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Research Article

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The response of Rock Tunnel When Subjected to Blast Loading: Finite Element Analysis

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Abstract

Tunnels had been undergone accidental and intentional blast in the past. An analysis of a rock tunnel when subjected to internal blast loading has been presented in this paper. A three-dimensional finite element model of a huge rock mass comprising the tunnel has been developed in Abaqus/CAE. Diameter of the tunnel has been kept constant to a two-lane transportation tunnel. However, liner thickness of the concrete, overburden pressure on the tunnel has been varied to observe the response in different possible conditions. To incorporate the elastoplastic response of rock mass, Mohr-Coulomb constitutive material model has been considered. For modelling of trinitrotoluene (TNT), Jones-Wilkins-Lee material model has been adopted. Concrete Damage Plasticity material model has been adopted for tunnel lining. For the blast loading, Coupled-Eulerian-Lagrangian (CEL) model has been considered. Results highlight the importance of tunnel lining thickness and overburden depth while designing the tunnel in rocks. Under any amount of explosive, deep tunnels have been found to be safer than shallow tunnel.

KEYWORDS

Rock Tunnel, CEL, JWL, TNT

1 | INTRODUCTION

Underground structures have become an essential part of the metro cities. Construction of the underground structures especially tunnels for the efficient movement of humans and goods has resulted in the investment of a massive amount of money in the underground space. Therefore, underground structures especially rock tunnel has been an active area of research since mid-nineteenth century. Manouchehrian and Cai carried out a finite element study for static and dynamic loading for a circular tunnel. They have used finite element software Abaqus/Explicit and Python scripting for the study. They have shown the importance of using a finite element

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analysis for case histories are useful for the rockburst phenomenon due to the presence of discontinuities [1]. Mishra et al., [2] carried out the study for tunnels when subjected to static and dynamic loading using finite element software Abaqus/Explicit. The analysis has been carried out for different geomaterials, and it has been concluded that the settlement of the tunnel crown has a direct relationship with the friction angle. Mishra et al., [3]concluded that the effect of load in deformation of tunnel reduces as the distance of loading position increases. They have calculated different zones of deformations for different rock mass for shallow rock tunnels. Bobet carried out the study under static and seismic loading for the effect of pore water pressure on the stability of tunnel support. It has been concluded that the racking deformation and the flexibility of the tunnel are directly related [4].

Furthermore, the underground tunnels have been subjected to dynamic loads such as seismic loads, impact loads, blast loads and other types of loading. Stability of tunnels under blast loading has attracted several researchers in recent decades [5]–[13]. Moreover, Matsagar has carried out the comparative study for composite sandwich panel and non-sandwich panel for blast loading. They have utilised finite element analysis for comparison of different materials and concluded that cenosphere aluminium alloy syntactic foams found to be the superior material for the reduction in the damage caused by the blast load [14][15]. Jaini and Feng have studied the response of reinforced cement concrete (RCC) slab using computational modelling. They have carried out a finite discrete element analysis for the damage analysis of RCC slab. It has been concluded from the study that the use of both positive and negative phase of blast response may give more realistic results [16].

Further, blast study has also been carried out for the response of concrete pavement slab by Luccioni and Luege [17]. They have considered three different explosive charge weights and the stand-off distance of explosive remains constant as 5m. Based on experimental, numerical and limit analysis, they have proposed an equation that relates the diameter of crater and the explosive charge. The behaviour of spherical explosive charge has been discussed by Brode [18]. When a blast event occurs, there has been the presence of vibrations in addition to heating effect of blast. Hence, Berta has carried out the study on the vibrations induced in tunnel by the blast loading [19]. Jingbo et al., [20] had studied the blast wave propagation in the tunnel by using finite element software LS-DYNA. Chen and Zhao have utilized UDEC modeling for the study of blast wave propagation in the jointed rockmass [21]. Choi et al., have used AUTODYN software for the 3D nonlinear dynamic analysis of tunnel subjected to internal blast loading. They have used Coupled-Eulerian-Lagrangian modeling to simulating the blast response[22]. Buonsanti and Leonardi had carried out the study on rail tunnel subjected to internal blast loading using ANSYS code [23]

The present paper deals with the response of a rock tunnel when subjected to internal blast loading using finite element software Abaqus/Explicit [24], [25]. The Mohr-Coulomb constitutive material model has been considered for the Quartzite rock. In the present study, the effect of the weight of explosive charge has been carried out. Also, the response of rock tunnel under varying thickness of tunnel lining has been incorporated. The four different overburden depths are also considered.

2 | FINITE ELEMENT MODELING

The finite element software Abaqus/Explicit has been used for the present analysis of rock tunnel subjected to internal blast loading. The model dimensions of the tunnel are 30m x 30m of cross-sectional dimensions and 35m of extruded length [6,26]. The dimensions of the finite

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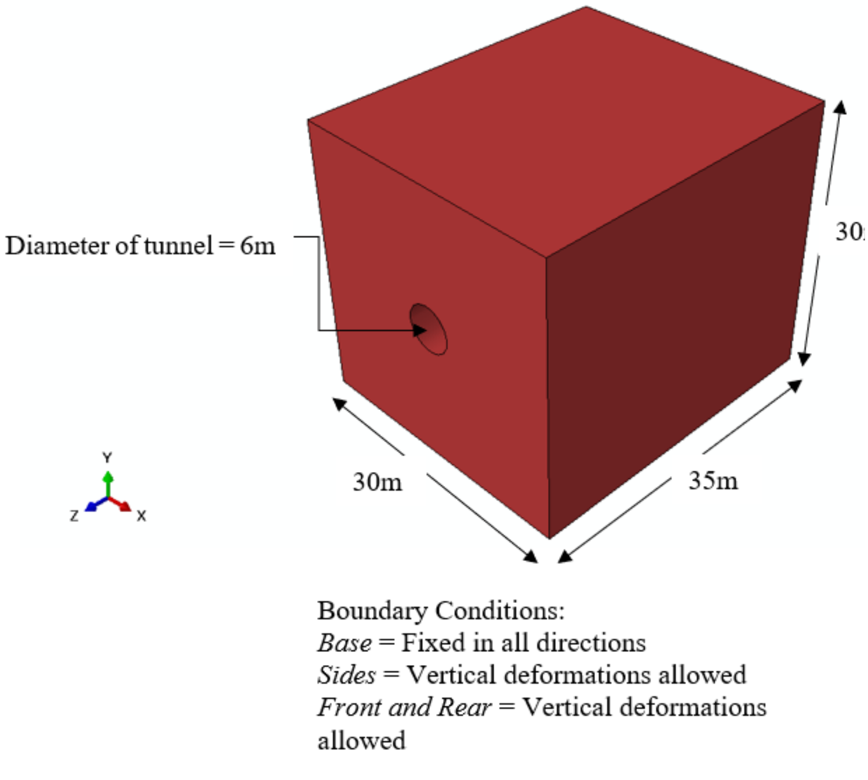
element model are based on boundary convergence study. Initially, the thickness of tunnel lining has been kept as 0.22m and later, it has been varied as 0.35m, 0.45m and 0.55m. Four different depth of overburden has been considered in the present analysis are 5m, 7.5m, 10m and 12.5m. The tunnel has a diameter of 6m. The element size of the model has been kept as 0.2m based on the mesh convergence study. The tunnel lining and rock model has been meshed with an element type of C3D8R (Eight-node brick element with reduced integration). Moreover, the Eulerian Model of Trinitrotoluene (TNT) and air has been modelled as EC3D8R (8-node linear brick, multimaterial, reduced integration with hourglass control). The boundary conditions at the base of the rock model have been restrained in all directions as the rock has infinite depth. The front and rear of the model has been restrained in all directions and the deformations are allowed in the vertical direction. The right and left sides of the model were allowed the deformation in vertical directions and restrained in other. The finite element model has been shown in Figure 1.



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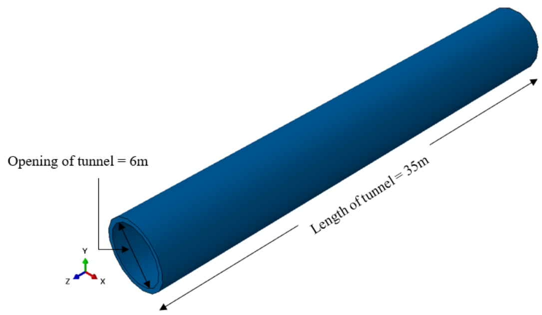

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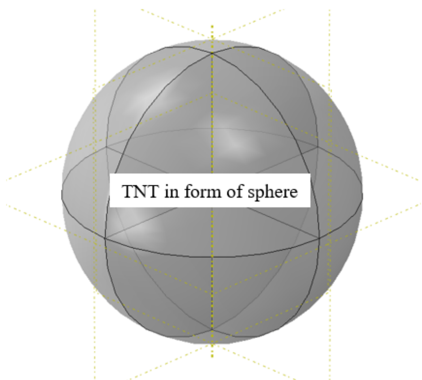

(c)

Figure 1 The Geometry and Mesh of the Rock Tunnel Model (a) model of rock, (b) lining and (c) TNT explosive

The Mohr-Coulomb constitutive material model has been adopted for the elastoplastic behaviour of Quartzite Rock. The properties of Mohr-Coulomb material model have been shown in Table 1.

Table 1 Input Parameters for Mohr-Coulomb Model [27]

Parameter	Quartzite Rock
Density (kg/m³)	2550
Elastic Modulus (GPa)	28
Poisson's Ratio	0.25
The angle of Internal Friction	42°
Cohesion (MPa)	2.3
RQD range	75-80
RMR	47

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Concrete Damage Plasticity (CDP) model has been used for the modelling of tunnel lining. The CDP model properties are listed in Table 2.

Table 2 Input Parameters of Concrete Tunnel Lining [28]

PARAMETERS	VALUE
Density (kg/m^3)	2400
Modulus of Elasticity (N/m^2)	2.7386 x 10^{10}
Poisson's Ratio	0.17
Dilation Angle (degrees)	30
Eccentricity	1
Initial equi-biaxial compressive yield stress to initial uniaxial compressive yield stress	1.16
Bulk Modulus	0.666
Fracture Energy (N/m)	720
Uniaxial Failure Stress (Tension) (MPa)	10.8
Cracking Displacement (m)	0.0001332
Tensile Strength (MPa)	3.86
Compressive Strength (MPa)	30

For the simulation of blast loading, the TNT explosive has been modeled in the finite element software by the method of Coupled-Eulerian-Lagrangian (CEL) modelling. For the CEL modelling, the Jones-Wilkins-Lee (JWL) constitutive model has been used for the TNT explosive. The properties of TNT explosive are shown in Table 3.

Table 3 Properties of JWL material model of TNT explosive [29]

Density (kg/m^3)	***Detonation Wave Speed (m/s)***	***A (MPa)***	***B (MPa)***	***ω***	***R_1***	***R_2***	***Detonation Energy Density (kJ/kg)***
1630	6930	373800	3747	0.35	4.15	0.9	3680

For the air in the tunnel and the TNT explosive, the EVF option in the Abaqus has been used. In EVF option, the TNT has value as 1, which represents that the spherical model volume has been filled with TNT. Further, for the air 0.8 has been used, which shows that air has 20% of voids.

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3 | NUMERICAL VALIDATION WITH EXPERIMENTAL RESULTS

Experimental study related to blast loadings on full structures had been performed rarely, due to involvement of high expenditure and permissions from local government. However, experiments were carried out on structural component at lab sale [30-34]. Hence, in present study, for the validation of the numerical method of blast loading, the experimental study carried out by Zhao and Chen has been referred [30]. An RCC slab of 1m x 1m has been designed with 0.04m depth, similar to Zhao and Chen [30]. Two-way reinforcement of 6mm diameter @ 75mm c/c has been provided with clear cover of 25mm. Moreover, the blast validation has shown results in vicinity of the experimental and numerical study of Zhao and Chen. Thus, the present study has been validated. Table 4 shows the validation results and compares with the Zhao and Chen.

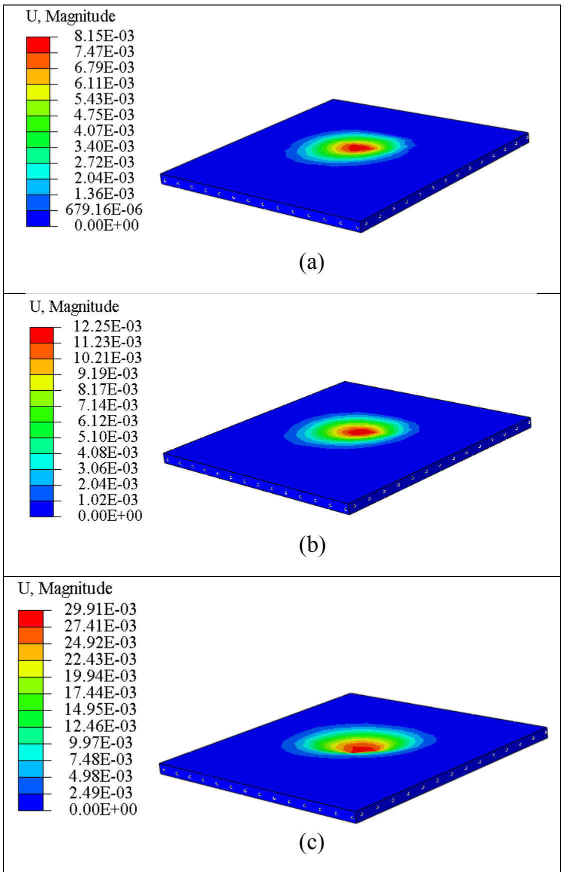

Figure 2 Deforamtion contours for validation of numerical model for (a) 0.2kg, (b) 0.31kg and 0.46kg explosive (compared as shown by Zhao and Chen [30])

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Table 4 Validation of the TNT explosive for deformation at the Centre of the RCC Slab

Explosive Charge (kg)	***Deformation at the centre of panel (mm)***		
	***Zhao and Chen*[30]**		***Present***
	Experimental Study	***Numerical Study***	***Numerical Study***
0.2	10	8.8	8.15
0.31	15	12.7	12.25
0.46	35	31.1	29.91

4 | RESULTS AND DISCUSSION

A three-dimensional numerical study of the response of underground rock tunnel subjected to internal blast loading has been analyzed. The tunnel has 6m of diameter and 30m x 30m x 35m of rock model surrounding the tunnel. Four different thickness of tunnel lining considered in the present study is 0.22m, 0.35m, 0.45m and 0.55m. The mass of TNT explosive for the present paper is 10kg, 20kg, 30kg, 40kg, 50kg and 60kg. The analysis has been carried out for four different cases of depth of overburden, i.e., 5m, 7.5m, 10m and 12.5m. The Mohr-Coulomb material model has been adopted for rock and Concrete Damage Plasticity Model has been used for tunnel lining. The TNT explosive has been modeled using JWL material model. Further, the present study incorporates CEL modelling for simulating the blast loading event. Following results have been found out and were discussed.

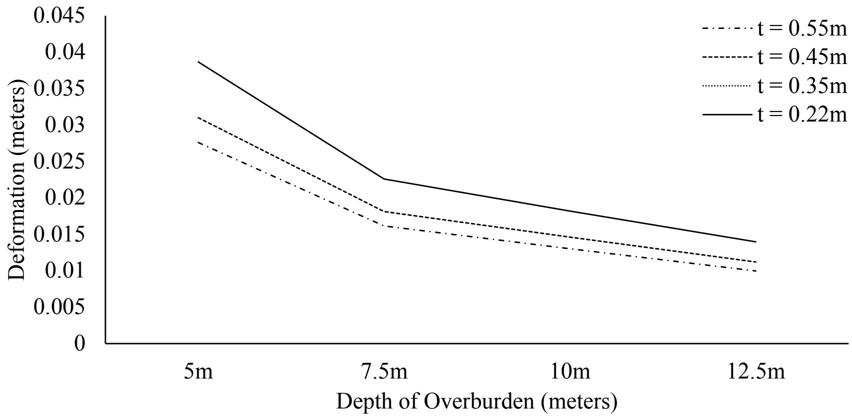

Figure 2 Comparative response of tunnel lining for 60kg mass of TNT explosive

The comparative response of the thickness of tunnel lining when subjected to a constant (60kg of TNT) blast load has been plotted in Figure 2. The deformation decreases as the depth of overburden increases from 5m to 7.5m @ 70%-73% and for increase in depth of overburden from 7.5m to 10m and from 10m of overburden depth to 12.5m, the decrease in deformation has been observed as 23%-28%. Hence, it may be noted that deep tunnels are more blast resistant in comparison to the shallow tunnels. Moreover, for the increase in the tunnel lining thickness initially from 0.22m to 0.35m a significant decrease in deformation has been observed, i.e., 20% decrease in deformation. However, relatively smaller increase in resistance to deformation has been noted for the increase in the tunnel lining thickness from 0.35m to

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0.55m. Hence, it may be concluded that an optimum tunnel lining thickness should be taken into account for less damage due to blast loading.

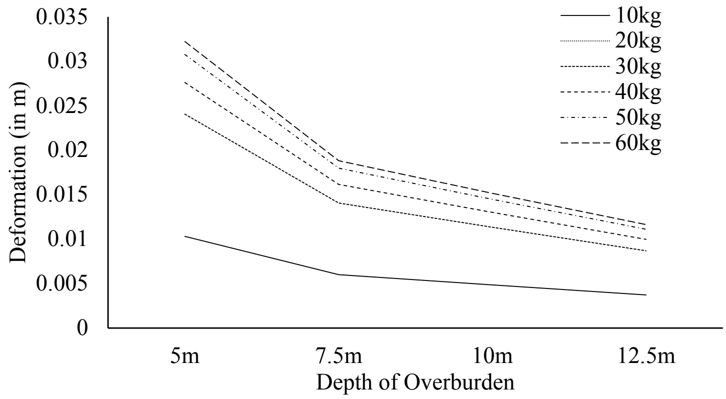
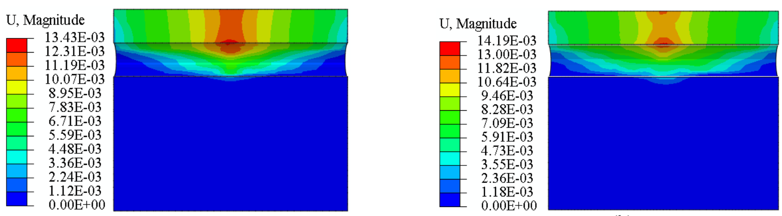


Figure 3 Comparison of deformation due to the different amount of TNT explosive at various depth of overburden having a tunnel lining thickness of 0.22m

Further, the amount of TNT has been varied to observe the response. A comparative result of the deformation caused by the different amount of TNT explosive has been shown in Figure 3. As reported earlier, the decrease in deformation has been observed with an increase in the depth of overburden. Furthermore, sharp decrease in deformation has been observed for the case of 5m to 7.5m increase in depth of overburden. While up to 30kg of TNT, the deformations reported were significant and sharp increase has been observed. Furthermore, it has been observed that from 40kg to 60kg of TNT explosive deformations noted were in proximity.

The deformation contour of the rock tunnel under varying mass of TNT, has been plotted in Figure 4. It has been observed that for increase in the amount of TNT explosive the zone of deformation along the tunnel alignment has increased linearly. Moreover, for small amount of TNT explosive, the deformation was concentrated in small zone in the internal surface of tunnel. While as the amount of TNT in the tunnel increases the more amount of deformations have been transferred to the surface which has resulted in the heaving of surface instead of settlement.



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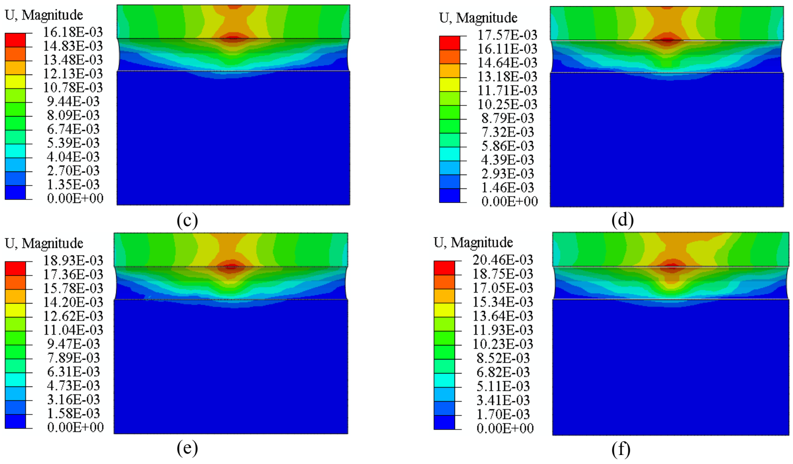

Figure 4 Deformation contours for 0.55m lining thickness of tunnel and 5m depth of overburden for (a) 10kg, (b) 20kg, (c) 30kg, (d) 40kg, (e) 50kg and (f) 60kg of TNT explosive

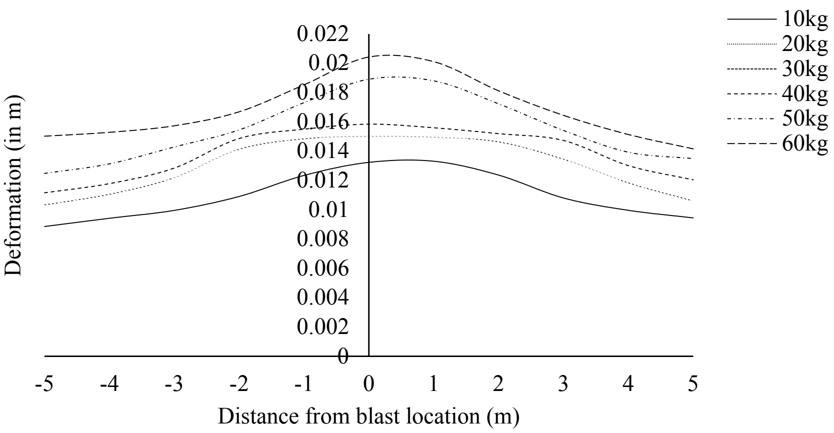

Figure 5 Deformation profile for different TNT explosive mass having 0.55m tunnel lining thickness

Deformation profiles along the tunnel length have been plotted for the different amount of TNT explosive in Figure 5. From this plot, is has been noted that throughout the tunnel length the deformation increases with increase in TNT. However, the heavier mass of TNT cause local damage much severe.

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5 | CONCLUSION

The present study for internal blast loading of Quartzite rock tunnel using CEL model for simulating the TNT blast in Abaqus/Explicit has been carried out. The significant conclusions observed from this study are as follows.

Deep tunnel has been found to be more blast resistant than shallow tunnel. The effect of increase in explosive mass has been quite obvious. However, it has been noticed that this effect is more significant in shallow tunnel rather than deep tunnel. The thickness of tunnel liner plays important role in blast resisting but up to a limit only. Further, increase in thickness will make the section uneconomic and heavier, however, enhance in the blast resistance will not significant. Hence, under any proposed depth of tunnel a study should be carried out for optimum thickness of blast resistant tunnel.

CONFLICT OF INTEREST

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The author declares no potential conflict of interest.

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