Analysis of Twin Circular Tunnels Subjected to Impact Loads

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Abstract. Tunnels are important underground structures which require due attention at all stages of their construction process. This task involves huge expenditure and time. Hence, other factors which may affect the functioning of the tunnel in the long run must also be incorporated in the studies. With the growing demand of space for developing various facilities, the best possible way to economize the underground space is being looked after. The purpose of this paper is to study the tunnel behavior addressing both issues of space and impact loading, i.e., twin circular tunnels running parallel to each other are analyzed under impact loading. Synthetic rock material is prepared in the laboratory and its engineering properties are determined. These properties are used to develop FEM model of the twin tunnel using ABAQUS to study stress and displacements induced in the rock model due to incidence of impact load. The point of load application has a major effect on the deformations in the tunnels. This effect is studied by considering two cases of point of load application on the top surface: (i) at the midpoint between the tunnels, and (ii) at the centre of one of the tunnels. Extent of damage suffered by the tunnels due to combined effect of rock strength, magnitude and application of impact load and overburden depth is quantified.

Keywords: Twin Tunnel; Impact load; Synthetic rock mass; Characterisation.

1 Introduction

Civil engineering structures form a major part of any country's economy and development, be it, megastructures or underground structures Numerous research works have been carried out on single tunnels to study the effect of overburden, uniaxial compression, impact loading, blast loading, varying geological conditions such as presence of weak interlayer and jointing orientations[2] - [7]. It is better to construct two tunnels with smaller diameter than one large tunnel [8]. Also, tunnels can be excavated adjacent to the existing tunnels. Researchers have continuously been putting their efforts to bring out the best but neither the scientific processes are ideal nor the human activities. On one hand if a community is striving hard towards development, there are always antisocial elements present to disrupt the order. Recent surge in the terrorist activities directed towards destruction of engineering structures is a major concern.

Hence, numerical analyses have been carried out for a twin tunnel model in order to understand the behavior of the tunnel when subjected to impact load due to a falling projectile. Hammers can be of different shapes, be it, hemispherical nosed, flat headed, curved surface with different radius of curvature and wedge shaped [9]. Most of the projectiles such as missiles have curved nose. There can be different ways in which a projectile can hit the ground surface, be it, inclined or straight; above the centre of the tunnel or above the rock pillar between the tunnels. The rock mass strength itself varies from place to place owing to different rock material or degree of weathering. The tunnels are also located at different depths from the ground surface. There are a number of variables to deal with. The pillar width is an important factor to be considered as reduction in pillar width makes the interaction effects prominent. In adverse geological conditions, stability issues have known to occur at pillar width less than two and half times the radii of the tunnels [10]. Twin tunnels can be present in different settings having horizontal alignment, vertical alignment or inclined alignment [11]. However, the numerical study in this paper has been limited by taking into account a few cases. These are as follows:

1) Parallel twin circular tunnels, i.e., tunnels having horizontal alignment.
2) Projectile hitting above the centre of the tunnel and the centre of the rock pillar.
3) Two different rock masses.
4) Tunnels having different rock pillar width.

2 Numerical Modelling

The problem of twin tunnels has been solved numerically using the FEM based software ABAQUS. The numerical model for this study is based on the impact test setup for the single circular tunnel model by Mishra et al. (2018). This test consists of preparation of small scaled models from artificially prepared rock mass of dimensions 30 cm x 30 cm x 35 cm. A hammer is allowed to fall freely and strike the top of the rock model in order to simulate the falling projectile mass. The deformations at various locations are recorded. The numerical results are validated against the experimental results.

2.1 Numerical model

The numerical model on a small scale prepared in ABAQUS has two parts: twin tunnels in rock mass and the drop hammer. The numerical model is shown in Fig.1. Three different configurations of the rock model are used owing to the changing rock pillar width of 2D, 4D and 6D, where D is the diameter of the tunnel. Thus, the three models have sizes: 45cm x 30 cm x 35 cm; 55cm x 30 cm x 35 cm; 65cm x 30 cm x 35 cm. The hammer used in the model is hemispherical nosed hammer with radius of hemispherical portion being 25mm and length of the cylindrical section being 50 mm.

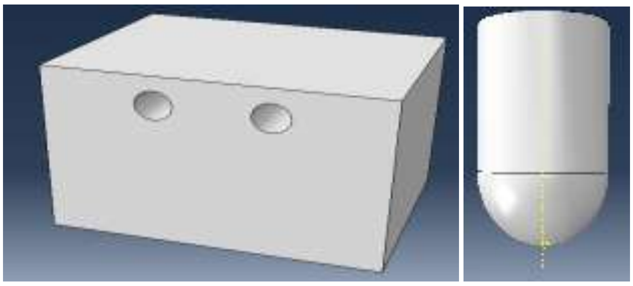


Fig. 1. Numerical model of rock mass with parallel circular tunnels and Drop Hammer

Different cases that have been dealt in this study. The diameter of the tunnels is same in all the cases, i.e., 5cm.
Case 1. Effect of different overburden depth. Two different overburden depths have been dealt with, i.e., 5 cm and 2.5 cm.
Case 2. Effect of different rock material; the properties of two different materials used in the material modeling are tabulated in Table 1.
Case 3. Effect of changing pillar width; 2D, 4D and 6D, where D is the diameter of the tunnel
Case 4. Effect of different impact position of hammer; on the surface of the rock model at the centre of the tunnel and the rock pillar between the tunnels.

The rock material used for the numerical analyses have been artificially prepared in the laboratory and tested for the physical and mechanical properties relevant to the modelling following the guidelines of Indian Standards Code[12] - [15].

Table 1. Material properties used in the study (Mishra et al., 2019)

Material	E (GPa)	Poisson's ratio	Density (kg/m^3)	Friction angle (°)	Cohesion (MPa)	UCS (MPa)
M1	3.675	0.163	1216.68	39.12	0.790	3.51
M2	2.809	0.216	1093.90	31.40	0.627	1.97

Table 2. Input properties for drop hammer

Height of fall	Tup diameter	Mass	Impact velocity	E (GPa)	Poisson's ratio	Density (kg/m^3)
100 cm	25 mm	17 kg	50 m/s	210	0.30	7850

Mohr-Coulomb plasticity model is used for the rock model while Johnson-Cook Damage model is used for the drop hammer.

Mohr-Coulomb yield criterion is given by equation (1) as follows:

$$\tau = c + \sigma tan\phi \tag{1}$$

where τ is the shear stress of the rock, c is the cohesion of the rock, σ is the normal stress and ϕ is the internal friction angle of the rock.

Johnson-Cook Damage model is damage model for ductile metals and is used for modelling steel. The dynamic tests involves high strain rates and Johnson-Cook model remains valid for impact tests [16]. It is given by equation (2) as follows:

$$\sigma^0 = (A + B(\varepsilon^p)^n)\left(1 + Clog\left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}\right)\right)(1 - \hat{T}^m) \tag{2}$$

where σ^0 is yield strength of steel, $\dot{\varepsilon}^p$ is effective plastic strain, $\dot{\varepsilon}_0$ is strain rate and T is the homologous temperature.

The parameters of Johnson-Cook Damage model are listed in Table 3.

Table 3. Johnson-Cook Damage model parameters

d1	0.0705	Reference strain rate	10
d2	1.732	Melting Temperature	1800
d3	0.54	Transition temperature	293
d4	-0.015	Displacement at failure	0.1
d5	0		
A	4900	n	0.73
B	8070	m	0.94

The model is meshed keeping the element size to be 0.01. The time period of the step is 0.02 which is adequate to capture the dynamic effects as the peak of first impact force comes within this duration. The properties of the meshed model are presented in Table 4.

Table 4. Properties of meshed model

Part	Element type	No. of elements
Hammer	C3D8R	240
Rock 2D	C3D8R	54530
Rock 4D	C3D8R	67480
Rock 6D	C3D8R	79695

The General contact (Explicit) is used to simulate the interaction between hammer and the rock. The tangential behavior is kept frictionless with normal behavior set to “Hard contact”.

As the numerical model simulates the small scale model, the boundary conditions complies accordingly. The bottom boundary is kept fixed with the upper and side boundaries free for movement.

3 Results and Discussion

3.1 Effect of different overburden depth

Two different twin tunnel assemblies are modelled with different overburden to study the effect of change in overburden depth. The depths considered are 25 mm and 50 mm with the material properties and other geometries being the same. The material of rock is M1 and the pillar width is 2D. The deformations obtained in both the cases are listed in Table 5. Though, the tunnel crown suffers severe damage in both the cases, still the effect of larger overburden is quite evident in resisting a deformation to a considerable extent. Hence, shallow depths tunnels are more vulnerable to high impact loads.

Table 5. Deformation values at the crown of the tunnel

Cases	Deformation at the crown
M1-50mm	21.9mm; tunnel crown damaged
M1-25mm	51.8 mm; tunnel completely damaged

The deformation contours for tunnels placed in material M1 at 50 mm overburden depth are shown in Fig. 2(a).

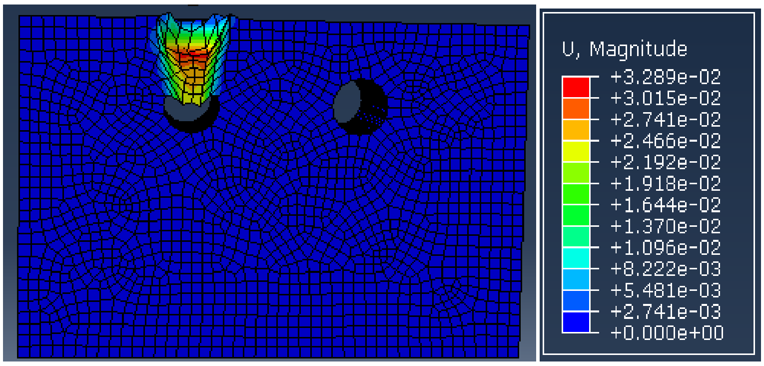


Fig. 2(a). Deformation pattern for M1-50mm overburden depth

The deformation contours for tunnels placed in material M1 at 25 mm overburden depth are shown in Fig. 2(b).

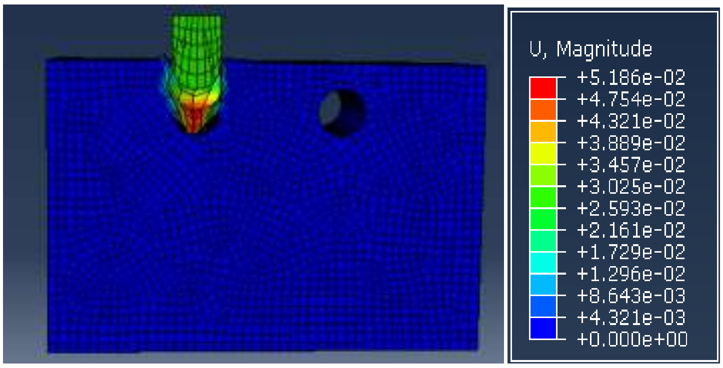


Fig. 2b). Deformation pattern for M1-25mm overburden depth

3.2 Effect of different rock material

The response of different rock to external loads is different due to different mechanical properties. Hence, a comparison has been made by modelling same geometry with M1 and M2, keeping other parameters constant. The overburden is kept 25 mm. the hammer is made to fall above one of the tunnels. The deformations obtained in both are cases are presented in Table 6.

Table 6. Deformation values

Cases	Deformation at the crown
M1	51.8 mm; tunnel completely damaged
M2	64 mm; tunnel completely damaged

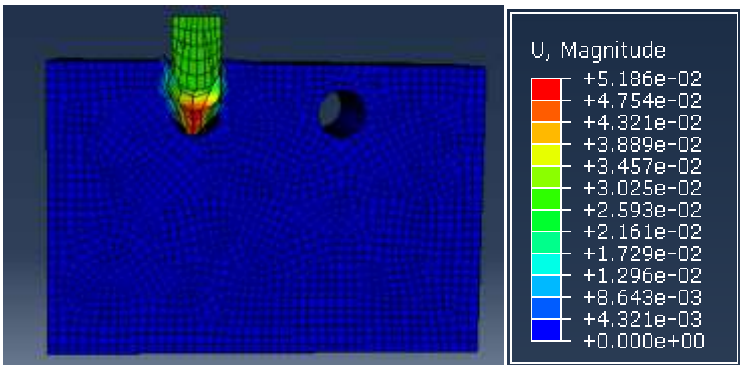


Fig. 3(a) Deformation pattern for M1 material

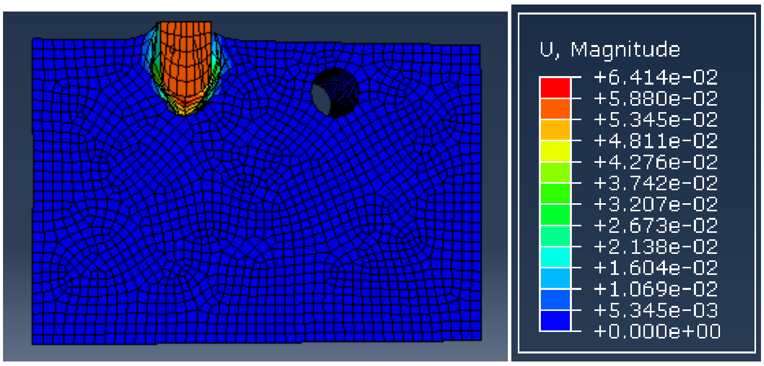


Fig 3(b). Deformation pattern for M2 material

The load of 17 kg is sufficient to completely destroy the tunnel section at the point of impact for both the material at a shallow overburden of 25 mm. However, M2 showing weaker material properties suffer more deformation than that of the model with M1. In both the cases, the hammer is punched into the tunnel cavity but in that with M2, heave can be seen on the surface.

3.3 Effect of changing pillar width

The distance between the tunnels should be carefully chosen as too less of the distance can cause stability problems even without any considerable external loads. In the event of impact load by projectile, the effect on the tunnels is studied by modelling the tunnels having inner end-to-end distance being 2D, 4D and 6D, where D is the diameter of the tunnel. The different cases are modeled keeping the material of rock to be M2, 25 mm overburden and the impact location being the centre of the pillar width.

Table 7. Deformation values

Cases	Deformation at		
	Crown	Side	Maximum
2D	-	6.72 mm	40 mm
4D	-	-	55 mm
6D	-	-	31 mm

The case with 2D is the most critical among the three cases as the effect of impact load manages to reach the tunnel , though it does not cause deformation of the crown but the sides are deformed enough to hamper the serviceability. The cases of 4D and 6D makes tunnel safe from impact load. In all cases, crater formation still occurs on the rock surface.

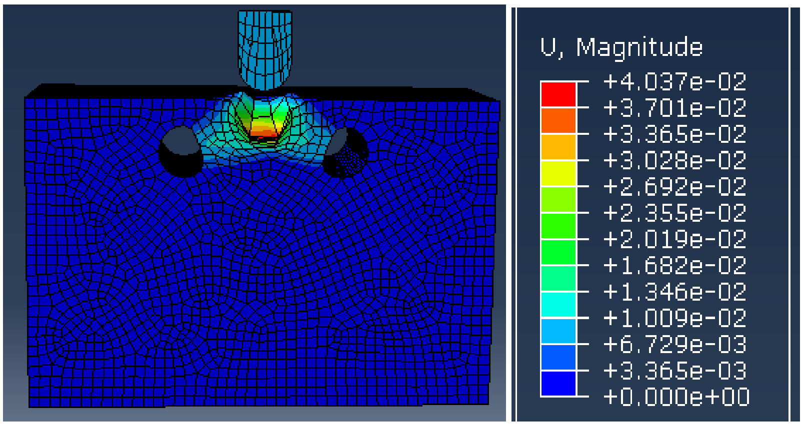


Fig.4 (a). Deformation pattern for pillar width 2D

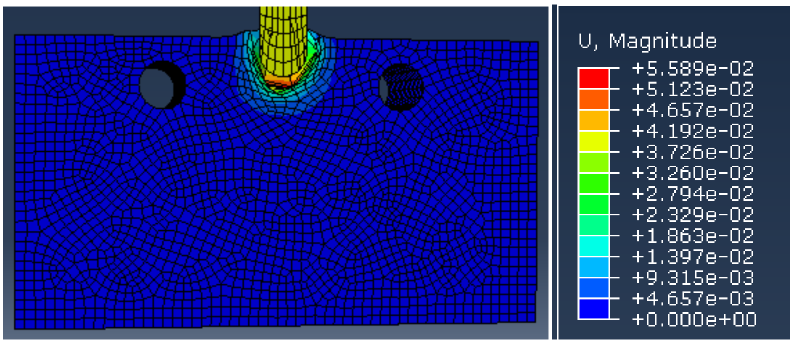


Fig.4 (b). Deformation pattern for pillar width 4D

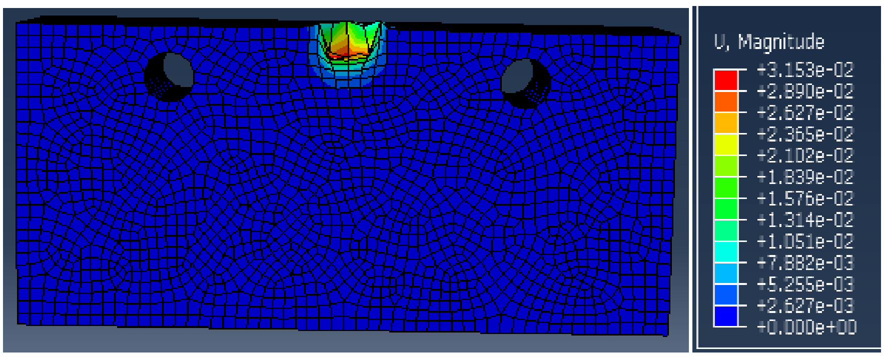


Fig.4 (c). Deformation pattern for pillar width 6D

3.4 Effect of different impact position of hammer

The effect of impact location is considerable as the tunnels completely collapse in case of fall of hammer just above the tunnel disrupting the function while as the location is changed onto the central rock mass, the effect reduces on the tunnel. The material is M2 for all the combinations and the overburden depth is 25 mm .

Table 8. Deformation values

Cases	Deformation at		
	Crown	Side	Maximum
2D tunnel	Tunnel is complelety crushed	Tunnel is complelety crushed	64 mm
2D centre	-	6.72 mm	40 mm
4D tunnel	Tunnel is complelety crushed	Tunnel is complelety crushed	62 mm
4D centre	-	-	55 mm

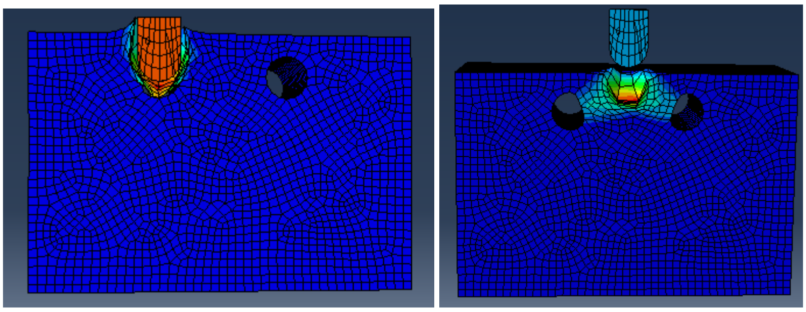


Fig. 5(a). Deformation in tunnels when hammer falls above tunnel versus the pillar (2D)

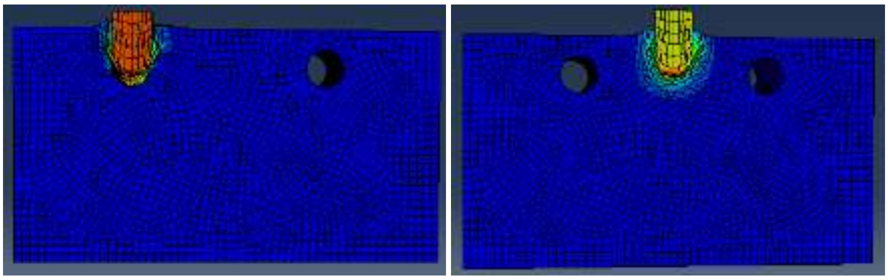
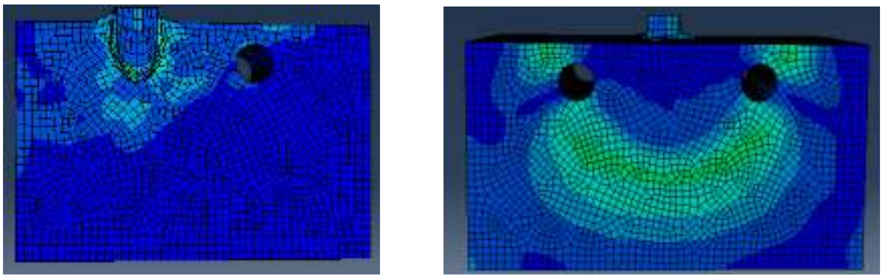


Fig. 5(b). Deformation in tunnels when hammer falls above tunnel versus the pillar (4D)

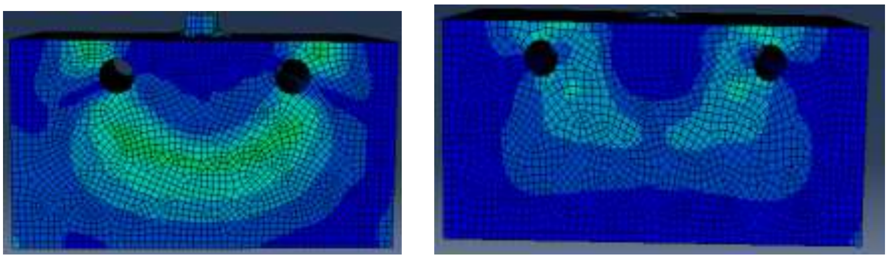
3.5 Stress patterns around the tunnels

The stress distribution around the tunnels largely determines its stability. It is redistribution of stresses that causes the failure of tunnels. The stress contours helps to understand the interaction between the two tunnels.



(a) (b)

Fig. 6. (a)Stress pattern around tunnel subjected to drop hammer with pillar distance of 2D; hammer dropped above the tunnel; (b) Stress pattern around tunnel subjected to drop hammer with pillar distance of 2D; hammer dropped above the pillar



(c) (d)

Fig. 6. (c)Stress pattern around tunnel subjected to drop hammer with pillar distance of 4D; hammer dropped above the pillar; (d) Stress pattern around tunnel subjected to drop hammer with pillar distance of 6D; hammer dropped above the pillar

Fig. 6(a) shows that the stress lines are concentrated around the tunnel section at the impact location. Though, one of the tunnels suffers from high local damage, still the effect of impact is able to manifest itself to the adjacent tunnel. Thus, if the impact location is far away from the tunnel section, the tunnels are spared from local damage.

From Fig. 6(b), (c) and (d), it can be seen that the crown of the tunnels towards the outer end are more stressed. Also, the base of the tunnel is also stressed with the stress lines of both the tunnels joining each other. The case of 6D distance shows independent stress contours around the tunnels indicating lack of interaction of stress zones, i.e., as the pillar distance increases, the interaction effect diminishes. This makes it the most ideal case for locating the tunnels.

4 Conclusions

The numerical models for various cases are formulated in the present study which helps to arrive at the following conclusions:

1. All the parameters varied for the model, namely, overburden depth, rock material strength, pillar distance and the impact location of projectile, have a considerable significance in the tunnel response. A cover depth of 2.5 cm is not suitable when high mass projectile strikes the tunnel.
2. High strength material is better in resisting the damage.
3. As pillar distance increases, the damage on tunnel reduces. The pillar distance of 2D is not recommended. In case of 4D and 6D, no deformation is observed on the tunnel periphery. Case of 6D is the safest as the rock mass extent around each tunnel is sufficient for those to behave as single circular tunnel.
4. The outer upper crown portion and the base of the tunnel seems to be the most stressed parts of the tunnel periphery.
5. The projectile load which is capable of completely destroying the tunnel can be resisted well by the tunnels if the impact location of the projectile is away from the tunnel centerline.

Earlier, small scaled models have been successfully used to predict the deformations and stress response in the prototype. Thus, similar behavior is expected in the tunnels constructed in the actual rock mass and the deformations can be predicted.
The spectrum of this study can further be widened by incorporating different impact loads and orientations.

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