur ahead of the tunnel face before the face is reached.

In a typical design, 2D finite element analyses confirm the support requirements from the Q-system and RRA. Due to the limitation of the 2D plane-strain problem, a method was developed by Vlachopoulos and Diederichs (2009) to estimate the amount of convergence occurring before the bolts are installed. The numerical process is referred to as the ground convergence-support reaction approach. As illustrated in Figure 2 for a fictitious case, the Longitudinal Ground Convergence curve (Figure 2B) is predicted based on the equations and calibration works from Vlachopoulos and Diederichs (2009); the supports are installed at a distance behind the face (Point A), and the supports in the 2D finite element program is activated (Point B) to bring into equilibrium for arriving the stress redistributed state (Point C). In the numerical process, the simplified procedure is to reduce the face support pressure (by internal pressure or modulus reduction) from full overburden to zero in multiple stages to represent the tunnel face advance, measure the deformation to generate the ground convergence curve (u in transverse direction in Figure 2A), measure the plastic zone radius, generate the Longitudinal Ground Convergence curve, determine the bolt installing distance from the face (Point A), calculate the amount of movement (Point B) occurring before the tunnel reaches the face, activate the bolts at the stage when the ground has converged some distances (Point B in Figure 2A) and finally let the computer runs until equilibrium is reached (Point C).



A) Ground Convergence – Support Reaction Curve

B) Longitudinal Ground Convergence Curve

Figure 2: Concept of Convergence-Support Reaction Approach

2 FINTIE ELEMENT MODELLING

2.1 *Rock Stress to Strength Ratio*

For general purposes, the finite element analysis usually assumes the rock mass to be homogeneous and isotropic, including distinctive weak planes representing rock joints. For a nominal tunnel/cavern depth of 200 m, typically in Hong Kong, with a moderate unconfined compressive strength of 50 MPa of Grade III or better rock where the unit weight is taken as 27 kN/m^3, the stress-to-strength ratio is considered low 0.11. Based on the work by Martin, Kaiser and McCreath (1999), for a low in-situ stress ratio of less than 0.15, linear elastic rock response to falling of rock blocks between weak joint features is expected depending on whether the Rock Mass Rating (RMR) is higher than or lower than 75, essentially stating that it is a kinematic controlled stability problem rather than a stress-yielding problem. With this fundamental principle in mind, the author has worked on a few tunneling and cavern projects in Hong Kong and observed that the ground convergence-support reaction curves obtained from 2D finite element studies are usually linear and that the ground has already significantly moved before the supports are activated in the program. A late activation of support in the convergence curve can be interpreted as most of the stress redistribution due to excavation is taken up by the rock mass instead of the structural capacity of the rock bolts. The above observations triggered the author to analyze the contribution of systematic rock bolts under the RRA approach. With the help of a 3D finite element program, the assumption in Vlachopoulos and Diederichs (2009) can be eliminated for predicting the longitudinal ground convergence curve for use in a 2D finite element program. First, we look at the results from the 3D finite element program (RS3) and then from the 2D finite element program (RS2).

2.2 Geometry and Rock Properties

A hypothetical case is presented in Figure 3, with the geometry set close to some typical caverns in Hong Kong to make the outcome practically near what is usually experienced.

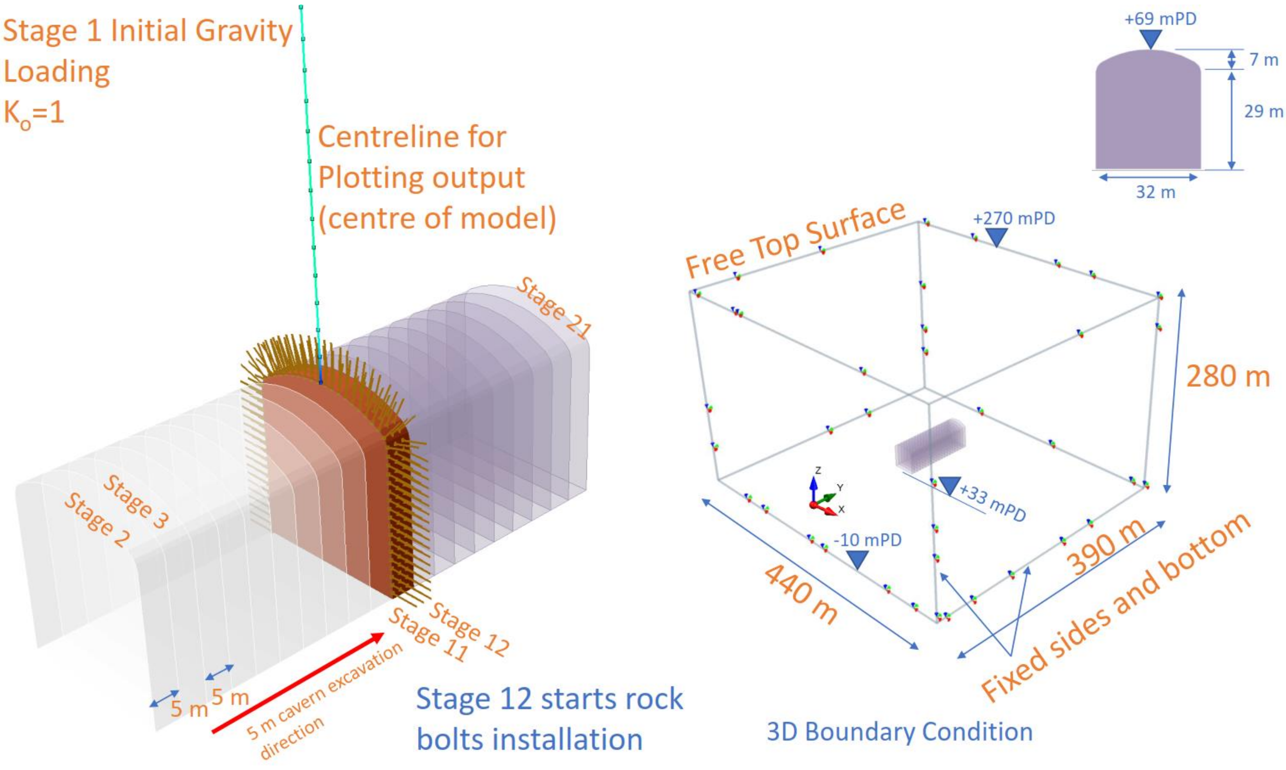


Figure 3: Geometry and Boundary Condition of a 3D Model

The cavern has a span of 32 m and a height of 36 m, situated about 200 m below the ground surface. The model has a free top surface with the bottom fixed in the boundary conditions. Gravity is turned on at Stage 1 for K^0 equal to 1, allowing the side boundary to slide down, and the stresses arrive at equilibrium before the subsequent tunneling stages at 5 m intervals. The boundary surface is set at more than 10 times the geometry to avoid the effects of the boundary constraints. Tunneling is represented by modeling a 5 m full-scale excavation from left to right, as shown in Figure 3, where Stage 11 is just before reaching the center section line of interest and Stage 12 is the stage of excavation and bolt installation in one step. The tunnel continues until it is far from the center section line of interest, essentially modeling from a virgin ground; it passes through the section line of interest and finally away outside the zone of influence.

The rock properties are based on the author's experience and simplified to allow a relatively low Q value of 1.9 in the study, with the key parameters shown in Table 1. Parametric studies to lower the Q value to 0.22 have been carried out. Still, they will not be reported here because the mechanism being developed has not changed. The mechanism discussed in the later section is not sensitive to the assumed parameters but to the modeling sequence.

Table 1: Rock Properties Assumed

Unit weight = 26 kN/m^3	Poisson's Ratio = 0.3	
Intact Rock UCS = 75000 kPa	Young's Modulus = 7.7e+06 kPa	

Generalized Hoek-Brown Criterion	Peak Strength	Residual Strength
	GSI=54	GSI=37
	m_i=32	m_i =3.39
	m_b=6.18965	m_b=0.316198
	s=0.006029	s=0.000912
	a=0.504342	a=0.513932
	σ_{cm}=24.7 MPa	σ_{cm}=17.7 MPa
Rock Mass Elastic Modulus EI=2e+07 kPa		
Bolt diameter = 25 mm	Bolt modulus = 2e+08 kPa	Tensile capacity = 125 kN
Bolt type = fully bonded	Bolt spacing = 1.67 m c/c transverse and longitudinal direction	Bolt length = 6 m

2.3 RS3 3D Finite Element Results

The nominal thickness of the plastic zone after all the stages are completed and with systematic bolts added in Stage 12 is about 5.3 m, which is slightly less than the bolt length. Figure 4 shows the change in vertical stresses at the cavern crown centerline as the tunnel advances.

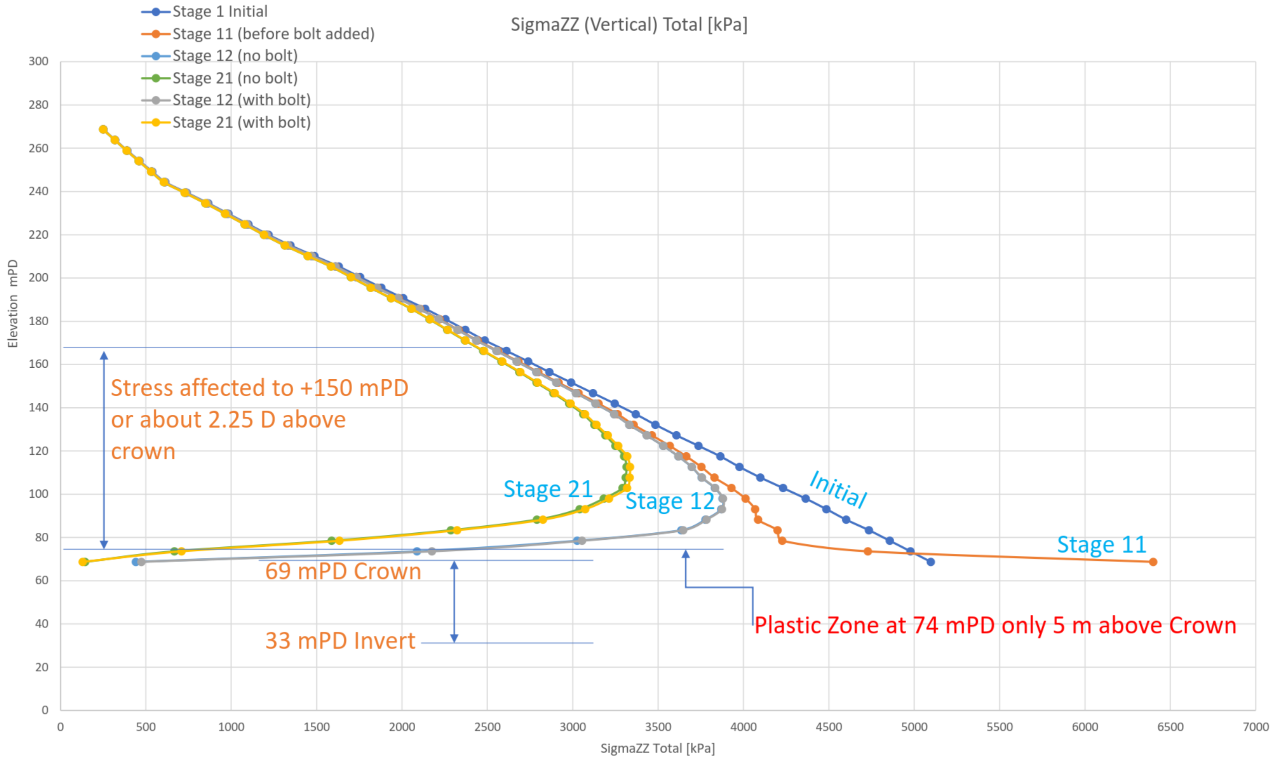
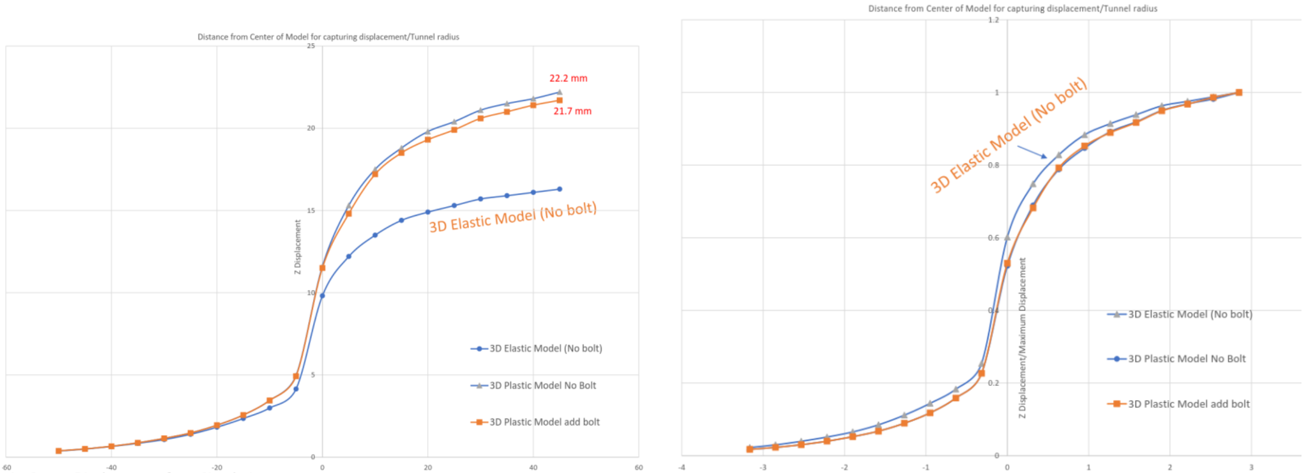


Figure 4: Change of Vertical Stress at the Model Cavern Centerline

1) Some observations can be made. Just before the excavation and without the bolts installed (Stage 11), the vertical stresses increased due to arching developed ahead of the tunnel crown in a longitudinal manner. Immediately after excavation and bolt added (Stage 12), the vertical stresses were reduced below the

initial hydrostatic reference due to stress redistribution. Vertical stress was further reduced when the tunnel reached the end (Stage 21). The stresses were affected within a zone of about 2.25 D above the crown, where D is the equivalent diameter of the cavern. What is most interesting and the study's objective is that the stresses are not influenced by whether systematic bolts were added to the cavern.

2) The longitudinal ground convergence curve is depicted in Figure 5A, whereas the normalized displacement (vertical displacement divided by maximum displacement as the tunnel passes through) is shown in Figure 5B. It can be seen from Figure 5A that there is no difference between with or without bolts added to the convergence curve. In Figure 5B (after displacement normalized), the shape of the convergence curve follows closely to that of the 3D model if it is treated as an elastic material without bolts. The observation echoes the concept in Section 2.1 that for a low in-situ stress ratio, a linear elastic rock response may dominate the mechanism.



A. Crown Displacement from Simulation

B. Crown Displacement Simulation Normalized

Figure 5: Longitudinal Ground Convergence Curve at the Model Cavern Centerline

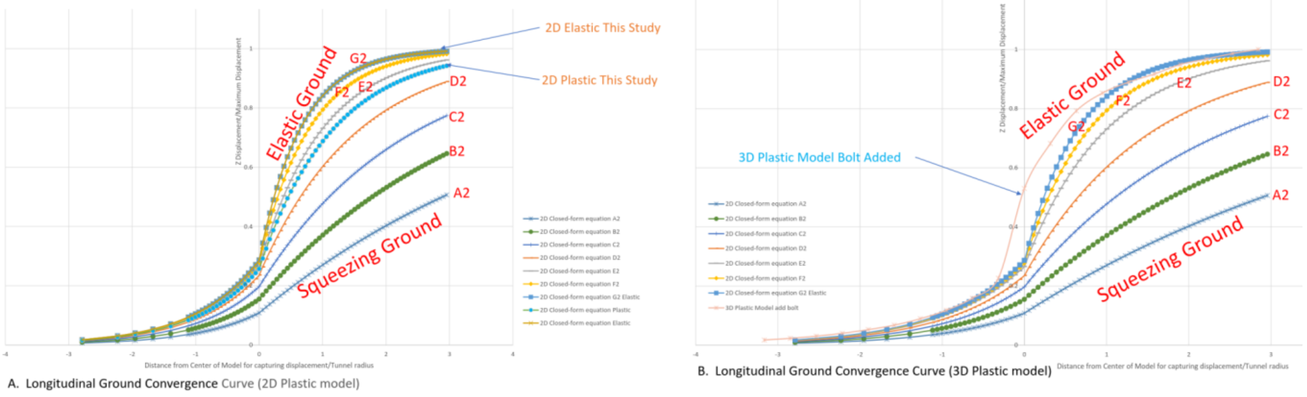
3) Figure 5B also suggests that 50% of the convergence occurred before the excavation reached the study centerline of the crown, which may be interpreted as the rock mobilizing its strength earlier than the bolts can be added after excavation.

2.4 RS2 2D Finite Element Results

As discussed in Section 1, the Longitudinal Ground Convergence curves have been developed based on analytical equations by Vlachopoulos and Diederichs (2009) by parametric studies of varying tunnel radii; overburden stresses, in-situ stress to rockmass strength ratio for a 2D problem. The normalized longitudianl displacement profiles from Vlachopoulos and Diederichs (2009) against the normalized plastic radius (R^*) for seven different cases (A_2, B_2, C_2, D_2, E_2, F_2 and G) under a constant unconfined compressive strength for rock mass are reproduced in Table 2 and plotted together in this study for comparison.

Table 2: R* vs maximum displacement after Vlachopoulos and Diederichs (2009)

Constant unconfined compressive strength rock mass 2.8 MPa	A_2	B_2	C_2	D_2	E_2	F_2	G_2
R*	7.5	6.3	5.0	3.3	2.2	1.6	1
$u_{\max}$ (m)	2.14	1.25	0.632	0.242	0.0585	0.00167	0.0753



A. Longitudinal Ground Convergence Curve (2D Plastic model)

B. Longitudinal Ground Convergence Curve (3D Plastic model)

Figure 6: Longitudinal Ground Convergence Curve 2D and 3D Models, Generated after Vlachopoulos and Diederichs (2009)

Figure 6A reveals that under this study for 2D elastic or 2D plastic analysis, the Longitudinal Ground Convergence Curves, when compared to Vlachopoulos and Diederichs (2009), who carried out an extensive range of analysis under varying in-situ stress/rock mass strength ratios, show that our failure mechanisms should more resemble the elastic ground or slightly plastic behavior. The 3D plastic model with bolts added in this study (Figure 6B) shows about 90% of the displacement would behave elastically.

Figure 7 compares the Longitudinal Ground Convergence Curves for the 2D elastic model, 2D plastic model, 3D plastic model without bolts and 3D plastic model with bolts added. Two observations can be made. First, the 3D plastic model is close to the 2D elastic model. Second, there is no difference between whether bolts are added in the 3D analysis.

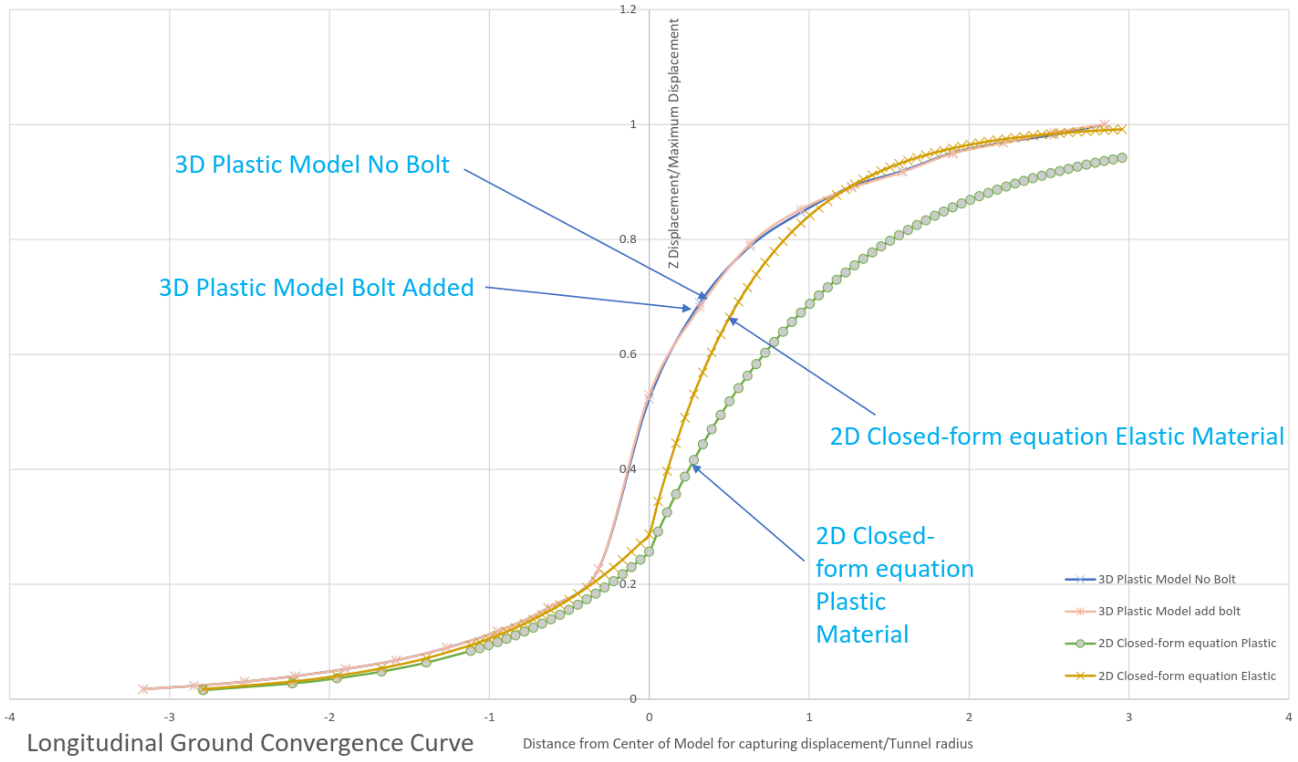


Figure 7: Longitudinal Ground Convergence Curves for 2D and 3D models

The above assessment provides insight into the problem that our failure mechanisms should more resemble the elastic ground or slightly plastic behavior for a low stress-to-strength ratio and that more than 50% of the convergence occurred before the excavation reached, which means that the rock mobilizing its full strength before the bolts can be added after excavation.

All the bolt forces are mobilized due to the movement of the ground, as shown in Figure 8. However, it cannot be seen if there is any contribution to reducing the convergence of a tunnel or stress redistribution. In other words, the concept of forming a reinforced rock arch by increasing the confining stresses due to introducing the systematic rock bolts within the stress redistributed zone is not supported.

Rock bolts can only be installed after the excavation is completed. Whether using a 2D or 3D program, the modeling process and sequencing mimics the construction sequence and controls the outcome more than the material properties. The following section explains why the added bolts do not reduce the convergence and stress state.

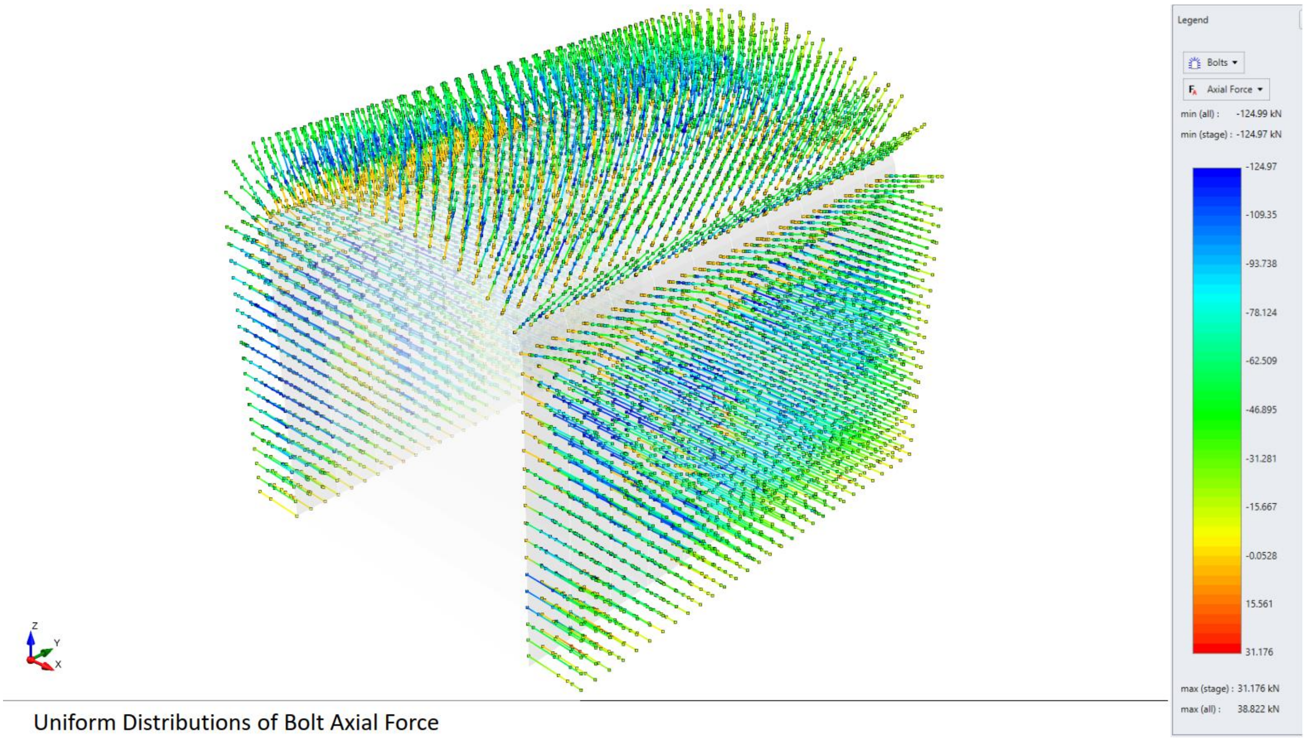
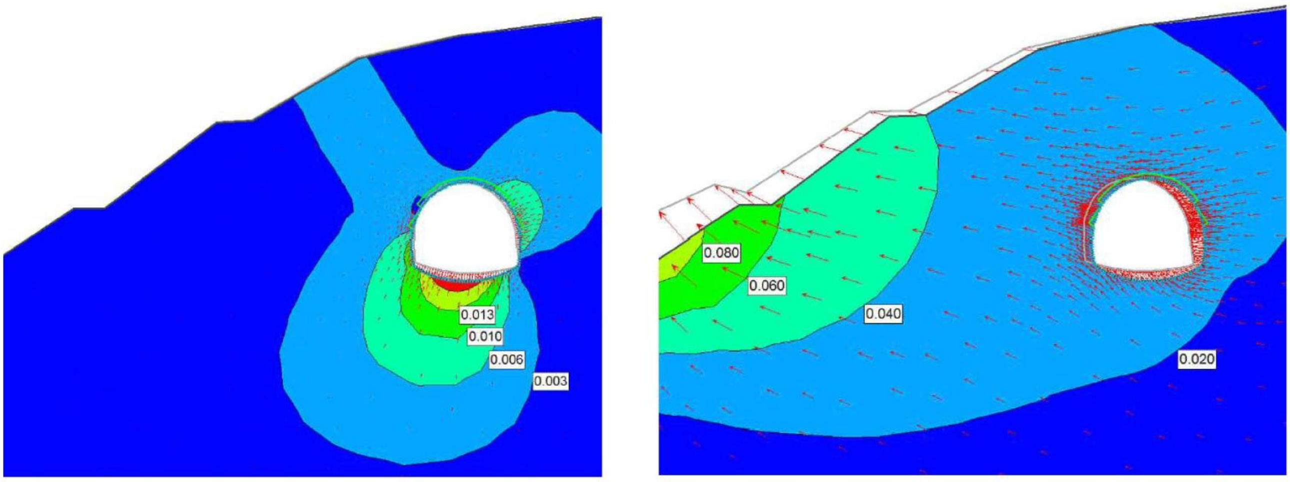


Figure 8: Distribution of Rock Bolt Axial Forces

3 STRESS PATH DEPENDENT PROBLEM

It is well-recognized that geotechnical problems are stress path-dependent, where the outcome depends on the loading sequence far more than the adopted material properties. Figure 9, using an example available from RS2, illustrates that for the same geometry, initial stress state and material properties, the tunnel will behave entirely differently depending on whether the slope is cut first or the tunnel is excavated first.

For the 3D model in this study, Figure 10 shows the extent of the plastic zone and the affected elastic zone based on the plot of stress distribution from Figure 4. It can be seen that the rock bolt length slightly extended beyond the plastic zone into the elastic zone. However, stresses and displacement are affected about 2 times the cavern span, and the cavern boundary perimeter is free to move inward together with the bolts. Unless the bolts are very long and anchored into the undisturbed zone, similar to an analogy of a soil nail grouted outside the slip planes, the bolts and the rock mass will move inward together, stresses in the radial direction are released and confining stresses cannot be built up due to the cavern perimeter has a free moving boundary condition during the unloading excavation sequence.



A. The slope is cut first and then tunnel excavated.

B. The tunnel is excavated first, then slope is cut.

The effects of excavation sequence

Figure 9: Illustration of a Stress Path Dependent Problem

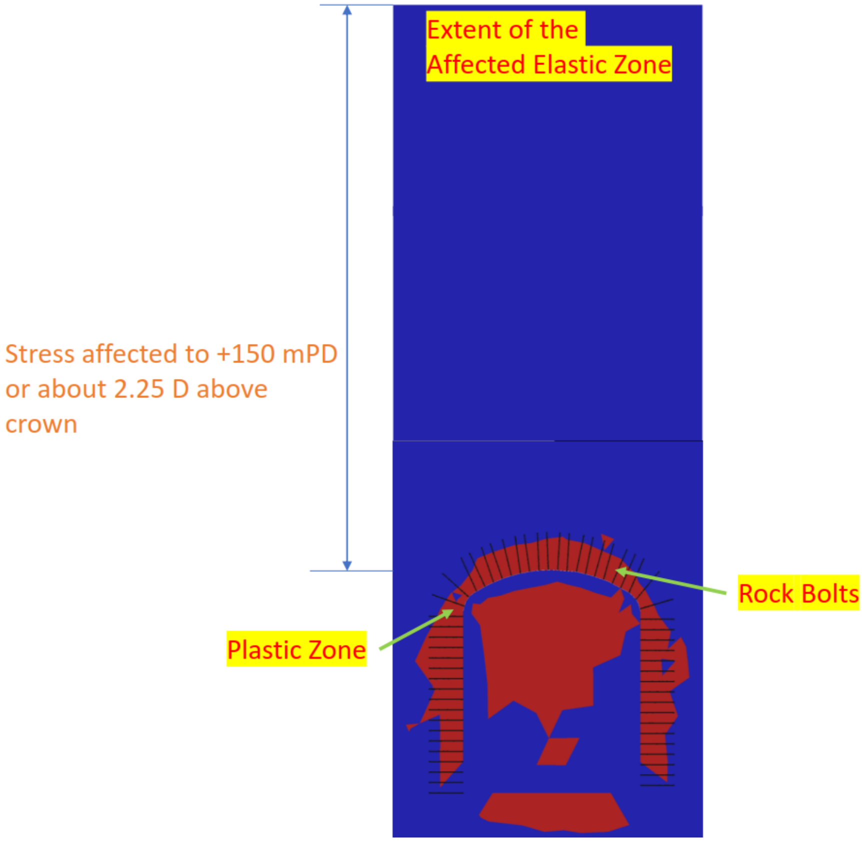


Figure 10: Plastic Zone and Affected Elastic Zone in 3D Model

3.1 Tunnel under a Fixed Boundary and Loading Up.

We can arbitrarily create a boundary condition and loading stage for an opening using the 3D program (RS3) to see if displacement can be reduced and the radial stresses increased due to the contribution of the rock bolts added to the system, as shown in Figure 11. In this example, a small 2 m diameter tunnel in an elastic medium under K_0 equal to 1 is applied with a uniform stress of 10 MPa with the Y longitudinal direction fixed to mimic the plane strain condition. The bolt diameter is 25 mm, the modulus is 116667 MPa, the tensile capacity is 100 MN, 1 m long, and 0.1 m center-to-center is installed. The tunnel is assumed to be formed already, and the load is applied at the far-field boundary. Such boundary and loading conditions do not represent the actual cavern/tunnel excavation sequence; perhaps they represent a reinforced structure with a window opening under some externally applied loads. The results are presented in Figure 12.

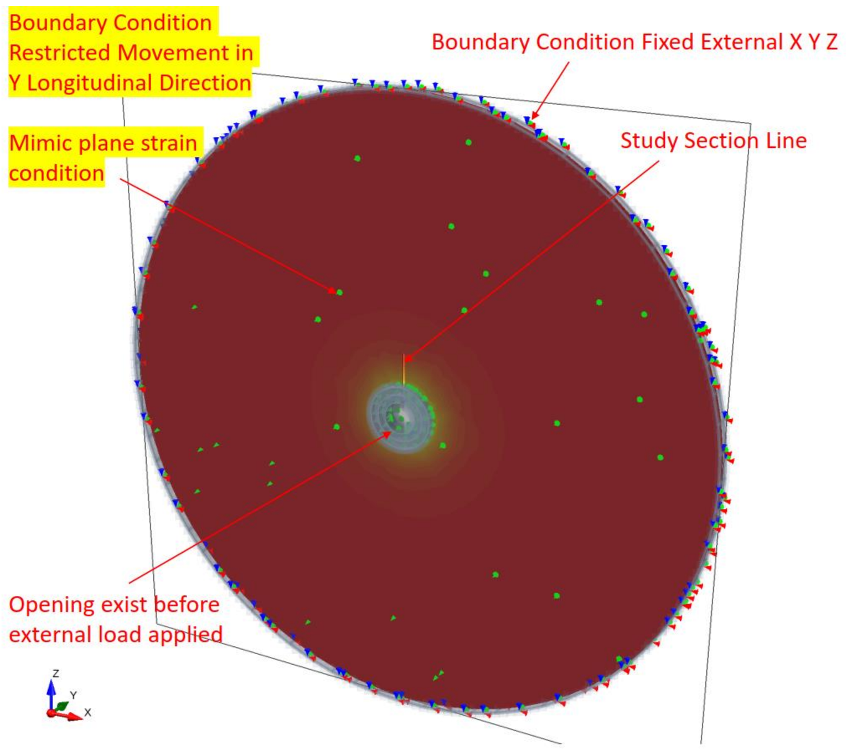
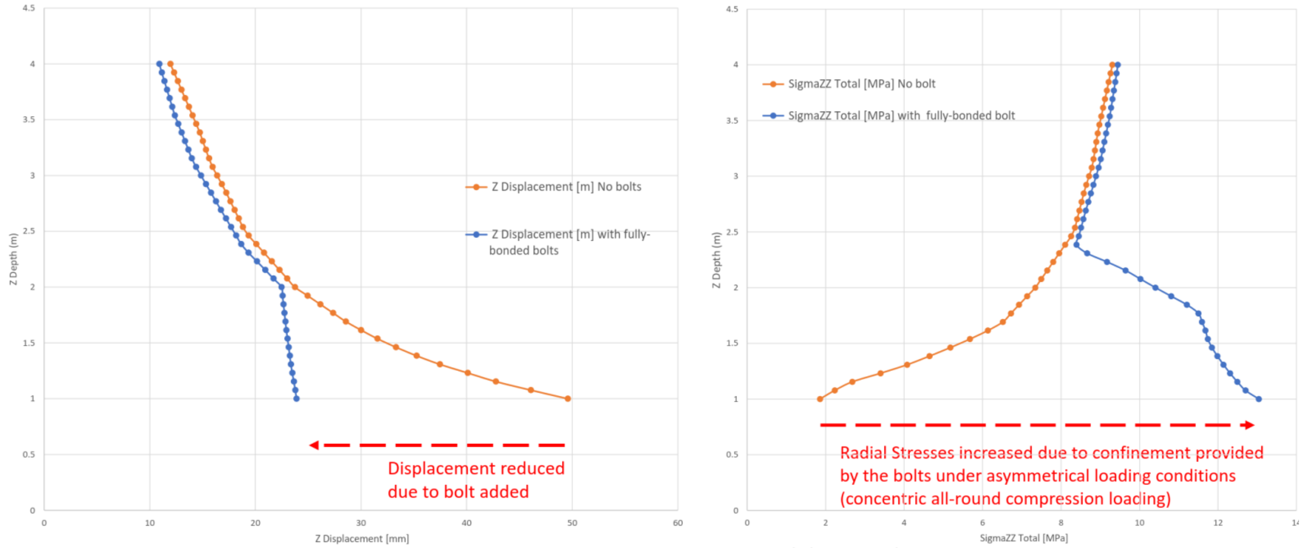


Figure 11: Opening under Axisymmetric Loading with Bolts Added



A. Displacement along Center Line

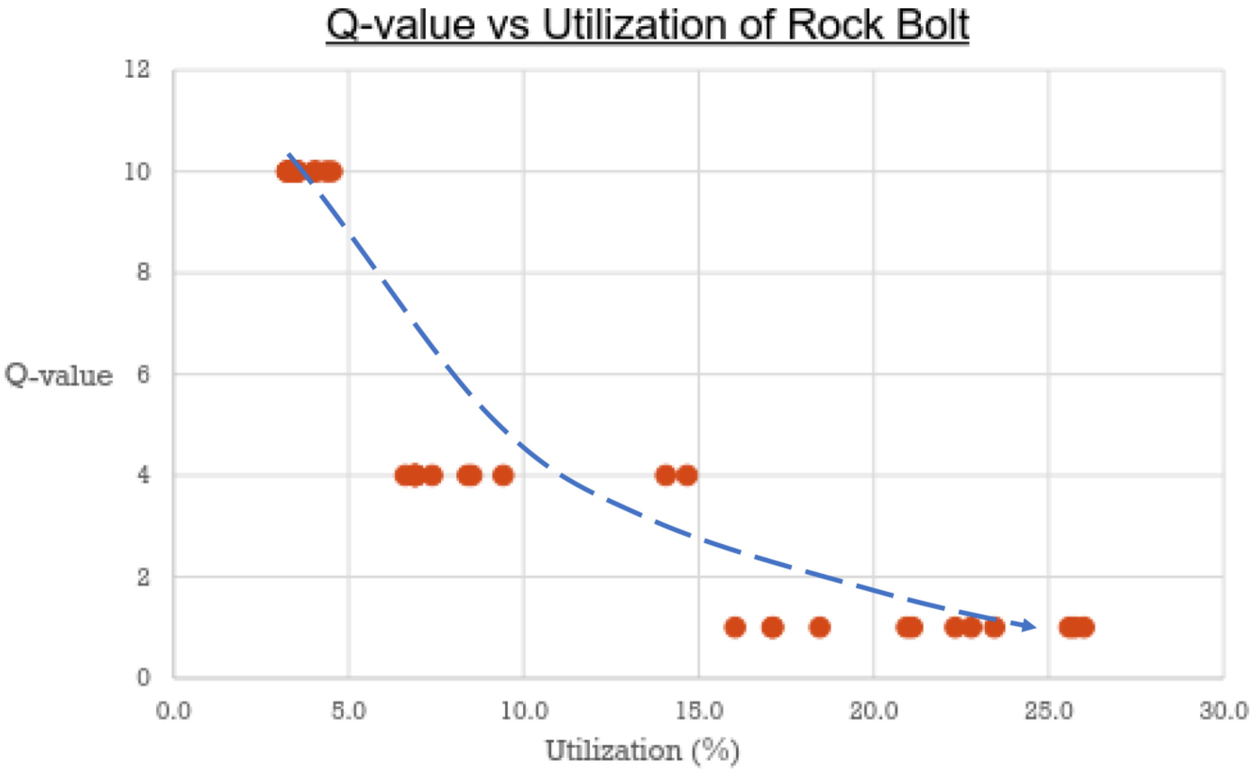
B. Radial Stresses along Center Line

Figure 12: Displacement and Stress Changes under Axisymmetric Loading with Bolts Added

It can be seen from Figure 12A that the displacements are reduced and from Figure 12B that the radial stresses are increased under a very specific boundary condition, which unfortunately does not represent tunneling.

3.2 Benefits of Rock Bolts

The utilization rate (axial bolt force mobilized divided by the bolt tensile capacity) is generally low at less than 5%, as shown in similar studies with different material properties, stress range, and depth. It increases with the decrease of the Q value, which suggests that the rock mass shared the load from redistribution rather than the structural capacity of the bolt.



Rock is heterogeneous and anisotropic, a condition different from the assumption made in the 3D finite element studies. The systematic bolts from the ideal homogeneous rock mass study are redundant because they neither reduce the convergence of a cavern/tunnel nor change the stress state during the redistribution process. However, the rock bolts can be considered prescriptive because they lessen the possible kinematic failure of rock blocks formed in adverse joint orientation. They also limit joint slippage, dilation and movement, indirectly increasing the rock joints' strength and maintaining the opening's stability.

3 CONCLUSIONS

Some observations can be made from this study:

Vertical stresses increase ahead of the tunnel crown in a longitudinal manner due to arching developed forward.

There is no difference between with or without bolts for stress redistribution and convergence.

For a cavern excavation, the bolts are situated in the plastic zone and relatively short compared to the cavern perimeter size, where bolts, plastic zone and cavern boundary (crown and two sidewalls) all move inward together, which will not allow the confining stresses to build up, a condition very different from that of an ideal circle under axisymmetric loading.

The 3D model shows that the normalized longitudinal ground convergence curve resembles the elastic ground or slightly plastic ground.

The low in-situ stress-to-strength ratio causes a linear elastic rock response.

The 3D model suggests that 50% of the convergence occurred before reaching the excavation face.

A low utilization rate suggests that the rock mass strength is mobilized, sharing the load from redistribution instead of relying on the structural capacity of the bolt.

The systematic bolts in an ideal homogeneous rock mass study may be redundant. Still, the benefit of its prescriptive uses arises from reducing the kinematic failure of rock blocks formed in adverse joint orientation and maintaining the stability of the opening.

The current research is based entirely on homogenous rock mass, excluding the study of volcanic rock, in which the failure mechanism may be dominated by the degree of fracture relative to the opening size

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