Numerical Study of Blast Analysis of Thottiyar Concrete Tunnel-Case Study

Reshma Rajan
Department of Civil Engineering
Mangalam College of Engineering
Kerala, India

Sharon Treassa Biju
Department of Civil Engineering
Mangalam College of Engineering
Kerala, India

***Abstract*—Nowadays terrorist attacks are becoming intensive and more frequent. It's impossible to predict many of the hazardous events that can occur in different structures like blast, explosion, impact of flying debris, gas leaks and terrorist attacks. Terrorist attacks on tunnels in Russia, UK, Spain and other cities have resulted in Fatalities, injuries and structural damage. Tunnels should be protected from the blast effects, which are likely to be the targets of terrorist attacks. It should be analyze and design the blast loads to prevent structural collapse.**

In this present study blast analysis of a circular concrete tunnel is performed to analyze the effects of blast loading on the structure. The case study of thottiyar concrete tunnel is taken for the analysis to find out the critical point by comparing peak particle velocity (PPV) and pressure inside and outside the tunnel. The numerical analysis of tunnels are done load by using FE package AUTODYN and ANSYS .

Keywords: Dynamic response, Insideblast, Outside blast concrete tunnel, Critical point ,Autodyn

1.INTRODUCTION

An expanding terrorism has prompted worries about bombing of structures and cause minor to severe structural damage. It is important to evaluate the damage of structures to ensure safety. Mainly underground structures are taken into account . Terrorist attacks on transit tunnels in UK, Russia, London, Moscow, Spain and distinctive urban areas have brought about the monstrous death toll, wounds, property harm, and monetary results. An impact in a travel burrow is risky due to the kept underground space and the potential for ground collapse, as well as water entry into the tunnel even if it is built beneath a body of water. The current methods like visual inspection and non-destructive testing are expensive and time consuming. Therefore numerical method are selected for the analysis of tunnel blast. Ansys software is used for the finite element modeling (FEM) and assigning material properties. Autodyn is used for the blast analysis to compare the effect of blast inside and outside the tunnel by fining the peak particle velocity (PPV) and peak pressure.

The blast analysis is done by a AUTODYN software. AUTODYN software is a completely integrated analysis program particularly for non-linear dynamic problems. It is designed to simulate nonlinear dynamics, large strains and deformations, fluid-structure interactions, explosions, shock and blast waves, impact and penetration, and contact problems (Shin et al. 2014). AUTODYN is widely used in dynamic related fields, including the defense, oil and gas industry, aerospace, nuclear power, chemical and automotive field. (Choi et al.2013)

The impact of blast vibration on underground structure have been considered by numerous researchers utilizing the field experiments. The tunnel response will get decrease by increasing distance from the blast point, due to reduction of compressive waves around the structural soil. And circular and horseshoe tunnels are less resistant to destruction. (Mobaraki.2015) .The blast effect of an explosion is in the form of a shock wave composed of a high pressure shock front that expands outward from the center of the detonation, with pressure intensity decaying with distance. As the wave front impinges on the tunnel, a portion of the tunnel will be engulfed by the shock pressures. The magnitude and distribution of the blast load acting on the tunnel then depends on the tunnel geometry and flexibility, blast pressure-time history, and the dynamic soil characteristics (Balsara, 2002).Behavior of Blast Loading is as the standoff distance increases the magnitude of blast pressure decreases. Blast pressure and blast scaled distance is inversely proportional. Blast pressure increases as weight of blast increases and blast pressure decreases when standoff distance increases. The variation of force in the structural members is such that the blast force must be considered in the analysis. As the distance from the charge increases the peak of positive phase decreases and also the time of arrival increases (Mishra, 2018)

2. METHEDOLOGY

This case study covers the blast-resistant analysis for a tunnel passing through the Kuthirakutti hills at Adimaly at Kerala , India. which is shown in Fig 1. This tunnel is a part of Thottiyar hydro electric power station which carries water to the turbine, which is under construction. At the end of the tunnel it connect with a penstock pipe from Thottiyar weir to lower periyar hydro electric power plant (Kerala, India). The numerical model of the circular concrete tunnel was developed using commercial numerical hydrocode-AUTODYN. Owing to symmetry, only a quarter span of the tunnel is modeled. The analysis briefly discusses the peak pressure, peak velocity, and temperature of bomb explosion inside and out side the circular concrete tunnel to find the critical point. A series of parametric studies have been carried out in order to evaluate the significance and sensitivity of several parameters on the lining thrust. The parameters evaluated are: intensity of blast loading, over pressure and peak velocity of the tunnel in different gauge points

3.1 Finite element model

The project of Thottiyar hydro electric power station tunnel is considered. The circular tunnel is with 3m diameter with a concrete tunnel lining 0.46m thick and 210m length is buried in 15m depth. The tunnel lining is with concrete and steel bars. The main bars are 16 mm dia. with 250 mm spacing and the distribution bars are 12 mm dia. with 30 mm spacing. The charge is based on a 1000 kg TNT charge as representation of a vehicular bomb at a stand-off distance of about 2500 mm. The charge was assumed to be a cube and then dimensions were calculated based on TNT density of 1.63 g/cm^3. The center of the charge is located on the ground and which is outside the tunnel. Air element size is provided as 20 mm and circular concrete tunnel is modeled with element size of 50mm. The compressive strength of concrete is 25 MPa, respectively and their property includes a porous density of 2.314 g/cm^3. Fig.1 the geometrical data and AUTODYN model of the Thottiyar tunnel

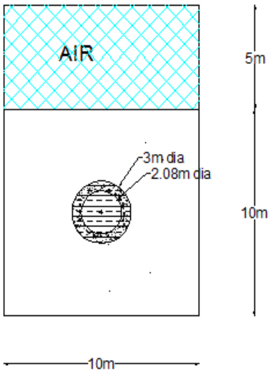

Figure 1 FE model of tunnel in AUTODYN

3.Modeling TNT detonation

Chapman et al. (1994) demonstrated the capability of AUTODYN to map the solution from 1D to 2D axisymmetric computational domain so as to reduce computational time. TNT charge was modelled in 1D domain as a wedge model. The length of the wedge model is taken approximately equal to, the stand-off distance in the model. The wedge was filled with explosive and air. The start point for the wedge was considered 1 mm from the origin to avoid a zero thickness element at the origin. Although this correction reduced the volume of the explosive, the percent reduction was negligible. The angle of the wedge is defined by AUTODYN and only the wedge inner radius and outer radius needs to be defined. The 1D analysis was continued until the blast wave reached the boundary. The results of 1D analysis was saved as '.fil' file and mapped onto AUTODYN 3D to fill the Eulerian domain. Mapping leads to When the charge detonated on ground surface produce hemispherical burst, some modification had to be made on the TNT calculation for the 1D model

TNT is modelled using JWL (Jones- Wilkins-Lee) EOS, which models the pressure generated by chemical energy in an explosion. The energy equation is given by (Ray et al., 2008):

$$p=C_1\left(1-\frac{\omega}{rv}\right)e^{-vr_1}+C_2\left(1-\frac{\omega}{r_2v}\right)e^{-vr_2}+\frac{\omega e}{v} \qquad \text{……………………(2)}$$

where, p is the hydrostatic pressure, v is the specific volume, e is the specific internal energy

and C_1, r_1, C_2, r_2 and ωe are material constants.

TNT is modeled as a spherical burst in 1D wedge model. The radius of spherical charge of 1000kg TNT is calculated using the default density of TNT (Density = 1.63 gm/cm3) and is obtained as per the following calculation:

$$\text{Volume of TNT} = \frac{\text{mass of TNT}}{\text{density of TNT}}$$

Density of TNT = 1.63 gm /cm3
Volume of TNT = 4/3 x π x R^3
R= 527.23 mm
Where, R= Radius of spherical charge
M = Mass of TNT

The radius of the explosive was 527.23mm. The 1D analysis was continued until the blast wave reached the boundary at 3000 mm.

The termination time for the 1D analysis determined by trial and error was found to be 0.2 ms. Material parameters of tnt is shown in table 1.

Table 1

Material parameter of TNT

Properties	Value
Reference density (kg/m^3)	1630
C1	37400
C2	3750
R1	4.15
R2	0.09
W	0.35
C-J detonation velocity (m/ms)	6.93
C-J Energy/unit volume (MJ/m^3)	6000
C-J pressure (MPa)	21000

Table 2

Properties of concrete

Properties	Value
EOS	P-Alpha
Reference density (g/cm^3)	2.75
Porous density (g/cm^3)	2.314
Porous sound speed (m/s)	2.92x10^3
Initial compaction pressure (kPa)	2.33x10^4
Solid compaction pressure (kPa)	6x10^6
Compaction exponent	3
Bulk modulus (kPa)	2.5x10^7
Elastic strength/ft	0.7
Elastic strength/fc	.53

Table 3

Material properties of reinforcement

Properties	Values
EOS	Linear
Reference density	7.85 g/cm³
Bulk modulus	1.59e8 kPa
Strength	JC Steel
Yield stress	5.6e5 kPa
Shear modulus	8e7 kPa
Failure Principal	Principal stress
Tensile failure stress	5.6e5 kPa

Table 4
Rock parameters

Properties	Value
Specific Gravity (G)	2.65
Density (Kg/M3)	2550
Elastic Modulus (Gpa)	28
Poisson's Ratio	0.25
Angle Of Internal Friction (U)	42
In Situ Stress Ratio	0.5
Dilation Angle	5
Cohesion (C) (MPa)	2.3
Rc (MPa)	40
RQD Range	75-80
RMR	47

Table 5
Parameters of air

Properties	Value
Density (Kg/m^3)	1.225
Gamma	1.40
Specific heat (KJ/gk)	0.000718
Reference temperature (K)	288

4. MODELLING OF CONCRETE

Lagrangian element is used to model the concrete part of the concrete tunnel. The concrete is with 50cm mesh size. An equation of state (EOS) is the relation between state variables. In most of the studies, concrete is assumed to be a homogenous porous material ,the material parameters are shown in Table. 4.

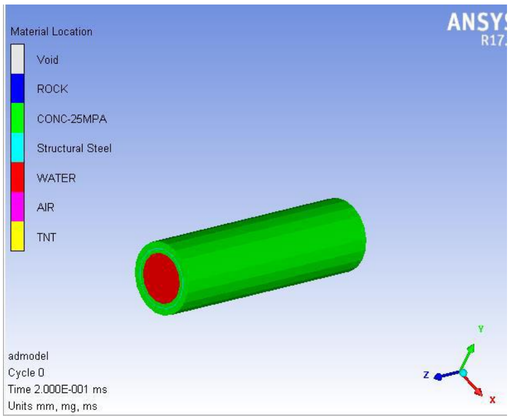

Fig. 2. Model of circular concrete tunnel

5. MODELLING OF STEEL REINFORCEMENT

The tunnel lining is with concrete and steel bars. The main bars are 16mm dia with 250mmspacing and the distribution bars are 12mm dia with 30mm spacing. The longitudinal and transverse reinforcements separately to represent the proper configuration as shown in fig 3. The steel is modeled by Johnson's hook strength and linear Equation of State (EOS). and the material properties are shown in table 3.

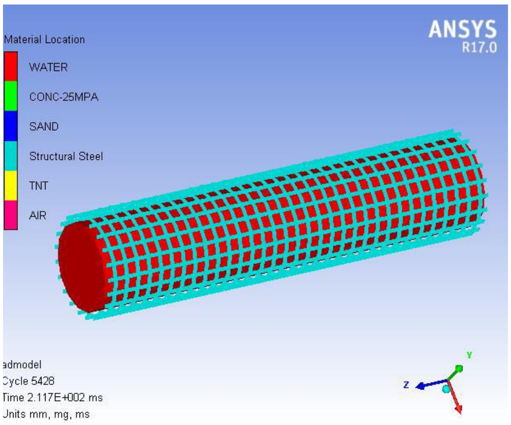

FIGURE 3. Model of Steel Reinforcement in ANSYS

7. ROCK MODELING

Tunnel is made up of reinforced concrete of M25 . and it is surrounded by rock. The materials used to model the tunnel is shown below in table 4.

6. MODELLING OF WATER

Water is flowing through the tunnel to lower periyar hydro electric power plant to rotate the turbine. Therefore water is modeled inside the tunnel with a density of 1 g/cm^3. The polynomial equation of state (EOS) and cutoff pressure of 0 Pa were used for water.(Huang, 2013) This form of EOS defines the pressure as follows:

$$\mu > 0\ (compression) \qquad (6)$$

$$P = A_1\mu + A_2\mu^2 + A_2\mu^3 + (B_0 + B_1\mu)\rho_0\ e \qquad (7)$$

$$\mu > 0\ (tension) \qquad (8)$$

$$p = P = T_1\mu + T_2\mu^2 + B_0\rho_0\ e \qquad (9)$$

Where, A1, A2, A3, B0, B1, T1, and T2 are constants. The term e is the specific internal energy (energy=unit mass), which can be described as follows:

$$e = (\rho g h + p_0)/(\rho B_0)\text{..........................}(10)$$

where q and h are density and depth of water, and g and p$_0$ are acceleration due to gravity and atmosphere pressure, respectively. The parameters of water is shown in table x.

7. MODELLING OF AIR

So as to provide the space needed for the blast wave to propagate and interact with the circular tunnel, air was modelled around the tunnel as presented in Fig. 6. The modelled air should extend beyond a distance equal to the stand-off distance so as to simulate the blast process.10mm cell division is provided for zoning air model.

The air medium is modelled using ideal gas EOS. The internal energy of air is 2.068×10^5.The relationship between pressure and energy is given by (Hao and Hao, 2014):

$$p = (\gamma - 1)\ \rho e\text{...............................}(3)$$

where, □□is a constant, □□is the density and e, the specific internal energy. Linear Polynomial equation of state can also be used to describe the behaviour of the air (Tai and Chu, 2011). Pressure is given by:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_2\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where, *E0* is the internal air density and $\mu = \frac{\rho}{\rho_0} - 1$

For ideal gases, the coefficients in the EOS are *C0*=*C1*=*C2*=*C3*=*C6* = 0 and *C4*= *C5* = □□1. Thus EOS can be simplified as Gamma Law EOS:

$$P = (\gamma - 1)\frac{\rho}{\rho_0} - E_0 \qquad (5)$$

Where □□□□ is the relative density, □□is the rate of change to the specific heat of air, □□□is the initial air density value and □□is the current air density.

Parameters of air is shown in table 5.

8. *Interaction*

So as to obtain exact results interaction between the slab and air part is necessary. AUTODYN have the unique provision to provide interaction for both Eulerian and Lagrangian elements. For Lagrangian elements gap size is calculated and checked whether the input parameters are consistent with geometry. Fully couple interaction was provided for both Eulerian and Lagrangian elements. To ensure perfect bond with no slippage (strain compatibility) both the beam elements and concrete elements should be rigidly jointed at the nodes.

9. *Gauges for Output Data Acquisition*

To measure the tunnel deflection and over pressure history gauges (monitoring points) are provided at various points in the numerical model of the tunnel. Gauge 1, Gauge 3, Gauge 6, Gauge 4 are provided on the slab edge and Gauge 2 ,Gauge 5 is provided at the slab midspan to capture the midspan deflection. Location of gauges at different location on the circular concrete tunnel is shown in Fig. 7

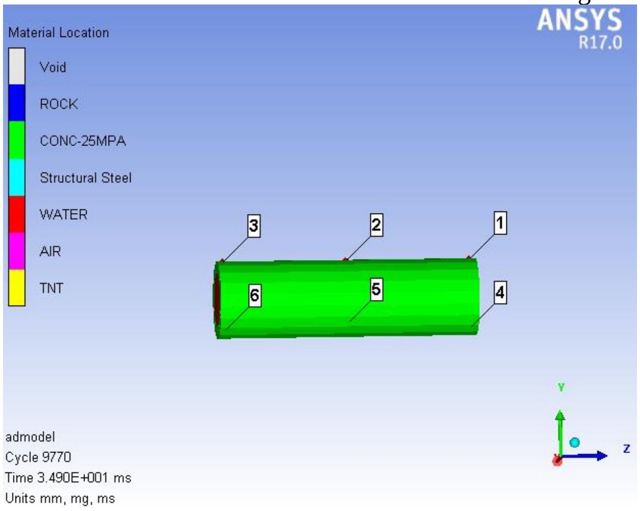

Fig. 7. position of gauges in the tunnel model

10. *Numerical Analysis*

The start time of the 3D analysis was set equal to the end time of the 1D analysis and the output of the 1D analysis was transformed into the 3D domain. When the output was remapped to the single material 3D Euler-FCT domain, the explosion gases had to be converted to air defined in the 3D domain. The solution controls were defined using run wrap-up criteria and time step options. Although the wrap-up criteria consisted of cycle limit, time limit, energy fraction and energy reference cycle, only the time limit wrap-up criteria was used. For the simulation a run time limit of 30 ms was used. To ensure stability and accuracy of the solution, the size of time step used in explicit time integration is limited by Courant-Friedrich-Levy (CFL). This condition implies that the time step be limited, such that a disturbance (stress wave) cannot travel further than the smallest characteristic element dimension in the mesh in a single time step. The time step was also calculated using the Courant-Friedrich-Levy criterion with a safety factor of 0.6667.

11. *Result and discussion*

11.1 *Tunnel velocity*

The critical points of the tunnel is find out by comparing the inside and outside blast of the circular concrete tunnel. The TNT is placed at the centre of the tunnel above the soil in the outside blast and at the centre of the tunnel at inside blast. The peak velocity of gauges within 20s are compared and shown in the Fig.10 and in Fig. 11.

The peak velocity inside and outside thottiyar tunnel is compared in the table 6.

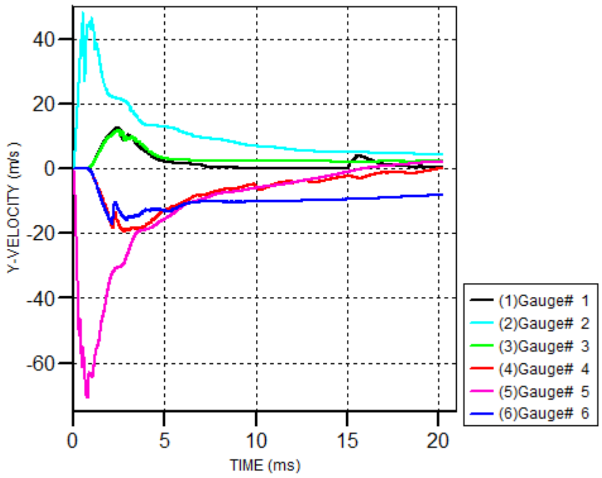

FIGURE. PEAK PARTICLE VELOCITY INSIDE THE TUNNEL

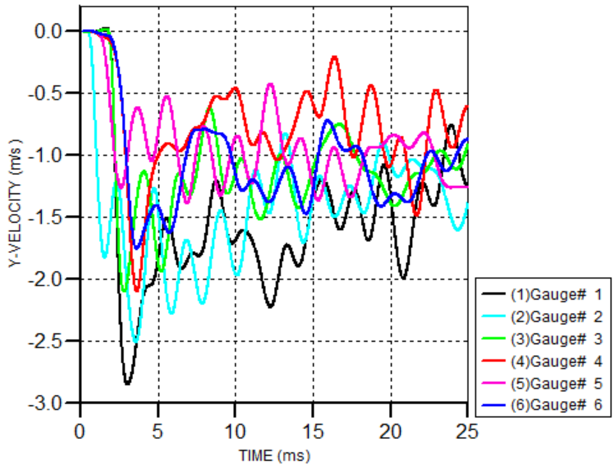

FIGURE. PEAK PARTICLE VELOCITY INSIDE THE TUNNEL

Table 6
Comparison of peak velocity

Inside the tunnel (m/s)	Outside the tunnel (m/s)
68.150	2.860

From the literature Mobaraki (2015), the peak particle velocity damage criterion damage zones are described and its shown in table 7. As per the table the proposed tunnel damage has tight closure. Therefore there is a high chance of rock fall in 1000kg TNT.

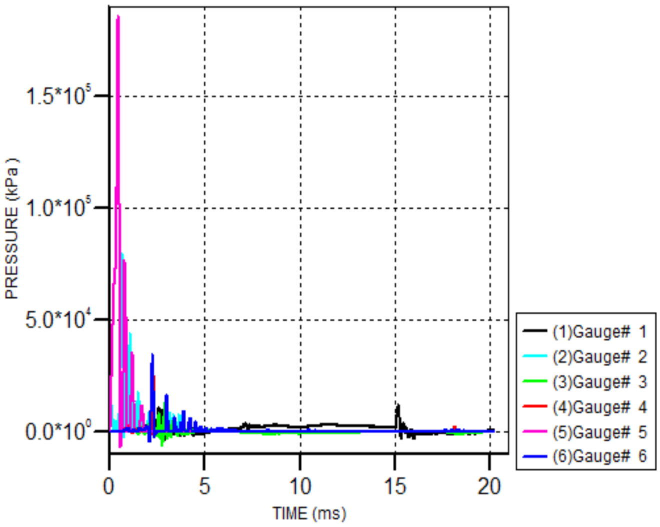

FIGURE PEAK PRESSURE OF BLAST INSIDE THE TUNNEL

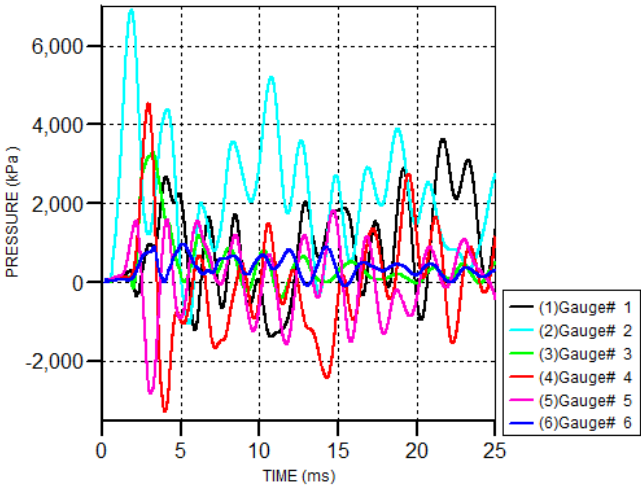

FIGURE PEAK PRESSURE OF BLAST OUTSIDE THE TUNNEL

11. 2 Tunnel Pressure

The critical points of the tunnel is find out by comparing the inside and outside blast of the circular concrete tunnel. The TNT is placed at the centre of the tunnel above the soil in the outside blast and at the centre of the tunnel at inside blast. The peak pressure in 20s are compared and shown in the Fig. 12 and in Fig. 13.

The peak pressure inside and outside thottiyar tunnel is compared in the table 8.
The pressure inside the tunnel is greater than that of outside blast.

11.3 Temperature of The Tunnel

The critical points of the tunnel is find out by comparing the inside and outside blast of the circular concrete tunnel. The TNT is placed at the centre of the tunnel above the soil in the outside blast and at the centre of the tunnel at inside blast. The peak temperature in 20s are compared and shown in the Fig. 14 and in Fig. 15.

The temperature inside blasted the tunnel is greater than that of outside blasted tunnel. And the peak temperature is compared in table 8.

12. CONCLUSION

Blast analysis was carried out for Thottiyar circular concrete tunnel subjected to blast loading, to predict the dynamic response duly considering the effects using hydrocode AUTODYN. Simulations on 3D numerical model are presented. Structural responses such as peak velocity and peak pressure were obtained from the numerical simulations and compared to the corresponding experimental results available from the literature. Results revealed that peak pressure, velocity and damage can be predicted with good quality from the numerical model. Moreover, with the case study of Thottiyar concrete tunnel model, detailed parametric studies were carried out to investigate the effect of charge weight, standoff distance, aspect ratio, steel bar reinforcement ratio on the damage pattern of the Thottiyar tunnel. From the results, the following conclusions are drawn:

- The tunnel response decreases with the increase of distance from the blast center.
- The velocity of blast inside the tunnel is greater than outside blast. And tight closure damage is present by the 1000kg TNT blast inside and outside the tunnel. It was found that, on average, rock fall occurred in tunnels when the ppv exceeded 0.9 m/s.
- Temperature and pressure of 100kg blast inside the blast is greater than that of outside tunnel blast.

From the, analysis of this study on Thottiyar concrete tunnel, inner blast is more critical than the outer blast.

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