Investigation of Dynamic Response for Blast Hole Wall in Rock Excavations

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ABSTARCT

When it comes to mining operation and civil engineering activities like tunnelling and dam constructing the importance of blasting cannot be underestimated. A nearly perfect estimate of explosion loading on rock mass is an essential prerequisite to initiating such activities. The ability of transmitting vibrations differs in different rock types due to their differing rock mass properties. For example, rigid competent rock types with high compressive strength and high density have a good transmitting ability. The present study focuses on different qualities of rock mass properties including good and average quality. Moreover, it is in effect a comparative study between numerical simulation and empirical equations. The results indicate that in empirical equations only compression wave of pressure are taken into account and the tensile waves are ignored. It is also demonstrated that the dynamic load on the borehole wall is more in the rock mass of good quality than in the average quality.

Keywords: Rock mass; Blast hole; Blast; Empirical equations; Numerical simulation

1. INTRODUCTION

Explosives are widely used in mining engineering for excavations. They are chemical substances which intensively react to the presence of suitable stimuli and release energy quite rapidly in microseconds (Persson et al., 1993). According to the hydrodynamic theory of blasting, the explosive energy shrinks to zero in a very short time. This energy propagates instantaneously through the unreacted material and turns it into blasting products which in turn results in a pressure increase on the borehole wall. Then immediately this pressure decreases to the atmospheric pressure again (Lopez, 1997). As the borehole wall is pushed outward, the country rock crashes and two main parts are then recognizable; the elastic zone and the plastic zone. The explosive has a definite amount of energy which is comprised of shock energy and gas energy. The gas energy is in turn comprised of two energy types; the “rock inplace” which acts for cracking the rock and the “heave” which looses and displaces the rock (Hustrulid, 1999). The shock or impulse wave passes through the country rock and affects the material. The intensity of this effect differs for different rock types depending on their ability for transmitting energy. Actually some empirical relations are available for estimating the effect of pressure wave on borehole wall but the point is that none of these relations have taken into account the rock properties. The present study has investigated the effect of pressure wave on borehole walls while focusing on different rock mass qualities. This investigation has been carried out using both empirical relations and numerical methods and these two procedures are compared herein. In numerical modelling AUTODYN 3D has been used and it is worthy of notice that this software is generally used for non-linear dynamic simulation purposes (Century dynamic is a subsidiary of ANSYS INC, 2005).

2. EXPLOSIVE AND ROCK MASS PROPERTIES

An underground structure in rock can be loaded by large and relatively distant detonated explosion in several ways. Underground structural loading is influenced by the flexibility and shape of the structure. This loading process depends on the properties of the surrounding rock and the interaction effects between the explosive and the rock mass. When underground and surface excavations are exposed to the explosion dynamic load, their reaction depends on the intensity of the movement inducted by the passing wave propagation. The impulse frequency results in two waves; a body wave and a surface wave. An important part of the physical-mechanical properties of rock is related to the propagation of elastic waves. Therefore, the rock quality can affect the blasting results. This study investigates the effect of two different qualities of rock mass, (i.e. good and average qualities), on the borehole blasting results. These data are presented in Table 1.

Table 1 - Rock mass classification by Hoek (2001)

Parameters	Average Rock	Good Rock
Friction angle (degree)	33	46
Cohesive strength (MPa)	3.5	13
Rock mass compressive strength (MPa)	13	64.8
Rock mass tensile strength (MPa)	-0.15	-0.9
Deformation modulus (MPa)	9000	42000
Shear modulus (MPa)	3600	17500
Poisson's ratio	0.25	0.2
Dilation angle (degree)	4	11.5
Compression wave velocity (m/s)*	4000	5500
Shear wave velocity (m/s)*	2100	3000
Density (kg/m^3)*	2500	3000

*These parameters are obtained from Brady and Brown (2005), Franklin and Dusseault (1989) and Bell (1992).

The explosive used in this study was dynamite and its properties are listed in Table 2. The borehole was excavated 200 meters deep and 50 mm in diameter while the explosive was 30 mm in diameter. The total length of the borehole was 4 meters which was filled by a 280 cm charge and 120 cm stemming.

Table 2 - The explosive properties –Dynamite (Parchin Chemical Industries, 2007)

Internal energy (MJ/m^3)	7190	Cover type	Paraffin
Resistance of water	Good	Trazol (ml)	> 350
Weight (gr)	165+5	Density (gr/cm^3)	1.45±0.05
Diameter (mm)	30	Detonation velocity (m/s)	> 3000
Length (mm)	195	Sensitivity	8 – 12
Relative power	1.2		

3. CALCULATION OF LOAD ON BOREHOLE WALL

3.1 Shock Wave Pressure

The shock wave pressure value is a function of the velocity of detonation and the density of explosive (Lopez, 1997). Despite the complexity of this relationship some formulas are available for calculating the detonation pressure.

$$PD = 432\times10^{-6}\frac{\rho_e\ .\ VD^2}{1+0.8\rho_e} \tag{1}$$

In the above formula PD stands for pressure of detonation in MPa, ρ_e for density of explosive in gm/cm^3 and VD for velocity of detonation in m/s. Upon inserting the values from Table 2 in the above formula a PD value of 2610 MPa was obtained for dynamite.

3.2 Gas Pressure

The gas induced from the detonation expands and hence pushes the borehole walls outward. The amount of this pressure is half of the shock pressure, i.e. PE=0.5 PD. Therefore, based on the previously calculated PD the shock pressure is estimated as 1305 MPa.

3.3 Borehole Pressure

When the borehole and the explosive are different in diameters the pressure put upon the borehole wall is damped due to the space between the explosive and the wall. As a result of that the pressure put upon the borehole wall is not as much as the gas pressure (Bulson, 1997). The borehole pressure (PW) is as follows:

$$PW = PE\left(\frac{r_h}{b}\right)^{-q\gamma} \tag{2}$$

The borehole diameter and the explosive diameter are respectively indicated by r_h and b the above formula. Moreover, γ refers to the adiabatic expansion coefficient of the explosive (γ=1.2), q to the shape factor of the explosive which equals 2 and 3 for the cylindrical and spherical charges respectively. For a borehole diameter of 50 mm and an explosive diameter of 30 mm, this equation gives a PW value equal to 382 MPa.

4. CALCULATION OF DYNAMIC PRESSURE

The dynamic pressure [P(t)] produced in the borehole wall is a function of time and it creates a series of interaction between the rock mass and the impulse wave (Jiang, 2005). Equations of Starfield (1968) and Duvall (1953) are the empirical equations that gives the dynamic pressure.

$$P(t) = PW.\frac{8\,\rho_r.C_p}{\rho_r.C_p + VD.\rho_e}\left[e^{(-Bt/\sqrt{2})} - e^{(-\sqrt{2Bt})}\right] \qquad (3)$$

In this equation ρ_r stands for density of rock in gm/cm^3, ρ_e for density of explosive in g/cm^3, VD for velocity of detonation in m/s and C_p for compression wave velocity in m/s. Moreover, t refers to the explosion elapsed time and B to the constant which equal 16338.

According to Eq. 3, the amount of dynamic pressure on the borehole wall depends on the density of rock mass, the type of explosive and the compression wave velocity. The present study addresses different rock mass types (i.e. good quality and average quality) and each type will experience a different dynamic pressure. Equations 4 and 5 show pressure equations for different rock mass types:

$$\text{Good rock}: P(t) = 2416\left[e^{-11552.7\,t} - e^{(-\sqrt{32676\,t})}\right] \qquad (4)$$

$$\text{Average rock}: P(t) = 2128\left[e^{-11552.7\,t} - e^{(-\sqrt{32676\,t})}\right] \qquad (5)$$

These equations delineate the maximum values of dynamic pressure of compression waves within a time interval (Fig. 1).

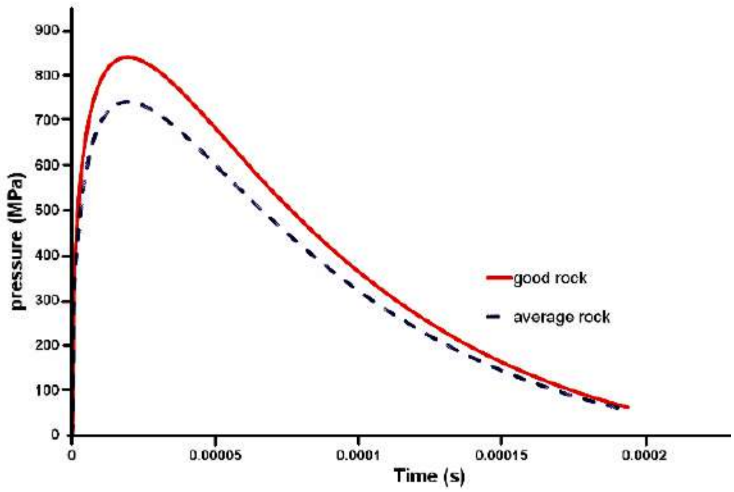

Fig. 1 - Dynamic pressure on borehole as estimated by Starfield equation for two rock mass types

5. NUMERICAL SIMULATION BY AUTODYN 3D SOFTWARE

The simulation process starts with constructing the geometry of the material types such as rock mass, air, explosive and stemming. Then the CJ pressure and the velocity produced by the volume-pressure curve of the explosive need to be estimated.

5.1 Estimation of Pressure and Velocity at CJ Point

As observable below, the Chapman-Jouguet (CJ) pressure P_{CJ} can be estimated using VD and the density of the unreacted explosive (ρ_0) (Cooper, 1997):

$$P_{cj} = \frac{\rho_0 \ . \ VD^2}{\eta + 1} \tag{6}$$

P_{CJ} here refers to the pressure of CJ or detonation pressure in GPa, ρ_0 to the initial density of the unreacted explosive in g/cm^3., η to the coefficient of specific heats of the detonation gases and VD to the detonation velocity in km/s. The detonation gases include, inter alia, H_2O, CO, CO_2 and N_2. For most explosives the density is within the range of 1 through 1.8 gr/cm^3 and η is approximately 3 (Cooper, 1992). If we insert this η value into the above relationship along with the values of 1.45 gm/cm^3 and 3 km/s for the density and velocity respectively, a CJ pressure value of 3.26 GPa will result for the dynamite. The relationship between the initial density and the CJ density can be estimated by these two equations (Langhaar, 1951) and (Kiefer, 1954):

$$\rho_{CJ} = 1.386 \rho_0^{0.96} \tag{7}$$

$$\rho_{CJ} = 1.33 \rho_0 \tag{8}$$

Upon inserting the initial density of dynamite into them, the first equation gives a value of 1.98 gr/cm^3 for the CJ density while the second equation results in a value of 1.93 gr/cm^3. Therefore, authors decided to include their mean, i.e. 1.955 gm/cm^3, as the CJ density value. Now one can calculate the velocity of detonation at CJ point (VD_{CJ}) as demonstrated below:

$$\frac{\rho_{CJ}}{\rho_0} = \frac{VD}{VD - VD_{CJ}} \tag{9}$$

Since all other variables are known (ρ_0 = 1.45gm/cm^3, ρ_{CJ} = 1.955 gm/cm^3 and VD=3 km/s) one can easily calculate the value for VD_{CJ} which equals 0.77 km/s. Moreover, using the Eq. 9 one can calculate the CJ pressure too.

$$P_{cj} = \rho_0 \ . VD_{CJ} \ . VD \tag{10}$$

Upon inserting the other values into this equation a CJ pressure value of 3.35 GPa is obtained. However the CJ pressure value used in AUTODYN software was the mean value of the above two CJ pressure values which equals 3.3 GPa.

5.2 Jones-Wilkins-Lee Equation of State

Different equations of state are available in the literature some of which are BKW (Becker-Kistiakowski-Wilson, 1941), JCZ (Jacobs-Cowperthwaite-Zwisler, 1976) and JWL (Jons-Wilkins-Lee, 1968). These equations have been created by drawing a line connecting the experimental data for specific explosives at specific densities. The Wilkins equation of state can be used as an appropriate means for predicting the motion provided that the product pressure does not go below 5 kbar. Having this set of data at hand the following energy Eq. 11 is derived:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{11}$$

Where A, B, R_1 and R_2 are constants to be calibrated, ω is the Gruneisen coefficient, V is relative volume and E is specific internal energy. This form is known as the “Jones - Wilkins - Lee” (JWL) equation of state. This equation is currently considered as an appropriate means for hydrodynamic calculations of detonation product expansions to pressures down to 1 kbar (Zukas and Walters, 1998). The consonant values of the above equation (A, R_1, B, R_2 and ω) have been already determined by dynamic experiments and are shown for the explosive dynamite in Table 3.

Table 3 - The JWL parameters for dynamite (Parchin Chemical Industries, 2007).

A (GPa)	**B (GPa)**	**R_1**	**R_2**	□	**E(Gj/m^3)**
573	20.16	1.8	6	0.29	7.2

5.3 Blast Hole Modelling

In AUTODYN, the Jones-Wilkins-Lee equation of state is used for modelling both the detonation and the expansion of explosives. To prevent wave reflections from infecting the results, boundary conditions were applied to the computational domain. It was assumed that the space available between the charge and the borehole wall is filled with an ideal gas. The blasting hole was modeled by using three approaches for the equations of state of the detonation products:

(a) Ideal gas EOS - simplified model proposed in analysis (Fairlie and Bergeron, 2002).
(b) Jones-Wilkins-Lee (JWL) EOS – empirical EOS widely used in mine blast simulation (Table 3) (Dobratz and Crawford, 1985)
(c) Linear EOS - stemming and rock mass can be described as a linear elastic material.

The rock mass strength criteria have been defined based on the Hoek and Brown criteria (Hoek, 2001). Since the pressure is only considered on the borehole wall, the modelling can be carried out in small dimensions. The dimensions of this model are shown in Fig. 2. The model comprises of four materials including air, dynamite, type of rock and stemming. The state equation and processor modes of the model are shown in Table 4.

Table 4 - The equations of state and processor modes used in modelling

	AIR	DYNAMTE	ROCK MASS	STEMMING
Strength Criteria	-	-	Hoek - Brown	-
State Equatio	Ideal Gas	JWL	Linear	Linear
Processor modes	Auler	Lagrange	Lagrange	Lagrange

To offer real conditions in this model, stress boundary conditions have been applied in hydrostatic state, but authors did not apply that to the tunnel face due to lack of horizontal stress in this part.

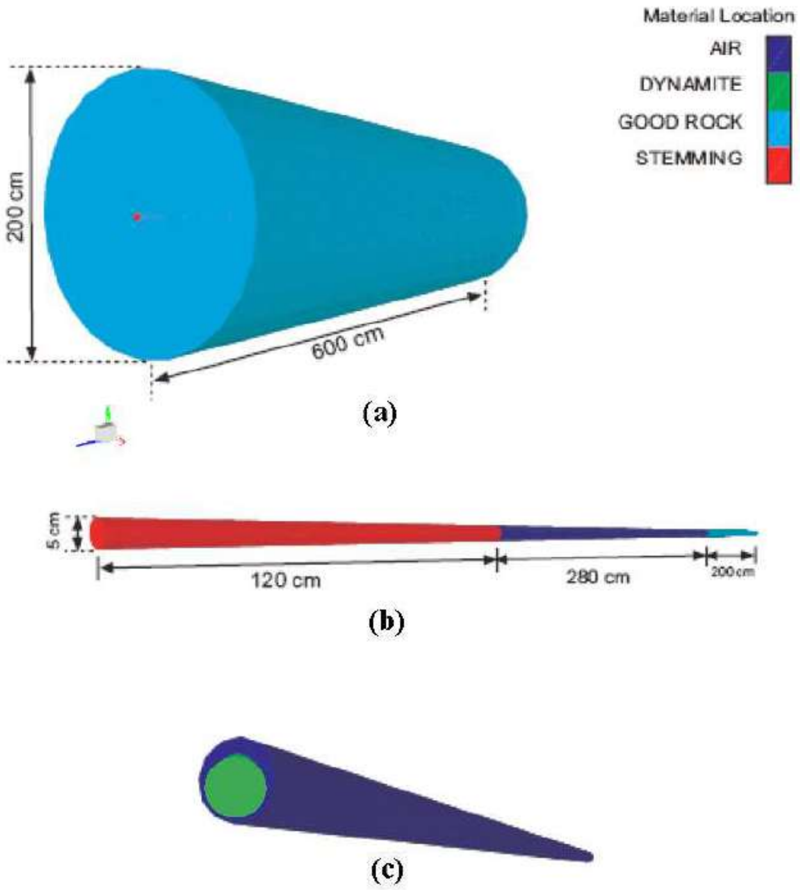

Fig. 2 - (a) Geometry of country rock, (b) Geometry of stemming and explosive in blasthole, (c) Explosive location in blast hole.

5.4 Dynamic Pressure on Country Rock by AUTODYN Modelling

Borehole is modelled in both good and average rock qualities. Wave propagation around borehole is illustrated in Figure 3. Pressure history is plotted on a point of borehole wall to determinate dynamic pressure [Figure 4]. As one can observe in Fig. 4 the dynamic waves are in both compression (+) and tensile (–) states.

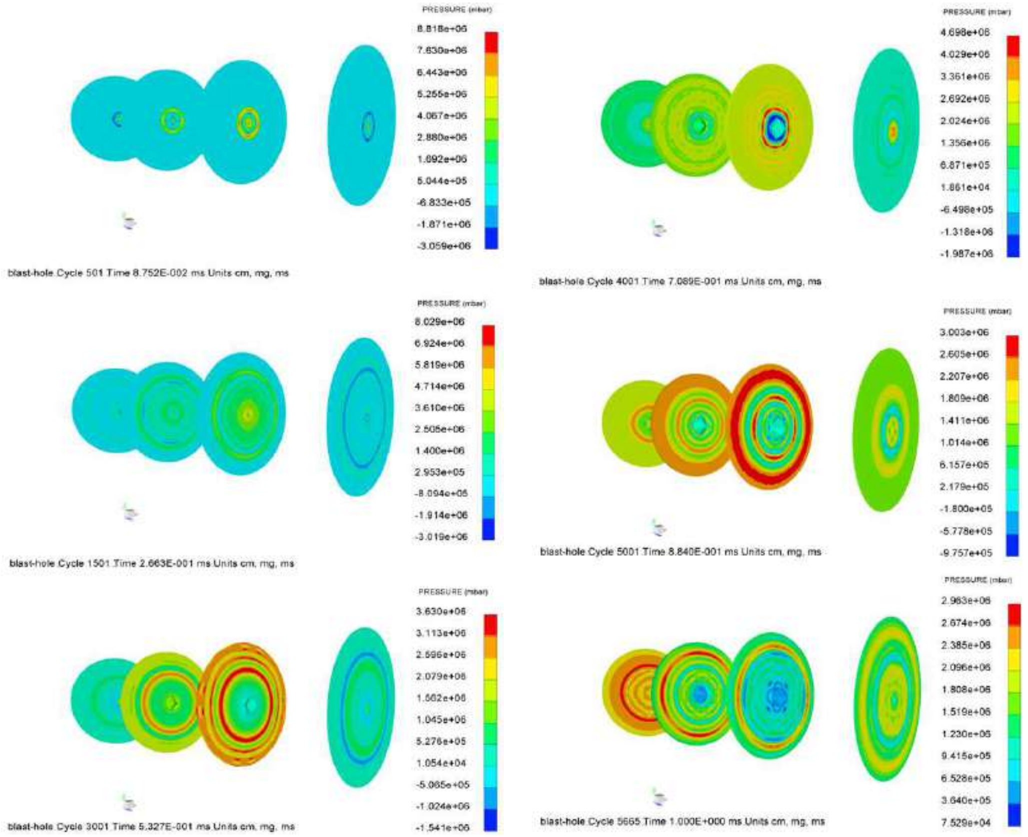

Fig. 3 - The pressure wave propagation in good country rock in a 0.087 millisecond time step

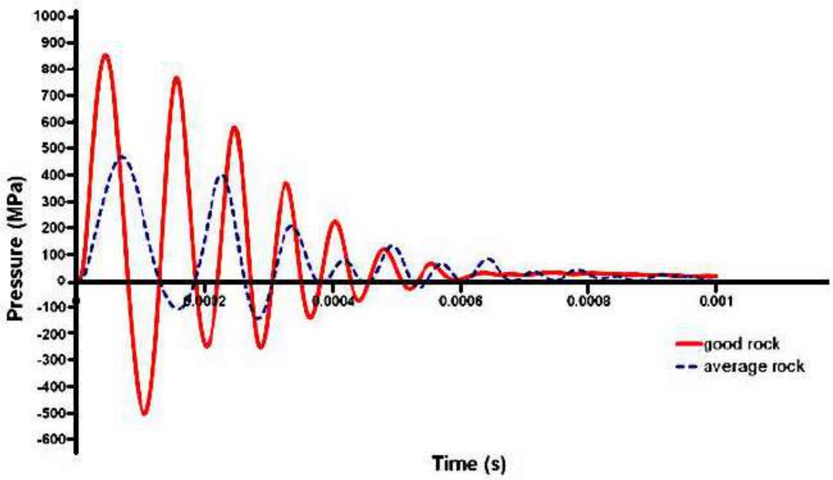

Fig. 4 - Compression (+) and tensile (-) waves in borehole wall

6. DISCUSSION AND CONCLUSIONS

In the present study the dynamic pressure on the borehole wall is estimated using both empirical equations and numerical modelling (AUTODYN 3D software). The results indicate that the empirical plots are in line with the modelling plots. When empirical equations are used the dynamic pressure is damped in 0.0002 seconds while numerical modelling resulted in a 0.0008 second damp interval. As can be observed, the numerical modelling has given an interval 4 times the length of the interval given by empirical equations. This difference is mainly due to the rock mass behavior. The maximum pressure on good quality rock mass is 850 MPa in both numerical modelling and empirical equations, but for the average quality rock this maximum pressure is 740 MPa in empirical equations and 480 MPa in numerical modelling. In other words, in numerical modelling the maximum pressure variance from the good quality rock to the average quality equals 13% decrease while it is 43% for empirical equations.

Despite the important role that tensile waves play in wave propagation through rocks, they cannot be determined using empirical equations. Therefore, numerical modelling has proved more appropriate for determining the dynamic load. The comparison of empirical and numerical plots in average versus good quality rock made the researchers conclude that the dynamic load on the borehole wall is more in the good quality rock than in the average quality due to the confinement of the explosive in this case.

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