Simulation of rock subjected to underground blast using FLAC\textsuperscript{3D}

Ranjan Kumar\textsuperscript{i)}, Deepankar Choudhury\textsuperscript{ii)} and Kapilesh Bhargava\textsuperscript{iii)}

\textsuperscript{i)} Former PhD Student, Department of Civil Engineering, IIT Bombay, Powai, Mumbai 400076, India. Also, Scientist-F, Bhabha Atomic Research Centre, Mumbai 400085, India.
\textsuperscript{ii)} Professor, Department of Civil Engineering, IIT Bombay, Powai, Mumbai 400076, India. Also, Adjunct Professor, Academy of Scientific and Innovative Research (AcSIR), New Delhi, India.
\textsuperscript{iii)} Assistant General Manager, Nuclear Cycle Board, Bhabha Atomic Research Centre, Mumbai 400094, India. Also, Associate Professor, Homi Bhabha National Institute, Mumbai, India.

\section*{ABSTRACT}

In recent past, effects of blast loads on structures/foundations have gained considerable attention due to increase in threat from various man-made activities. Protecting foundation systems from such threat has become a major concern for designers. Terrorist attack as a source of blast may be in the form of missile attack which will penetrate the ground and then explode. Mining, quarrying, construction activities and all other operations which involve the use of explosives for rock breaking are some of the other sources of blast load. Blast phenomenon can lead to excessive settlement or distortion of foundation systems which in turn may collapse the building. Full-scale experiments of blast are expensive and model tests are found to be unrealistic many a times, numerical simulation of blast is required to be done to understand the complex response of foundation subjected to blast. The finite difference method is a powerful numerical method to solve geo-mechanical problems which can be used to analyze soil foundation interaction. In the present paper, finite difference software Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC\textsuperscript{3D}) is used to model ground shock wave propagation in rock. In order to study the response of foundations to blast loads through numerical modeling, many factors such as fixity conditions, constitutive models, mesh size, time step need to be calibrated. Blast load is applied and Particle velocity time-history is obtained. Peak Particle Velocity (PPV) is estimated at various points away from blast. The FLAC\textsuperscript{3D} result has been compared with field data to arrive at suitable constitutive model, mesh size, time step etc. Calibration of FLAC\textsuperscript{3D} model is achieved. Effects of Young’s modulus and Poisson’s ratio have also been presented. The results will be very useful for evaluation of response of foundation subjected to blast.

\textbf{Keywords:} blast induced vibration, blast loading, peak particle velocity, numerical modeling, FLAC\textsuperscript{3D}

\section{INTRODUCTION}

Protection to personnel, equipment and structure against the effect of blast load is major concern. The prevention of foundation failure is very necessary. The problem of foundation subjected to blast loading has been addressed using theoretical, numerical and empirical methods in the past. In most of the methods, the rock behavior under blast and soil structure interaction (SSI) has not been addressed adequately. Finite difference method based software Fast Lagrangian Analysis of continua (FLAC\textsuperscript{3D}) can be used to analyze the SSI problem. Validation of material model and rock model parameters was established using experimental vibration parameters in rock. In practice, several shallow foundations for domestic and industrial buildings and structures are constructed in rocky strata. These shallow foundations subjected to blast loading can cause severe damage. The scarcity of study on behavior of shallow foundations subjected to underground blast shows a need for such study. Hence, in this paper, FLAC\textsuperscript{3D} is used to model blast wave propagation in rock medium. The rock medium is calibrated with respect to available experimental data. Underground blast load calculation has been done by three methods, namely, proposed methods by Drake and Little (1983), IS 6922 (1973) and rock model proposed by the authors. Results of the analysis have been compared and conclusions are provided to understand the complete behavior of rocks subjected to underground blast.

\section{CALIBRATION OF ROCK MODEL USING FLAC\textsuperscript{3D}}

The estimation of vibration parameters in foundation subjected to blast is a complex task. This involves shock wave propagation in the rock media and
soil structure interaction. Development of a proper numerical rock model is very important for evaluation of vibration parameters and response of foundation under blast loading. The numerical model needs to be first calibrated with respect to field data for its further use in estimating response of foundation subjected to blast loading. The calibration of the model involves identification of suitable material model and representative rock properties. Consequently, with the selected material model and rock properties, soil structure interaction can be carried out. FLAC3D is used for calibration of the rock model.

In order to study the response of shallow foundations to blast loads, many factors such as fixity conditions, constitutive models, mesh size, time step need to be calibrated. In this paper, rock in free-field condition is calibrated and field PPVs are compared with FLAC3D values in order to arrive at suitable material model, mesh size and dynamic time step required for rock structure interaction modeling to get response of foundation subjected to blast loading. Input to FLAC3D is given as free field pressure calculated at crater formed by explosion. This free field pressure is estimated by the model developed by present authors. PPV model by present author (Kumar, 2015) is written as Eq. (1) which is established based on 1089 published data of various researchers.

\[
v = \left(\frac{f_c}{0.642} \times D^{-1.463}\right) \times \gamma^{0.5}(r^2 = 0.783)
\]

where, \(v\) = peak particle velocity, m/s; \(f_c\) = Uni-axial compressive strength (UCS) of rock, MPa; \(\gamma\) = unit weight of rock, kN/m³; \(D\) = Scaled distance, m/kg \(r^2 = R/W; R = \text{Distance to the explosion}; W = \text{Charge weight (kg)} \)

For calibration of rock model, the PPV values are calculated at various points using FLAC3D and compared with the field values.

3 MODEL GENERATION IN FLAC3D

Developed PPV model for rocky site as given in Eq. (1) will be used to estimate free field pressure by Eq. (2) at explosion crater boundary as given by Bulson (1997).

\[
P_0 = \rho_c v
\]

Where, \(P_0\) = Peak pressure; \(v\) = Peak particle velocity; \(\rho_c\) = Acoustic impedance. PPV free field peak pressure can be calculated as present PPV model for rocky sites. Two and four field data for granite site (Test no. 152 and 153 respectively) of site no. 19 of Nicholls et al. (1971) have been selected which is caused by bench blast.

The site 19 was located at Doswell quarry, Doswell. This quarry was in the Baltimore granite-gneiss and it is fine to medium grained, light to dark grey gneiss. The site in the present study was approximated as granite site. Multiple rows of holes were used for detonation. Bench blasting was used here.

It is proposed to model the rock subjected to blast in FLAC3D and measure PPV at various points and compare with the field data. After blast, PPV is calculated from presently developed model given by Eq. (1).

4 ASSIGNING PROPERTIES AND MATERIAL MODELS IN FLAC3D

Test no. 152 and 153 of Site 19 are modeled in the present study using FLAC3D. There are 18 and 20 no. of boreholes each of 0.15m diameter for test no. 152 and 153 respectively. It is not possible to model detonation of blast and crater formation in FLAC3D. No. of rows and no. of boreholes in each row are not available with the field data. Hence, instead of 18 boreholes, one big crater of diameter 2 m and depth 14 m is modeled. Free field peak pressure is calculated from Eq. (2) and is applied on the cylindrical crater boundary. FLAC3D model is given in Fig. 1. Radial zone size is taken as 8 m X 8 m X 20 m. Element size in x-direction up to 16 m from face of the rock is kept as 1m and beyond 16 m, it is kept as 10 m. Element size in y-direction and z-direction is kept 1m and 0.5 m respectively. Rock is modeled as Mohr Coulomb model. Rock input parameters to FLAC3D, namely Young’s modulus (E), Poisson’s ratio (ν), shear modulus (K), bulk modulus (G), cohesion and angle of friction are given in Table 1.

![FLAC3D model for granite field site no. 19 and test no. 153 of Nicholls et al. (1971).](image)

5 APPLYING BOUNDARY CONDITIONS

The model size has to be limited by artificial boundaries. Quiet or viscous boundary is applied at bottom and three side faces. Front and top face are kept free. Dynamic frequency independent Rayleigh stiffness damping is applied. Damping raition is taken as 0.01 at 50 Hz frequency. Time independent peak pressure is applied on the crater boundary.
Table 1. Rock input parameters

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameters</th>
<th>Range in literature</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UCS, ε, MPa</td>
<td></td>
<td>173</td>
</tr>
<tr>
<td>2</td>
<td>Unit weight, γ, kN/m³</td>
<td></td>
<td>26.4</td>
</tr>
<tr>
<td>3</td>
<td>E, MPa</td>
<td>14-83 X 10³</td>
<td>48.5 X 10³</td>
</tr>
<tr>
<td>4</td>
<td>φ</td>
<td>0.26-0.30</td>
<td>0.28</td>
</tr>
<tr>
<td>5</td>
<td>K, MPa</td>
<td>K=E/3(1-2µ)</td>
<td>37.12 X 10³</td>
</tr>
<tr>
<td>6</td>
<td>G, MPa</td>
<td>G=E/2(1+µ)</td>
<td>19.14 X 10³</td>
</tr>
<tr>
<td>7</td>
<td>c</td>
<td>c=[(K+4G/3)/γ]¹/²</td>
<td>5000</td>
</tr>
<tr>
<td>8</td>
<td>Cohesion, C, KPa</td>
<td></td>
<td>447</td>
</tr>
<tr>
<td>9</td>
<td>Angle of friction, φ, degree</td>
<td></td>
<td>49</td>
</tr>
<tr>
<td>10</td>
<td>Tensile strength</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>Pc from Eq. (2), N/m²</td>
<td></td>
<td>6.38 X 10³</td>
</tr>
</tbody>
</table>

6 MODELING OF BLAST LOAD AND CRATER DIMENSIONS

Curves which describe the ground motion (acceleration versus time, velocity versus time, and displacement versus time curves) are not readily calculated. However, these relationships are not required since the design of protective structures/foundations to resist shock loads is based on the peak values of the induced motion rather than the actual motion-time relationships (UFC 3-340-02).

Blast is not explicitly simulated in analysis. Blast free field pressure is applied at the crater boundary. Pressure is applied normal to the crater boundary which is uniformly distributed along the crater boundary. The geometry of the crater and the dynamic load condition are symmetrical around a vertical axis through the centre of the crater. The crater diameter is taken as 2 m. Granite site/test no. 19/153 of Nicholls et al. (1971) has been modeled.

7 ANALYSIS OF RESULTS

FLAC³D results for granite site no. 19/152 and 153 are presented here. History of particle velocity versus time at granite site Doswell quarry 19/test no. 152 at various distances away from the blast is shown in Fig. 2. For test no. 152, the particle velocity versus time-history plot is obtained at distances 95m, 158m, 185m, 190m, 235m, 325m and 371m away from the blast point using Mohr-Coulomb model. For test no. 153, the particle velocity versus time-history plot is obtained at distances 82m, 94m, 111m, 132m, 158m, 190m and 235m away from the blast point using Mohr’s Coulomb model. It is observed from Fig. 2 that peak values of particle velocities are prominent at distances 95m and 185m, and at other distances, the peaks are not prominent. Comparison of PPV values obtained from field and FLAC³D is presented in Table 2. It is observed from Table 2 that PPV from FLAC for test no. 152 at 95m distance away from blast is more than the field PPV value and at 185m away from the blast, FLAC PPV value is less than the field PPV value.

It is also observed from Table 2 that PPV values from FLAC for test no. 153 at various distances are less than the field PPV values. Test no. 153 is having more number of boreholes, less depth of boreholes, stemming and face height which could be the possible reasons for FLAC PPV value coming to be less than field PPV value. Other possible reason could be the meshing for which aspect ratio is 10. In FLAC³D, estimation of PPV at distances 96m/186m for test 19/152 and at distances 86m/96m/116mm/136m for test 19/153 may result in underestimated FLAC values.

![Figure 2. Particle velocity at granite site (Doswell quarry 19/test no.152) at distances 95m, 185m, 325m, 371m, 158m, 190m, 235m away from blast point using Mohr-Coulomb model](image)

Table 2. Comparison of PPV (v, in m/s) values

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Site/Test No.</th>
<th>R, m</th>
<th>W, kg</th>
<th>R/W², m/kg²</th>
<th>v, m/s site</th>
<th>v, m/s FLAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19/152</td>
<td>95</td>
<td>945</td>
<td>3.1</td>
<td>0.030</td>
<td>0.043</td>
</tr>
<tr>
<td>2</td>
<td>19/152</td>
<td>185</td>
<td>945</td>
<td>6.0</td>
<td>0.020</td>
<td>0.006</td>
</tr>
<tr>
<td>3</td>
<td>19/153</td>
<td>82</td>
<td>734</td>
<td>3.0</td>
<td>0.061</td>
<td>0.057</td>
</tr>
<tr>
<td>4</td>
<td>19/153</td>
<td>94</td>
<td>734</td>
<td>3.5</td>
<td>0.050</td>
<td>0.041</td>
</tr>
<tr>
<td>5</td>
<td>19/153</td>
<td>111</td>
<td>734</td>
<td>4.1</td>
<td>0.036</td>
<td>0.022</td>
</tr>
<tr>
<td>6</td>
<td>19/153</td>
<td>132</td>
<td>734</td>
<td>4.9</td>
<td>0.027</td>
<td>0.012</td>
</tr>
</tbody>
</table>

It is clear from Fig. 2 that particle velocity reaches from zero to peak and then reduces. As distance increases, PPV decreases. In Table 2, for nearly same scaled distance 3.1m/test no. 152 and 3.0m/test no. 153, PPV observed at site is 0.030 m/s and 0.061 m/s respectively. This shows PPV variation of 100% for same granite site with two different tests. Similar observation is seen for other scaled distances. This shows large variability of experimental results.

8 PARAMETRIC STUDY FOR CALIBRATION OF FLAC³D SIMULATION

Mesh size is varied beyond elements at distances more than 16m from blast point. It is observed that as y-dimension of element increases, the PPV value decreases. Young’s modulus, Poisson’s ratio, run time
and time step are also varied. It is observed that the effects of variations of these parameters on PPV are not significant. Effects of various parameters on PPV in FLAC\textsuperscript{3D} are studied. Hence, optimum size of mesh should be selected. Mesh size plays important role in modelling blast wave propagation. Drucker Prager model and Mohr Coulomb model have been fixed and mesh size of model has been varied. It is observed from Table 5 that mesh size of 1x1x1 m gives best correlation with field value. Hence, mesh size of 1x1x1 m will be adopted in further Soil-structure modelling under blast loading.

### 8.3 Young’s modulus and Poisson’s ratio

Effects of Young’s modulus and Poisson’s ratio are studied and it is found that PPV decreases with increase in Young’s modulus, $E$ and PPV increases with increase in Poisson’s ratio. Effects of time step is also studied and it is found that as time step increases, there is no clear trend of increase/decrease. Initially, PPV decreases and then it increases.

### 9 CONCLUSIONS

Modelling of shock wave propagation in rock has been done with FLAC\textsuperscript{3D} to calibrate the model for further carrying out rock-structure interaction modelling. Peak pressure is applied at the crater using the PPV model developed by the authors. Mohr-Coulomb model has been found to give best correlations with the field data. The effects of mesh size, Young’s modulus, Poisson’s ratio and time step on FLAC simulation were also presented. The mesh size of 1x1x1 m gives best correlations with the field value. It is found that PPV decreases with increase in Young’s modulus, $E$ and PPV increases with increase in Poisson’s ratio. It is also found that as time step increases, there is no clear trend of increase/decrease. Initially, PPV decreases and then it increases.

### REFERENCES