The response of rock tunnel when subjected to blast loading: Finite element analysis

Mohammad Zaid | Md. Rehan Sadique

Department of Civil Engineering, Aligarh Muslim University, Aligarh, 202002, India

Correspondence
Mohammad Zaid, Department of Civil Engineering, Zakir Hussain College of Engineering and Technology, Aligarh Muslim University, Aligarh, Uttar Pradesh 202002, India.
Email: mohammadzaid1@zhcet.ac.in

Abstract
In the past few decade tunnels were targeted to explosives and that resulted in sizeable structural damage. The increase in the strategic importance of tunnel construction has increased the demand for the blast-resistant design approach. The present paper considered an internal blast loading on a rock tunnel constructed in Quartzite rock. A three-dimensional finite element model of the tunnel has been developed in Abaqus. The diameter of the tunnel has been kept constant to a two-lane transportation tunnel. However, the thickness of the concrete liner, depth of overburden, and mass of explosive charge has been varied to understand the response in different possible conditions. The Jones-Wilkins-Lee, Concrete Damage Plasticity, and Mohr-Coulomb material models have been used for the modeling of trinitrotoluene, concrete, and rock respectively. Blast has been formulated through Coupled-Eulerian-Lagrangian technique. The tunnel at 12.5 of the depth of overburden has been found 2.7-times more blast resistant than 5 m. Moreover, the extent of damage in shallow depth tunnels found to be more than the tunnels at higher depth of overburden.

Keywords
Abaqus, blast, coupled-Eulerian-Lagrangian, rock, tunnel

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, have been an active area of research since the mid-19th century. Tunnels are considered as high-risk zones due to the presence of numerous patronage in confined space at a single location. Some of the manmade hazards in the tunnels that have caused severe loss of life and property are Bayrampasa metro tunnel attack, London underground metro attack, Moscow metro tunnel attack, Minsk metro bombing, and Saint Petersburg metro attack. Therefore, the blast resistant design of tunnels and other underground utility structures is required.

Scientists and researchers have carried out blast-related studies using different approaches. Wu et al. carried out the study for the blast wave-induced shock wave propagation in jointed rockmass. They concluded that the characteristics...
of the joints play an essential role in the shock wave propagation. Moreover, the distance of propagation, weight of charge and angle made by incidence angle with the strike of joint are the governing factors in shock wave propagation. However, the effect of overburden and tunnel lining thickness was not considered.

Jayasinghe et al.\textsuperscript{14} and Shang\textsuperscript{15} had also studied the numerical modeling of blast loading on rockmass and concluded that the joint persistence significantly controls the blasting-induced damage in the rockmass. However, all the three studies\textsuperscript{13-15} had considered rock mass in its natural state. Nevertheless, in case of already constructed tunnel these joints sets had been treated to block the water inflow in the tunnel.\textsuperscript{16} Sealing of these joints with grouting, shotcreting, and so on, also improves the rock mass strength, which is desirable for long stability of projects.\textsuperscript{17,18} Hence, while investigating the blast response of an already constructed tunnel, the immediate rock mass may be treated as continuous.

Choi et al.\textsuperscript{19} carried out finite element study for the blast analysis of underground tunnel. They had studied the effect of different surrounding ground properties and concluded that the blast response of the tunnel depends on the properties of the surrounding ground. However, the vulnerability of the tunnel having different overburden depth and tunnel lining thickness had not been considered. Tiwari et al.\textsuperscript{20} studied the effect of rock weathering for the rock tunnel subjected to blast loading. The finite element method was used for blast analysis, and they concluded that shock wave propagation is higher in less weathered rock. The higher attenuation of shock waves had been observed in highly weathered rock. However, there had been rarely available discussion regarding the effect of tunnel lining thickness and overburden depth. Furthermore, several studies were carried out to understand the behavior of rock tunnel during blast loading due to explosives.\textsuperscript{21-25}

However, the effect of depth of overburden and thickness of tunnel lining had been rarely incorporated in the available literature. Moreover, trinitrotoluene (TNT) had not been adopted as material which is only possible through assigning the properties of TNT and modeling it as a part of a simulation. Further, the modeling of TNT as a material possesses several issues, and the problem of element distortion is the most common. Therefore, Coupled-Eulerian-Lagrangian (CEL) method of modeling needs to be considered to overcome the problem of element distortion which had rarely been considered in the past studies.

In the present paper, a numerical study of the rock tunnel constructed in Quartzite rock has been considered. A detailed finite element model has been presented and validated with available experimental and numerical results. The advanced method of coupled modeling, that is, CEL method, has been adopted for the modeling of the TNT and air inside the tunnel. The effect of thickness of tunnel lining and overburden depth has been incorporated to understand the stability of a rock tunnel under blast loading. Furthermore, the amount of TNT explosive charge has also been varied to observe the extent of the damage.

## 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.\textsuperscript{26,27} The model dimensions of the tunnel are 30 m \( \times \) 30 m of cross-sectional dimensions and 35 m of extruded length. The dimensions of the finite element model are based on boundary convergence study. Initially, the thickness of tunnel lining has been kept as 0.22 m\textsuperscript{7,28-30} and later, it has been varied as 0.35 m,\textsuperscript{31} 0.45 m, and 0.55 m. Four different depths of overburden have been considered in the present analysis are 5 m, 7.5 m, 10 m, and 12.5 m and the tunnel has a diameter of 6 m.

The element size of the model has been kept as 0.2 m based on the mesh convergence study. The tunnel lining and rock model has meshed with an element type of C3D8R (Eight-node brick element with reduced integration and hourglass control). Moreover, the Eulerian Model of TNT and air has been modeled as EC3D8R (eight-node linear brick element with reduced integration and hourglass control). A mesh convergence study has been carried out to find an optimum size of element for meshing, with mesh size 2 m, 1.8 m, 1.6 m, 1.4 m, 1.2 m, 1.0 m, 0.8 m, 0.6 m, 0.4 m, 0.2 m, 0.1 m, and 0.08 m. The aspect ratio of the elements has been kept 1. The displacement at the tunnel crown, which was just above the location of TNT explosive charge, has been compared for different mesh sizes. The mesh size of 0.2 m, 0.1 m, and 0.08 m have a negligible difference. With the optimization of result precision and computational efficiency of the workstation (Dell Precision Tower 7810) mesh size of 0.2 m has been adopted for the rock and the tunnel lining in the present analysis.

The boundary conditions at the base of the rock model have been restrained in all directions as the rock has infinite depth. The all four sides (vertical) of the model have roller support. The boundary conditions considered for the model are based on boundary convergence study. The base of the model has been used as fixed as the base behaves
FIGURE 1 The geometry and mesh of the rock tunnel model, location of TNT explosive, tunnel lining, and TNT explosive as a semi-infinite boundary and it extends to higher depth. However, the sides of the model show significant movement in a vertical direction; therefore, roller support has been applied. Moreover, interaction property has been defined between the different materials for proper interaction. In Abaqus interaction property module, hard contact in the average direction and frictionless in the tangential direction has been assigned. This interaction property gives rise to deformations in the Lagrangian material when Eulerian material flows through it. The finite element model has been shown in Figure 1.

The Mohr-Coulomb constitutive material model has been adopted for the elastoplastic behavior of Quartzite rock. The properties of the Mohr-Coulomb material model have been shown in Table 1. Mohr-Coulomb material model is defined as-

\[ \tau = c + \sigma \tan \phi \]

where
\[ \tau = \text{shear stress of rock}, \]
\[ c = \text{cohesion of rock}, \]
TABLE 1 Input parameters for the Mohr-Coulomb model\textsuperscript{32}

| Parameter                          | Quartzite rock |
|------------------------------------|----------------|
| Density (kg/m\textsuperscript{3})  | 2550           |
| Elastic modulus (GPa)              | 28             |
| Poisson’s ratio                    | 0.25           |
| The angle of internal friction (degree) | 42°      |
| Cohesion (MPa)                     | 2.3            |
| RQD range                          | 75-80          |
| RMR                                | 47             |

\(s\) = normal stress, and
\(\phi\) = friction angle.

For general stress conditions, the model can be represented in terms of three stress invariants defined

\[
F = R_{mc}q - p \tan \phi - c = 0
\]

where,

\[
R_{mc}(\Theta, \phi) = \frac{1}{\sqrt{3} \cos \phi} \sin \left( \Theta + \frac{\pi}{3} \right) + \frac{1}{3} \cos \left( \Theta + \frac{\pi}{3} \right) \tan \phi
\]

\[
\cos(3\Theta) = \left( \frac{r}{q} \right)^3
\]

\[
p = -\frac{1}{3} \text{trace}(\sigma)
\]

\[
q = \sqrt{\frac{3}{2} (S : S)}
\]

\[
r = (9(S \ast S : S))^\frac{1}{3}
\]

\[
S = \sigma + pI
\]

where
\(\Theta\) = deviatoric polar angle,
\(p\) = equivalent pressure stress,
\(q\) = Mises equivalent stress,
\(r\) = third invariant of deviatoric stress, and
\(S\) = deviatoric stress.

The Concrete Damage Plasticity (CDP) model has been used for the modeling of tunnel lining.

The stress-strain relation of the CDP model is represented

\[
\sigma_t = (1 - d_t)D_0^{el} : (\varepsilon - \varepsilon_t^{el})
\]

\[
\sigma_c = (1 - d_c)D_0^{el} : (\varepsilon - \varepsilon_c^{el})
\]

where
\(t\) and \(c\) refer to tension and compression, respectively,
\(\sigma_t\) & \(\sigma_c\) are stress vectors,
\(\varepsilon_t^{pl}\) and \(\varepsilon_c^{pl}\) are plastic strains,
\(d_t\) & \(d_c\) are the damage variables,
\(D_0^{el}\) is the undamaged initial elastic stiffness of the material.
The CDP model properties are listed in Table 2. It has been opted from the author’s previously published work.\textsuperscript{33} The justification of the values of different parameters has discussed in detail there.

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

The JWL equation of state (EOS)\textsuperscript{34} model is defined as

\[
p = A \left(1 - \frac{\omega}{R_1 \rho}\right) e^{-R_1 \bar{\rho}} + B \left(1 - \frac{\omega}{R_2 \rho}\right) e^{-R_2 \bar{\rho}} + \omega \rho e_{\text{int}}
\]

where
- \(p\) = pressure of the TNT explosive,
- \(A\), \(B\), \(R_1\), \(R_2\), and \(\omega\) are material constants for TNT explosive
- \(A\) and \(B\) = magnitudes of pressure,
- \(\bar{\rho}\) = ratio of the density of the explosive in the solid-state (\(\rho_{\text{sol}}\)) to the current density (\(\rho\)),
- \(e_{\text{int}}\) = specific internal energy at atmospheric pressure.

In the JWL EOS, the first two exponential terms on the right-hand side represent high pressure generated during an explosion and the last term on the right-hand side is a low-pressure term, which deals with high volume due to explosion.

The TNT and air inside the tunnel were modeled using CEL method of modeling. The CEL modeling has been incorporated in the present analysis by using Eulerian-Volume-Fraction (EVF) option available in Abaqus. The primary function of the EVF option is to fill the Eulerian part with material which flows through the Lagrangian part of the model and interact with the boundary of other parts. In the case of EVF, the value between 0 and 1 is assigned, which define the number of voids in the material or other words how much material is filled in the Eulerian part. Therefore, in the present study, EVF = 1, has been assigned for the TNT material. EVF = 1 means that the Eulerian part is filled with material, and there is no void space available. Further, the air has been assigned EVF = 0.8, where 20% of void space has been assumed.\textsuperscript{3}

For the proper interaction between the Eulerian and Lagrangian parts of the model, an interaction property, global hard contact has been assigned. The blast analyses have been carried out for the 30 milliseconds.

### Table 2: Input parameters of concrete tunnel lining\textsuperscript{33}

| Parameters                                           | Value |
|------------------------------------------------------|-------|
| Density (kg/m\(^3\))                                | 2400  |
| Modulus of elasticity (GPa)                          | 27.386|
| Poisson’s ratio                                      | 0.17  |
| Dilation angle (degrees)                             | 30    |
| Eccentricity (constant)                              | 1     |
| Initial equi-biaxial compressive yield stress to initial uniaxial compressive yield stress (constant) | 1.16  |
| Second stress invariant ratio, K                     | 0.666 |
| Fracture energy released (N/m)                       | 720   |
| Uniaxial failure stress (Tension) (MPa)              | 10.8  |
| Cracking displacement (m)                            | 0.0001332 |
| Tensile strength (MPa)                               | 3.86  |
| Compressive strength (MPa)                           | 30    |

### Table 3: Properties of JWL material model of TNT explosive\textsuperscript{34}

| Density (kg/m\(^3\)) | Detonation wave speed (m/s) | An (MPa) | B (MPa) | \(\omega\) | R\(_1\) | R\(_2\) | Detonation energy density (kJ/kg) |
|-----------------------|-----------------------------|----------|---------|------------|--------|--------|----------------------------------|
| 1630                  | 6930                        | 373 800  | 3747    | 0.35       | 4.15   | 0.9    | 3680                             |
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 a structural component at lab scale.\textsuperscript{35,36} Hence, in the present study, for the validation of the numerical method of blast loading, the experimental study carried out by Reference 35 has been referred.

A Reinforced-Cement-Concrete slab of 1 m × 1 m has been modeled with 0.04 m depth, similar to Reference 35. Two-way reinforcement in the form of steel bars having 6 mm dia @ 75 mm c/c has been provided with a clear cover of 20 mm. The concrete has been modeled using CDP material model, and elastic-plastic model based on stress-strain history has been used for reinforcement modeling. The default parameters of concrete compressive strength have been used in the validation.\textsuperscript{37-40} The concrete has 28.3 GPa of Young’s Modulus, 4.2 MPa tensile strength, and 39.5 MPa of compressive strength. The steel reinforcement bars have Young’s Modulus of 200 GPa and yield strength of 600 MPa.\textsuperscript{41} The sides of the slab have fixed boundary conditions and base and the top surface (see fig. 1 of Reference 35). There were

| Explosive charge (kg) | Displacement at the center of the panel (mm) | Error (%) |
|-----------------------|--------------------------------------------|-----------|
|                       | Zhao and Chen\textsuperscript{35} | Present Paper | w.r.t. Experimental study | w.r.t. Numerical study |
| 0.20                  | 10 | 0.88 | 0.815 | 18.5 | 7.4 |
| 0.31                  | 15 | 12.7 | 12.25 | 18.3 | 3.5 |
| 0.46                  | 35 | 31.1 | 29.91 | 14.5 | 3.8 |

**TABLE 4** Validation of the TNT explosive for displacement at the Center of the RCC Slab

**FIGURE 2** Displacement contours for validation of numerical model for (A) 0.2 kg, (B) 0.31 kg and 0.46 kg explosive (compared as shown by Zhao and Chen\textsuperscript{35})
three explosive charges assumed in the experimental test and numerical software for validation. The three different TNT explosive charges assumed were 0.20 kg, 0.31 kg, and 0.46 kg having scaled distance as 0.684 m/kg$^{1/3}$, 0.591 m/kg$^{1/3}$, and 0.518 m/kg$^{1/3}$ respectively. The TNT and the air have been modeled using CEL method of modeling. The properties of the TNT explosive material are the same as mentioned in Table 3. The mesh size has been finalized based on mesh sensitivity analysis.

Moreover, the blast validation has shown results in the vicinity of the experimental and numerical study of Reference 35. Thus, the present study has been validated. Table 4 shows the validation results and compare with Reference 35. Figure 2 shows the displacement contours of the square reinforced cement concrete slab for comparing with Reference 35. The maximum displacement has been represented by deep red contour, while the edges have no displacement due to the applied boundary condition. Therefore, it has been concluded that CEL method of modeling is an accurate method for the simulations having problem of element distortion and large displacements.

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 Mohr-Coulomb material model has been adopted for rock, and CDP Model has been used for tunnel lining. The TNT explosive has been modeled using the JWL material model. Further, the present study incorporates CEL modeling for simulating the blast loading event. Following results have been found out and were discussed.

The comparative response of the thickness of tunnel lining, when subjected to a constant (60 kg of TNT) blast load, has been plotted in Figure 3. The deformation decreases as the depth of overburden increases from 5 to 7.5 m @ 70%-73%, and for an increase in depth of overburden from 7.5 to 10 m and from 10 m of overburden depth to 12.5 m, the decrease in deformation has been observed as 23%-28%. Hence, it may be noted that tunnels having a higher depth of overburden are more blast-resistant in comparison to the shallow tunnels. Moreover, for the increase in the tunnel lining thickness initially from 0.22 to 0.35 m, a significant decrease in deformation has been observed, that is, a 20% decrease in deformation. However, a relatively smaller increase in resistance to deformation has been noted for the increase in the tunnel lining thickness from 0.35 to 0.55 m. Hence, it has been concluded that an optimum tunnel lining thickness should be taken into account for less damage due to blast loading.

The comparative results of the deformations caused by the different amount of TNT explosives have been shown in Figure 4. It has been observed that the magnitude of deformations in tunnels has a higher range for 5 m of the

![FIGURE 3](image1.png)  
**FIGURE 3** Comparative response of tunnel lining for 60 kg mass of TNT explosive

![FIGURE 4](image2.png)  
**FIGURE 4** Comparison of deformation due to the different amount of TNT explosive at various depth of overburden having a tunnel lining thickness of 0.22 m
depth of overburden. However, a sharp decrease in deformation has been observed for the case of 5-7.5 m increase in depth of overburden. The deformation further decreases with an increase in the depth of overburden, which concludes that stability in the tunnel results from an increase in the depth of overburden. Moreover, the maximum percentage change in the deformation magnitude occurred when the depth of overburden increases from 5 to 7.5 m. Furthermore, lesser change in the magnitude of deformation has been observed in comparison to the former. In terms of safety, tunnel having 12.5 m depth of overburden are 2.7-times safer than tunnel that has 5 m depth of overburden. Therefore, the choice of depth of overburden also contributes to the stability and blast-resistant designing of underground rock tunnels.

Figure 5 has been plotted to show the variation of deformations in the tunnel when an internal blast load with a varying charge of TNT explosive has occurred. It has been observed that the magnitude of deformation at the tunnel crown has 10% more value than the ground surface. Also, it has been observed that the zone of deformation along the tunnel alignment has increased linearly for the increase in the amount of TNT explosive. The deformation concentrates in a minor zone at the internal surface of the tunnel irrespective of a small amount of TNT explosive. As the blast load due to an increasing amount of TNT explosive increases in the tunnel, the further extent of deformations transferred to the ground surface, which results in the heaving of the surface instead of settlement. The heaving or bulging of the ground surface has been the common record phenomenon. The concentration of damage at the crown of tunnel results in the spalling of tunnel liner, and sometimes it results in the production of minor cracks. If these cracks further propagate, then it requires to treat the cracks thoroughly. However, the generation of smoke also has a significant contribution to casualties, but the present study is affiliated with civil engineering perspective on the event.
Deformation profiles along the tunnel length have been plotted for the different amount of TNT explosive in Figure 6. From this plot, it has been noted that throughout the tunnel length, the deformation increases with increase in TNT. Moreover, it has been observed that the depth of crater formed due to blast loading and its diameter increases with the increase in the amount of TNT explosive charge. However, the response of rock remains symmetrical on both sides of the location of the blasting event. It has been observed that 54% increase in the magnitude of deformation has been observed due to an increase in an explosive mass by six times. Furthermore, the value of deformation ranges between 10 and 20 mm for the varying mass of TNT explosive charge from 10 to 60 kg. The shock waves due to blast load propagate from the location of blast event to boundary of the rock. This propagation has significant effect near the blast location, and it diminishes toward the boundary. Due to the CEL modeling technique, this propagation of shock waves does not rebound back to the center of the tunnel.

5 | CONCLUSION

A three-dimensional non-linear finite element analysis has been carried out for internal blast loading of Quartzite rock tunnel, through the less conversant CEL modeling technique using the Abaqus/Explicit. The tunnel depth, tunnel lining thickness, as well as a mass of TNT, has been varied to observe the response in different possible conditions.

In the present study, tunnels constructed at higher depth of overburden are more blast resistant than tunnel at shallow depth. The effect of an increase in explosive mass has been evident. However, it has been observed that this effect is more significant in a shallow tunnel rather than tunnel having a higher depth of overburden. The thickness of the tunnel liner plays an essential role in blast resistance of rock tunnel, but up to a limit only. Further, the increase in lining thickness makes the section uneconomical and heftier, without any significant contribution in blast resistivity. Hence, for any proposed tunnel, a study should be carried out for optimum thickness of blast resistant liner considering the rock type and overburden. It has been concluded that a rock tunnel having 12.5 m depth of overburden has 2.7-times more resistance against blast loading than 5 m. Moreover, ground surface experiences heaving and the internal face of the tunnel has spikes and crack formation. The deformations at the ground surface have 10% lesser magnitude as compared to the internal surface of the tunnel.

As quartzite is a vital rock type present in major metro projects, its properties vary according to the condition in which it has formed. Therefore, its behavior against the blast load varies from the reported results in the present study depending on the properties of rock.

ACKNOWLEDGEMENT

Authors would like to acknowledge Mr Manojit Samanta Senior Scientist (CBRI-CSIR Roorkee, U.K., India) for assisting in the computational facility.

PEER REVIEW INFORMATION

Engineering Reports thanks the anonymous reviewers for their contribution to the peer review of this work.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/eng2.12293.
CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS
Mohammad Zaid: Conceptualization; formal analysis; methodology; resources; validation; visualization; writing-original draft; writing-review and editing. Md. Sadique: Investigation; methodology; supervision; validation; visualization; writing-original draft; writing-review and editing.

DATA AVAILABILITY STATEMENT
Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID
Mohammad Zaid https://orcid.org/0000-0001-6610-8960
Md. Rehan Sadique https://orcid.org/0000-0002-9570-6801

REFERENCES
1. Barton N, Lien R, Lunde J. Engineering classification of rock masses for the design of tunnel support. Rock Mech Felsmechanik Mécanique des Roches. 1974;6(4):189-236. https://doi.org/10.1007/BF01239496.
2. Dalgic S. Tunneling in squeezing rock, the Bolu tunnel, Anatolian motorway, Turkey. Eng Geol. 2002;67(1-2):73-96. https://doi.org/10.1016/S0013-7952(02)00146-1.
3. Tiwari R, Chakraborty T, Matsagar V. Analysis of curved tunnels in soil subjected to internal blast loading. Acta Geotech. 2020;15(2):509-528. https://doi.org/10.1007/s11440-018-0694-x.
4. Naqvi MW, Akhtar MF, Zaid M, Sadique MR. Effect of superstructure on the stability of underground tunnels. Transp Infrastruct Geotechnol. 2020;1-20. https://doi.org/10.1007/s40515-020-00119-6.
5. Tunnel Safety and Security/WSP. [Online]. https://www.wsp.com/en-US/services/tunnel-safety-and-security. Accessed May 29, 2020.
6. Chaudhary RK, Mishra S, Chakraborty T, Matsagar V. Vulnerability analysis of tunnel linings under blast loading. Int J Prot Struct. 2019;10(1):73-94. https://doi.org/10.1177/2041419618789438.
7. Oreste PP. A numerical approach to the hyperstatic reaction method for the dimensioning of tunnel supports. Tunn Undergr Sp Technol. 2007;22(2):185-205. https://doi.org/10.1016/j.tust.2006.05.002.
8. Liu H. Dynamic analysis of subway structures under blast loading. Geotech Geol Eng. 2009;27(6):699-711. https://doi.org/10.1007/s10706-009-9269-9.
9. Guan X, Zhang C, Zhao F, Mou B, Ge Y. Stress response and damage characteristics of local members of a structure due to tunnel blasting vibrations based on the high-order local modal analysis. Shock Vib. 2019;1–8. https://doi.org/10.1155/2019/7075024.
10. Gholipour G, Zhang C, Mousavi AA. Nonlinear numerical analysis and progressive damage assessment of a cable-stayed bridge piers subjected to ship collision. Mar Struct. 2020;69:102662. https://doi.org/10.1016/j.marstruc.2019.102662.
11. Zhang C, Gholipour G, Mousavi AA. Nonlinear dynamic behavior of simply-supported RC beams subjected to combined impact-blast loading. Eng Struct. 2019;181:124-142. https://doi.org/10.1016/j.engstruct.2018.12.014.
12. Gholipour G, Zhang C, Mousavi AA. Loading rate effects on the responses of simply supported RC beams subjected to the combination of impact and blast loads. Eng Struct. 2019;201:109837. https://doi.org/10.1016/j.engstruct.2019.109837.
13. Wu YK, Hao H, Zhou YX, Chong K. Propagation characteristics of blast-induced shock waves in a jointed rock mass. Soil Dyn Earthq Eng. 1998;17(6):407-412. https://doi.org/10.1016/S0267-7261(98)00030-X.
14. Jayasinghe LB, Shang J, Zhao Z, Goh ATC. Numerical investigation into the blasting-induced damage characteristics of rocks considering the role of in-situ stresses and discontinuity persistence. Comput Geotech. 2019;116:103207. https://doi.org/10.1016/j.compgeo.2019.103207.
15. Shang J. Rupture of veined granite in Polyaaxial compression: insights from three-dimensional discrete element method Modeling. J Geophys Res Solid Earth. 2020. https://doi.org/10.1029/2019JB019052.
16. Tseng DJ, Tsai BR, Chang LC. A case study on ground treatment for a rock tunnel with high groundwater ingestion in Taiwan. Tunn Undergr Sp Technol. 2001;16(3):175-183. https://doi.org/10.1016/S0886-7798(01)00055-4.
17. Wang X, Lai J, Garnes RS, Luo Y. Support system for Tunnelling in squeezing ground of Qingling-Daba mountainous area: a case study from soft rock tunnels. Adv Civ Eng. 2019;2019:1–17. https://doi.org/10.1155/2019/8682535.
18. Rawat DS, Naithani AK, Rao GS. Treatment of cavities during construction of twin tunnels in an irrigation project-a case study. Eng Geol Spec Publ. 2015;494-501.
19. Choi S, Wang J, Munfakh G, Dwyre E. 3D nonlinear blast model analysis for underground structures. GeoCongress 2006; 2006:1–6. https://ascelibrary.org/doi/abs/10.1061/40803(S8187)%29206.
20. Tiwari R, Chakraborty T, Matsagar V. Dynamic analysis of tunnel in weathered rock subjected to internal blast loading. Rock Mech Rock Eng. 2016;49(11):4441-4458. https://doi.org/10.1007/s00603-016-1043-8.
21. Zareifard MR. A new semi-numerical method for elastoplastic analysis of a circular tunnel excavated in a Hoek–Brown strain-softening rock mass considering the blast-induced damaged zone. *Comput Geotech*. 2020;122:103476. https://doi.org/10.1016/j.compgeo.2020.103476.

22. Yang J, Cai J, Yao C, Li P, Jiang Q, Zhou C. Comparative study of tunnel blast-induced vibration on tunnel surfaces and inside surrounding rock. *Rock Mech Rock Eng*. 2019;52(11):4747-4761. https://doi.org/10.1007/s00603-019-01875-9.

23. Jain P, Chakraborty T. Numerical analysis of tunnel in rock with basalt fiber reinforced concrete lining subjected to internal blast load. *Comput Concr*. 2018;21(4):399-406. https://doi.org/10.12989/cac.2018.21.4.399.

24. Deng XF, Zhu JB, Chen SG, Zhao ZY, Zhou YX, Zhao J. Numerical study on tunnel damage subject to blast-induced shock wave in jointed rock masses. *Tunn Undergr Sp Technol*. 2014;43:88-100. https://doi.org/10.1016/j.tust.2014.04.004.

25. Zaid M, Sadique MR. Blast resistant behaviour of tunnels in sedimentary rocks. *Int J Prot Struct*. 2020;204141962095121. https://doi.org/10.1177/2041419620951211.

26. Hibbitt D, Karlsson B, and Sorensen P. *ABAQUS User’s Manual*, 6.14, Dassault Systemes Simulia Corp., Providence, RI; 2014.

27. Systemes D. *Abaqus 6.14 Documentation*. Dassault Systèmes: Providence, RI; 2014.

28. Hoek E, Carranza-Torres C, Diederichs MS, Corkum B. The 2008 Kersten lecture: integration of geotechnical and structural design in tunnelling. Paper presented at: Proceedings University of Minnesota 56th Annual Geotechnical Engineering Conference; 2008; Minneapolis.

29. Barpi F, Peila D. Influence of the tunnel shape on Shotcrete lining stresses. *Comput Civ Infrastruct Eng*. 2012;27(4):260-275. https://doi.org/10.1111/j.1467-8667.2011.00728.x.

30. Qin G, Cao S, Yang F. Effect of deficiencies in the tunnel crown thickness on pressure tunnels with posttensioned concrete linings. *Adv Civ Eng*. 2018;1–14. https://doi.org/10.1155/2018/2757542.

31. Limited DMRC. *Design Specifications*. New Delhi, India: Delhi Metro Rail Corporation Limited; 2015.

32. Gupta AS. *Engineering Behavior and Classification of Weathering Rock*. New Delhi, India: Indian Institute of Technology Delhi; 1997.

33. Sadique MR, Ansari MI, Athar MF. Response study of concrete gravity dam against aircraft crash. *IOP Conf Ser Mater Sci Eng*. 2018;404(1):1–12. https://doi.org/10.1088/1757-899X/404/1/012027.

34. Larcher M, Casadei F. Explosions in complex geometries—a comparison of several approaches. *Int J Prot Struct*. 2010;1(2):169-195. https://doi.org/10.1016/j.ijprotstruct.2010.02.003.

35. Zhao CF, Chen JY. Damage mechanism and mode of square reinforced concrete slab subjected to blast loading. *Theor Appl Fract Mech*. 2013;63–64:54-62. https://doi.org/10.1016/j.tafmec.2013.03.006.

36. Wang W, Zhang D, Lu F, Wang SC, Tang F. Experimental study and numerical simulation of the damage mode of a square reinforced concrete slab under close-in explosion. *Eng Fail Anal*. 2013;27:41-51. https://doi.org/10.1016/j.engfailanal.2012.07.010.

37. Erduran E, Yakut A. Drift based damage functions for reinforced concrete columns. *Comput Struct*. 2004;82(2–3):121-130. https://doi.org/10.1016/j.compstruc.2003.10.003.

38. Wu KC, Li B, Tsai KC. The effects of explosive mass ratio on residual compressive capacity of contact blast damaged composite columns. *J Constr Steel Res*. 2011;67(4):602-612. https://doi.org/10.1016/j.jcsr.2010.12.001.

39. Malvar LJ, Crawford JE, Wesевич JW, Simons D. A plasticity concrete material model for DYNA3D. *Int J Impact Eng*. 1997;19(9–10):847-873. https://doi.org/10.1016/s0734-743x(97)00023-7.

40. Bao X, Li B. Residual strength of blast damaged reinforced concrete columns. *Int J Impact Eng*. 2010;37(3):295-308. https://doi.org/10.1016/j.ijimpeng.2009.04.003.

41. Malvar LJ. Review of static and dynamic properties of steel reinforcing bars. *ACI Mater J*. 1998;95(5):609-616. https://doi.org/10.14359/403.

How to cite this article: Zaid M, Sadique MR. The response of rock tunnel when subjected to blast loading: Finite element analysis. *Engineering Reports*. 2021;3:e12293. https://doi.org/10.1002/eng.2.12293