Numerical modeling simulations of spray-on liners support potential in highly stressed and rockburst prone rock conditions

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ABSTRACT: Extensive field study has been performed to assess the capabilities of thin spray-on liners (TSLs) and conventional spray-on support systems for preventing rock and support material damage that often results due to mining-induced rockbursts. Support performance was studied using field scale explosive detonation trials to simulate dynamic failure effects that are known to develop during typical rockburst events. Multiple seismic and high speed photographic monitoring techniques were used to provide detailed information concerning rock motion, surface fracturing, ejected fragment motion, and support liner survivability characteristics. Results of this study have demonstrated that TSL's and variant layer combinations may be as effective as or better than conventional support materials for mitigating rockburst or like damage in highly stressed mine environments.

In this study, field results have been verified using numerical modeling procedures to better understand the support behaviour of TSLs when subjected to highly stressed mine environments and mining-induced rockbursts, a factor that is essential when designing any rock support system. A series of numerical modeling assessments were conducted using FLAC^{3D} modeling of a half circular TSL-lined tunnel, influenced by anisotropic stresses and simulated mining-induced rockbursts, to investigate the support potential of TSLs under prototype conditions. The effect of a mine rockburst was simulated using the three-dimensional dynamic analysis option of FLAC^{3D}.

Results of TSL-lined tunnels in highly stressed and mine rockburst conditions indicated exceptional effectiveness of TSLs for suppressing rock deterioration resulting from stresses and rockbursts. The rock support potential of TSLs on tunnel surfaces was compared with that of thin shotcrete linings, and results indicated that thin spray-on lining products currently available may be equally as effective in support as shotcrete materials.

1 INTRODUCTION

This paper provides the preliminary results of numerical modeling performed to complement field assessment of support capabilities of TSLs and conventional spray products for mitigating rockburst or like damage in highly stressed mine environments. The field research was undertaken by the Queen's University Mining Engineering Department and funded by the Workplace Safety and Insurance Board of Ontario (WSIB) to characterize the support capabilities of innovative mining support agents, designated as TSL materials, conventional spray supports, as well as combinations of TSLs and conventional spray supports, for mitigating dynamic failure effects created by simulated rockbursts. The field assessment of support capabilities of TSLs and conventional spray products is novel and constitutes work that is unique in the field of underground excavation support design. In the research, various TSL products, shotcrete, fibrecrete and "superliner" combinations of TSL products with ultra-thin shotcrete or fibrecrete layers (at 5 and 3 cm thicknesses, respectively) have been tested. The research on TSL support application has been performed under the sponsorship of the Workplace Safety and Insurance Board of Ontario

(WSIB), with the principal goals being reduction in the incidence of underground worker injuries and enhancement of excavation stability or durability. A number of papers on the field study of TSLs were published in various forums and journals (Archibald *et al*, 1997, 1999, 2000, 2001, 2004, 2005, 2006 and 2007).

In this study, numerical modeling procedures were performed to verify field results and to better understand the support behaviour of TSLs when subjected to mining-induced rockbursts and highly stressed mine environments, a factor that is essential when designing any rock support system. Numerical modeling was carried out using FLAC^{3D} (Fast Lagrangian Analysis of Continua), a powerful three-dimensional elastic plastic-finite difference code, with a three-dimensional dynamic analysis option. In this work, modeling was performed using a polymer based TSL and shoctcrete, a conventional spray support that is commonly used in underground mines. The TSL product is currently commercially available for mine support application. Two numerical modeling simulations were conducted: 1) determination of the rock support capability of TSL's on a half circular tunnel in a Mohr-Coulomb material within a bi-axial stress field; and (2) assessment of the rock support capability of TSL's on a half circular tunnel in a Mohr-Coulomb material for preventing rock and support material damage due to mining-induced rockbursts. It is hoped that the numerical modeling procedures and methodologies developed will complement field testing procedures, providing comprehensive approaches for qualitatively and quantitatively assessing the potential support performance of TSL materials. The numerical modeling procedures and results are presented in the following sections.

2 MODELING SIMULATION OF A LINER-SUPPORTED UNDERGROUND EXCAVATION

The TSL capability for generating area support potential for rock in an underground excavation under high stress conditions and mining-induced rockbursts were simulated by numerical modeling. Three-dimensional elastic plastic underground excavation models were constructed with and without thin spray-on liner or shotcrete supports. The purpose of modeling the different conditions was to compare the responses for each case and to permit the assessment of the bearing or carrying capacity of the liner when subjected to static loading and dynamic stress. The geometry of the FLAC^{3D} model used is shown in Figure 1.

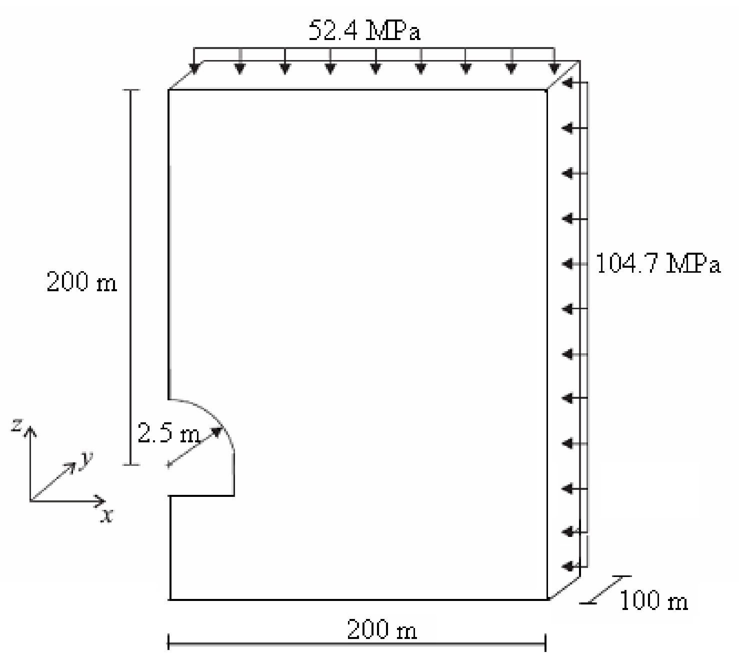


Figure 1. Geometry and loading of the FLAC^{3D} model.

2.1 *TSL Supported Underground Excavation Under High Stress Conditions*

2.1.1 *Numerical Model Development*

A vertical plane of symmetry through the center of a 5 m diameter half circular tunnel was constructed, and only one-half of the tunnel was modeled. Since displacements at certain observation points around the tunnel surface are important for assessing the bearing or carrying capacity of the liners, the boundaries of the model were located more than ten excavation diameters from the excavation periphery. The half circular tunnel model simulated was 50 m long in a 200 m high and 200 m wide dimension, and was located 2,000 m from the surface in a bi-axial stress field condition. The initial stress state corresponds to gravitational loading with the relationship between horizontal and vertical stresses being $\sigma_{xx} = 2\sigma_{zz}$. A system of coordinate axes was defined with the origin being 2 m above the floor of the tunnel; the z-axis pointed upward and the x- and y-axes pointed transverse and along the axis of the tunnel, respectively. The model contains approximately 7,400 zones.

The tunnel was constructed in a competent rock that was modeled as a Mohr-Coulomb strain softening material. The material properties of the rock, TSL and shotcrete materials are listed in Table 1. The strain softening model was used to initialize failure and displacement at the tunnel surface. The liner support was modeled with shell structural elements that are assigned properties representing the liner material. Figures 2(a) and 2(b) illustrate the 3-D geometry of the underground excavation without (Figure 2(a)) and with (Figure 2(b)) liner support. In order to initialize failure and displacement at the tunnel surface, a vertical velocity at the top of the model was fixed at a constant value of -1 x 10-5 m/step. The sum of the reaction forces at the base of the tunnel sidewall was obtained via a FISH function. For purposes of comparison, all models were programmed to run up to 3,000 time steps.

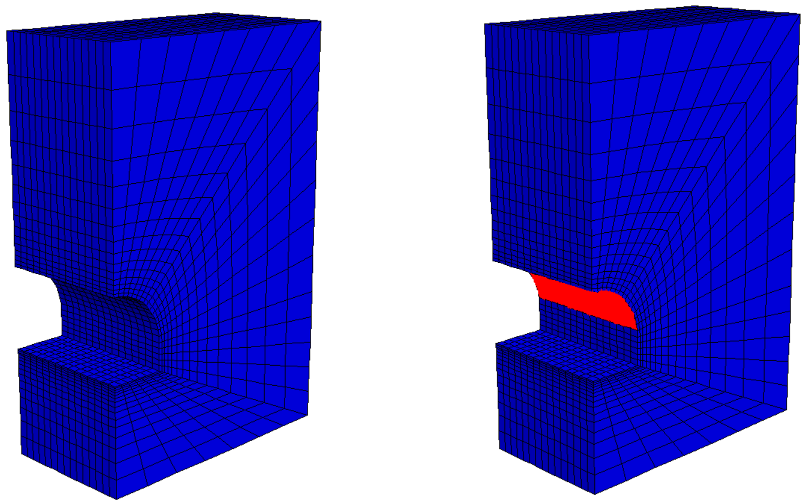
Table 1. Rock material, shotcrete material and TSL input parameters.

Properties	Materials		
	Tunnel Material	Shotcrete Material	TSL
Modulus of Deformation or Young's Modulus, MPa	54,790.00	10,500.00	111.69
Tensile Strength (σ_t), MPa	12.82	-	8.92
Cohesion (c), MPa	29.58	-	8.00
Internal Friction Angle (ϕ), Deg.	51.63	-	35.00
Density (ρ), kg/m^3	2,670.00	2,500.00	1,050.00
Shear Modulus (G), MPa	23,021.00	4,666.67	39.89
Bulk Modulus (K), MPa	29,457.00	7,000.00	186.15
Poisson's Ratio (ν)	0. 19	0.25	0.40

2.1.2 *Underground Excavation Under High Stress Conditions Numerical Model Results*

Figure 3 shows displacement plots at the tunnel crown (z-displacement, black line) and sidewall (x-displacement, red line) for the model without a liner. At 3,000 time steps, the displacements at the tunnel crown and sidewall were 6.6 and 6.5 cm, respectively, and indicated continuing deformation, evidenced by the downward trend of the plots. The maximum displacement is 1.32% of the effective diameter, which is 5 m.

Figure 4 also shows displacement plots at the same observation points as in Figure 3 for the model having a 3.5 mm thick (TSL A) thin spray-on liner. At 3,000 time steps, the displacements at the tunnel crown and sidewall were 4.6 and 5.8 cm, respectively, indicating a stalled deformation compared to the model with no liner. This is evidenced by the plot trends. The displacement at the tunnel crown was reduced by 30% while displacement at the tunnel sidewall was reduced by 10%. This indicated the effectiveness of the TSL liner support for suppressing rock deterioration.



(a) (b)

Figure 2(a). Tunnel with no liner, and (b). Lined tunnel.

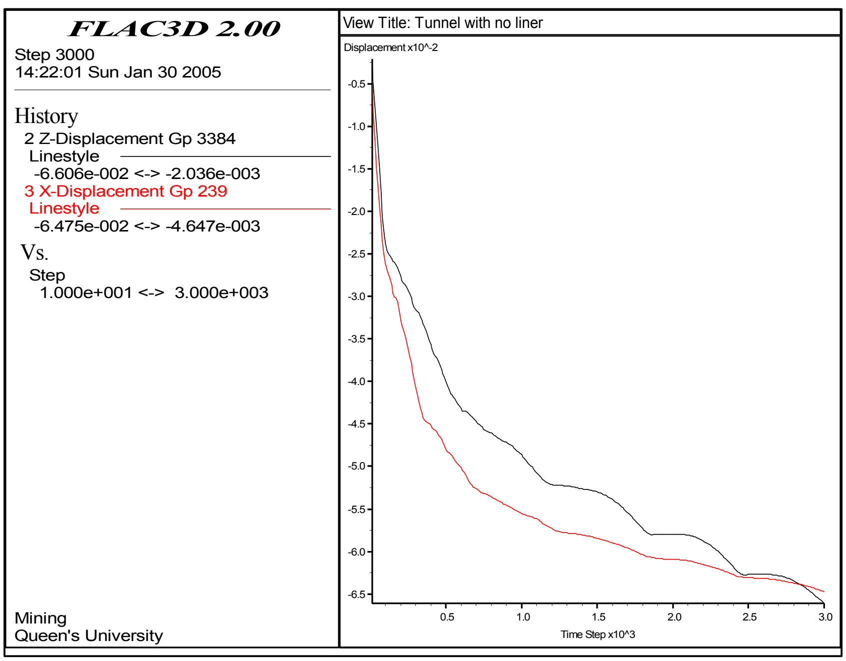


Figure 3. Displacement history plots versus time steps for tunnel with no liner.

A numerical model simulating a 10 cm thick shotcrete-lined tunnel was also conducted, with displacement plots being shown in Figure 5. The plots indicated that shotcrete was also able to effectively slow down rock displacement but only up to a certain distance. At a level approximating 1% of the tunnel diameter, the displacement at the tunnel crown starts to accelerate. This can be attributed to the brittle characteristic of the shotcrete. When its peak strength, either tensile or compressive, is attained, there remains no residual stress level capacity. The behaviour of shotcrete is similar to unreinforced rock subjected to uniaxial compression strength testing shown in Figure 6. The stress-displacement plot showed a distinct peak and no residual failure stress levels.

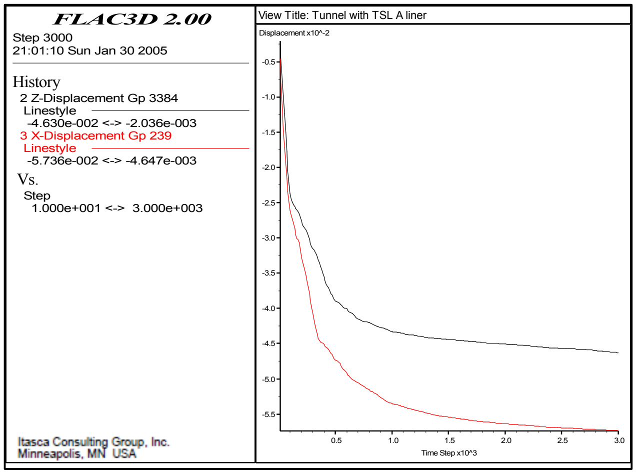


Figure 4. Displacement history plots versus time steps for tunnel with 3.5 mm (TSL A) liner.

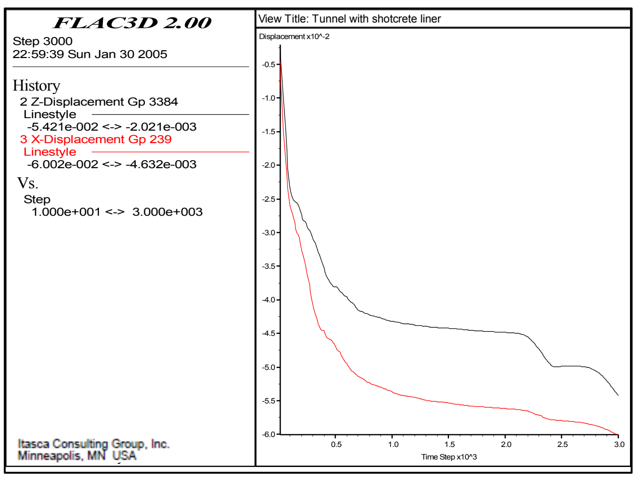


Figure 5. Displacement history plots versus time steps for tunnel with 10 cm shotcrete liner.

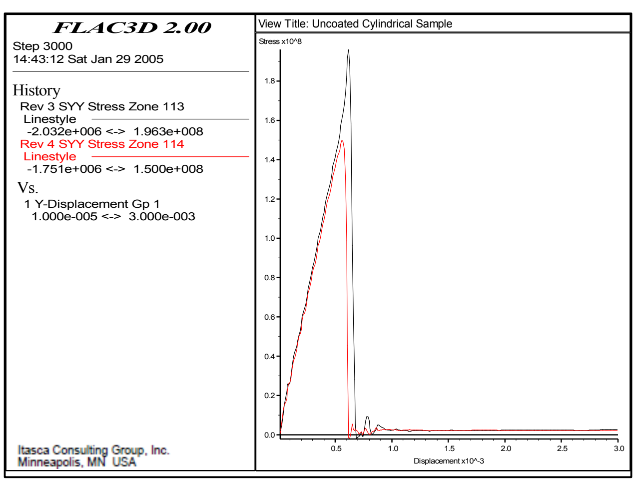


Figure 6. Stress-displacement plots for uncoated Mohr-Coulomb material.

2.2 *TSL Supported Underground Excavation Subjected to Mining-Induced Rockbursts*

2.2.1 *Numerical Model Development*

Model development follows the same procedure as the simulated excavation under high stress conditions as shown in Figure 1. The half circular tunnel model simulated was also 50 m long in a 200 m high and 200 m wide dimension, and was located 2,000 m from the surface in a bi-axial stress field condition. The initial stress state corresponds to those in Figure 1. A system of coordinate axes was also defined with the origin being 3 m above the floor of the tunnel; the z-axis pointed upward and the x- and y-axes pointed transverse and along the axis of the tunnel, respectively. The model also contains approximately 7,400 zones. The tunnel was constructed in a rock that was modeled as an elastic and isotropic material. The liner support was modeled with shell structural elements that are assigned properties representing the TSL liner material. TSL material thickness used was between 3.5 to 5 mm. The material properties of the rock, TSL and shotcrete materials are listed in Table 2. The geometry of the FLAC^{3D} model is shown in Figure 7. The unsupported condition of the tunnel was not simulated since it is expected to fail when subjected to mining-induced rockbursts.

Table 2. Rock material, shotcrete material and TSL input parameters.

Properties	**Materials**		
	Tunnel Material	**Shotcrete Material**	**TSL**
Modulus of Deformation or Young's Modulus, MPa	-	10,500.00	111.69
Tensile Strength (σ_t), MPa	-	-	8.92
Cohesion (c), MPa	-	-	8.00
Internal Friction Angle (ϕ), Deg.	-	-	35.00
Density (ρ), kg/m^3	2,670.00	2,500.00	1,050.00
Shear Modulus (G), MPa	23,021.00	4,666.67	39.89
Bulk Modulus (K), MPa	29,457.00	7,000.00	186.15
Poisson's Ratio (ν)	-	0.25	0.40

The propagation of a spherical wave due to an impulsive pressure (rockburst) in a sphere was performed by subjecting the material to an internal dynamic loading. Although compression and shear waves exist in unbounded (i.e., infinite) media, the axisymmetric nature of the problem eliminates the shear wave. Therefore, only the solution for the compression wave was used (Itasca FLAC^{3D} Manual). The analytical solution for elastic and isotropic material was derived by Blake (1952), based on the following governing equation:

$$\frac{\partial^2 \phi}{\partial t^2} = C_p^2 \nabla^2 \phi \tag{1}$$

where C_p = compressional wave velocity; t = time; ϕ = a potential function; and ∇^2 = Laplacian operator.

An internal dynamic input embedded in the infinite, isotropic medium is simulated in three-dimensions. The radius of the half circular tunnel was 2.5 m, and the outer boundary is located at a distance more than ten times that of the tunnel dimension. The normal movement of the grid is prevented on the vertical boundaries, and a quiet (viscous) condition is imposed on the horizontal boundaries to absorb the wave.

Although the minimum damage criterion of 2.0 m/s ground motion velocity is normally utilized to characterize rockburst events (Urbancic, 2001, Espley *et al*, 1996, and Persson *et al*, 1992), an approximate 20.3 m/s velocity was used in the rockburst event simulation. The ground motion velocity used was based on the results of field tests that include 480 ground vibration measurements, resulting in an extrapolated vertical velocity component of ground motion of approximately 20.3 m/s.

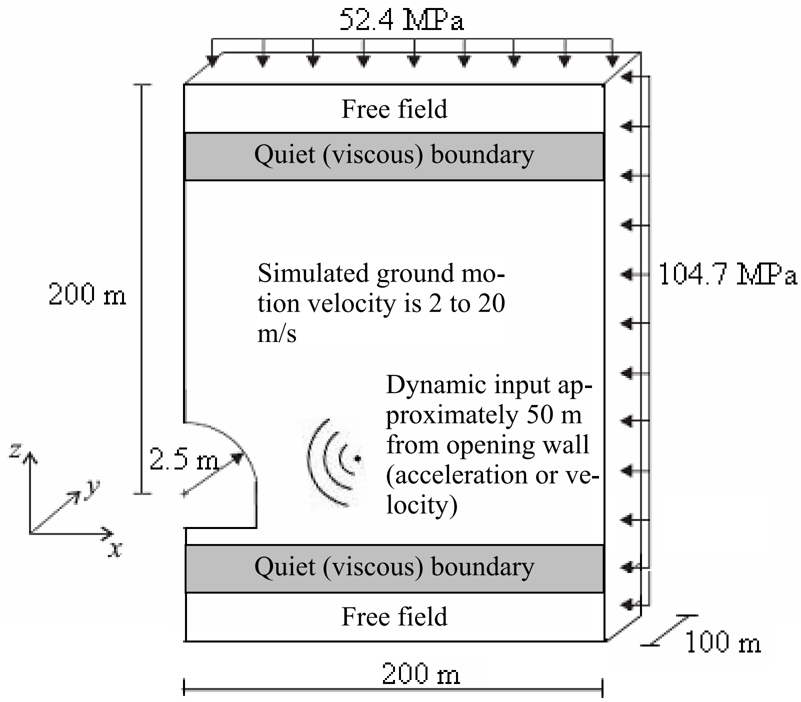


Figure 7. Geometry and loading of the FLAC^{3D} model.

2.2.2 *Underground Excavation Subjected to Mining-Induced Rockbursts - Model Results*

The displacement histories, recorded up to 0.1 second at the tunnel surface, on the tunnel wall 3 m above the floor, tunnel abutment, and tunnel roof, are given in Figure 8. The delay of the response at locations far from the source can be noted.

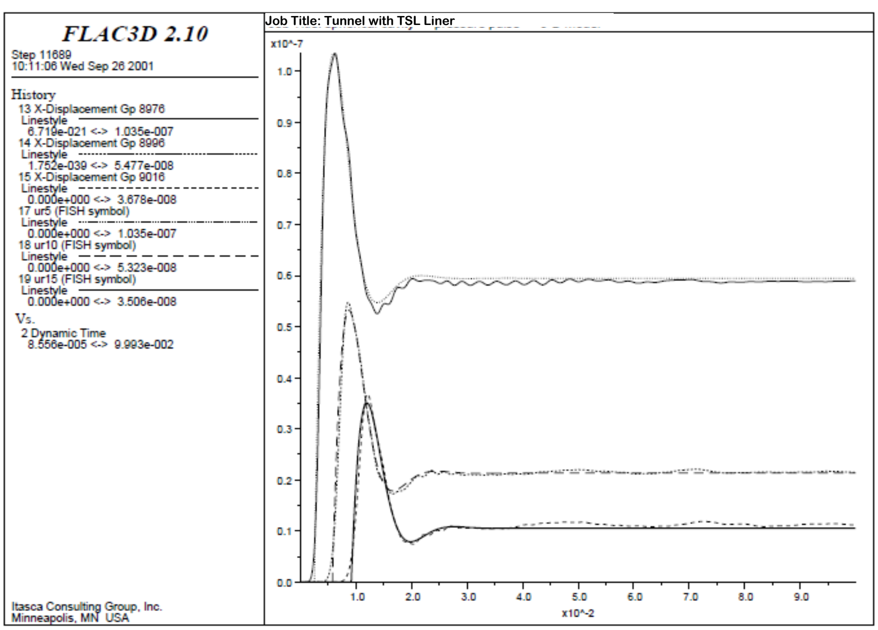
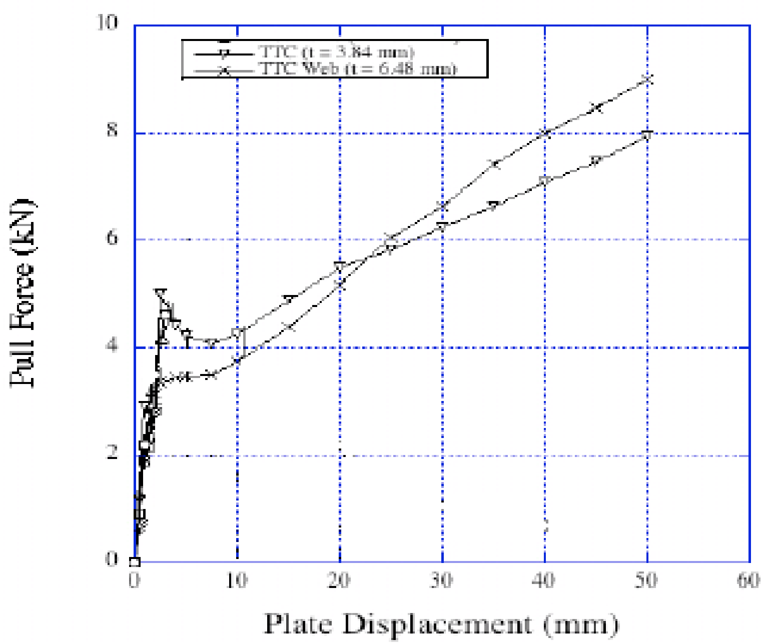


Figure 8. Displacement histories recorded up to 0.1 second at the tunnel surface.

The plot indicated that FLAC^{3D} is able to capture the response at peak and steady states. The steady state indicates that the failed materials were held by the TSL material. It also indicates that, as the failed materials are detached from the intact rock and the TSL adhesion is released progressively radially outward away from the failure centre, the TSL pull resistance may be increasingly developing with increasing pull displacements. The modeling result supported the laboratory pull testing results conducted on polymer based TSL materials shown in Figures 9(a) and (b). The fluctuation at late time may be due to the fact that the radiated wave is not absorbed completely by the viscous boundary.

(a) 



(b)

Figures 9(a). Typical view showing conditions at completion of pull tests (b). Average pull strength data for tested polymer-based TSL products (Archibald and Katsabanis, 2005).

3 CONCLUSIONS

The numerical modeling simulations successfully verified, if not complemented, field tests and standard material characterization test results conducted for a polymer based spray-on lining material, commonly designated as a TSL. The results indicated that the numerical modeling simulations of underground excavations, surface-coated with thin spray-on liners, indicated TSL capabilities for generating significant area support potential against gravity falls of loose rock in backs or sidewalls of excavations. This was substantiated by the stalled deformations at tunnel crowns in numerical modeling simulations of underground excavations coated with TSLs under high stress and mining-induced rockburst conditions.

4 REFERENCES

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