The present study also involved results of signature and multiple blast holes to understand the blast wave propagation mechanism and its damage effects surrounding the rock mass.

II. BLAST DAMAGE CONSTITUTE MODELS

Blast damage constitute models are founded on micro cracks which have been reported in many publication (Grady and Kipp, 1980; Taylor et al., 1986; Throne et al., 1990; Kuszmaul, 1987; Bawden et al., 1993). According to the concepts of continuum mechanics, for isotropic materials, when a material point is subjected to stresses, it changes in volume due to the volumetric portion of the stresses and in shape due to its deviatoric parts (Malvern, 1969). The volumetric strain $\theta$ is determined by the pressure $P$ at that point and the bulk modulus $K$ of the material

$$\theta = \frac{P}{3K}$$

The volumetric strain $\theta$ is the variable that determines whether the microcracks will be activated and grow. When a rock material is subjected to a tensile stress, it can support that stress and does not fail unless the value of the stress is larger than its static tensile strength. This is accounted for by setting a critical value $\theta_c$ for the volumetric strain $\theta$, i.e., when $\theta$ is less than $\theta_c$, the microcrack system in the material point remains stable, when $\theta$ exceeds $\theta_c$, micro cracks are activated according to the actual level of $\theta$. Furthermore, if a stress whose value is well above the static tensile strength is applied to a rock material, the rock material does not fail if the time duration for the stress is too short. As pointed out by Bawden et al. (1993), in dynamic loading, the stress can exceed the material strength, but it may not damage the material if its duration is too short. Blast damage is accumulated as a function of time and applied stress. This fact is supported by the experimental work of Li et al. (1994) who tested the dynamic strength of several types of rock materials under impulsive loading and concluded that, for a given rock sample and stress level, a critical time is required for fracture to occur. From the view point of microcrack activation and growth, micro cracks may be activated by a high stress level and show a tendency for further growth. However, complete growth is possible only when the time duration of the stress is long enough. The above can be expressed by a mathematical formula:

$$C_d = \propto (\theta - \theta_c)^\beta t$$

where $C_d$ is defined as the fraction of volume which has been influenced by cracks.
\(\alpha, \beta\) and \(\theta_c\) are material constants whose physical meaning was interpreted by various researchers. Rock materials encountered in blasting practice generally contain visible joints, beddings or other macro flaws which may have significant influence on the physical processes involved in rock blasting. In the present model, the rock mass is highly simplified by assuming that it is an isotropic, homogeneous and continuous medium.

The state of stress of a material point is treated in two modes (shear and tensile) under dynamic failure mode and depending on the value of volumetric strain compared to the critical value. Shear failure mode is determined for plastic yielding, whereas tensile failure for tensile loading. Shear model either used for the Mises or the Johnson-Cook plasticity models, whereas equation of state (EOS) is also supported additionally in tensile failure model. Tensile failure criteria were used for rock mass failure model in numerical results of this paper. The theory of rock breakage under dynamic loading in numerical simulation has been reported by Sazid and Singh (2012).

### III. SINGLE HOLE BLAST RESULTS

The above constitutive model was applied in Abaqus/explicit numerical tool and analyzed the behavior of rock mass under high impulsive loading of explosive energy. Movement of shock wave energy and its variation with detonation velocity has been represented in this model. Point load charge with axisymmetric section has been used in this model (fig. 1). The movements and reflection from free faces of shock energy with different intensity of pressure rings are shown in fig. 2. It was found that rock blasted material kinetic energy increased with velocity of detonation energy of explosive. More applied explosive energy generates more cracks around the rock mass (fig. 3) but trend of energy distribution were same encountered in all phases. The details of rock and explosive properties were referred from Sazid and Singh (2012).

![Fig. 1 Geometry of single blast hole model](image-url)
Fig. 2 Progression of Stresses as wave and reflected from free faces

Fig. 3 Variation of kinetic energy of blasted material with detonation velocity

Bench blast model with axisymmetric section has been also described in this section. It can be observed that the explosive energy in the form of pressure rings travels towards the free faces and reflected as tensile wave. The rock mass started to generate cracks where tensile stresses value reached above the tensile strength of the rock mass (Singh et al., 2012; Singh et al., 2013; Kainthola et al., 2012; Sarkar et al., 2009). The movement of shock wave energy and fragmented material are shown in fig 4 & 5.

Fig. 4 Movement of shock wave energy with different intensity

Fig. 5 fragmented blast material model
IV. MULTI HOLE BLAST RESULTS

Two blast holes with same initiation time were considered for dynamic numerical simulation. Centre point of both blast holes were targeted for analysis. The geometry of blast holes were shown in Fig. 6. It can be revealed from numerical simulation results central area damage zone developed during superimposed of two blast hole shock wave energy (fig. 7). Excessive damage represented the wastage of explosive energy. Therefore, optimum explosive energy can be obtained either by increasing spacing between holes or decreasing velocity of detonation of explosive. Furthermore, the rock class was also effect the central damage zone area (Sazid et al. 2012). Variation of developed pressure from more to less be found in rock class V to I (fig. 8).

Fig. 6 Geometry of two blast hole model

Fig. 7 Movement of shock wave energy and damage at superimposition of energy

Fig. 8 Pressure Variation with Rock Class

V. CONCLUSIONS

This paper introduced the blast damage constitute model and numerical results of rock blasting. Field testing of rock blasting is not economical and feasible all time and most of parameters are not possible to monitor during microsecond events of rock blast. Therefore, dynamic numerical tools are very effective and easiest way to analysis and control the rock blasting. Abaqus/explicit numerical results with single and multi-blast holes were showed the behavior of shock wave energy and utilization of explosive energy.
REFERENCES


