NUMERICAL AND EXPERIMENTAL STUDIES ON ROCK PRESPLITTING[①]

Ding Dexin
Department of Mining Engineering,
Central-South Institute of Technology, Hengyang 421001, P. R. China
Reddish D J and Lloyd P W
University of Nottingham, Nottingham NG7 2RD, England

ABSTRACT On the basis of the theory that quasistatic pressure resulted from the detonation generated gases plays a major role in the mechanism of rock presplitting, Fast Lagrangian Analysis of Continua (FLAC) was employed to predict the appropriate quasistatic pressure for generating a presplit in a presplit blast under a given set of conditions and investigate the influence of detonation sequences on the predicted pressure. The simulation results showed that when the quasistatic pressure in each blast-hole was appropriate, tensile failure would occur along the line connecting the centres of the blast-holes and a presplit would be formed, and that the detonation sequences did not have significant influence on the appropriate quasistatic pressure. In order to obtain this pressure, a formula was derived to estimate the amount of explosive for each blast-hole. Furthermore, field experiments were carried out, and the test results demonstrated that they are consistent with the numerical simulation results and the numerical simulation method, therefore, is very effective in modeling rock presplitting, and that the suggested formula could be used to estimate the amount of explosive for each blast-hole on the predicted quasistatic pressure.

Key words FLAC numerical simulation rock presplitting

1 INTRODUCTION

An accurate blasted rock contour is particularly important not only in the high wall of a surface mining operation but also in dams, highway cuts and building foundations. Presplitting is one of the techniques of controlled blasting which could be employed to keep the natural strength of rock intact so as to avoid rockfall and/or post-blast maintenance work.

Many theories have been suggested during the past years to describe the mechanism of rock presplitting by blasting. Some of them are based on the interaction of the explosion-induced stress waves, whereas others rely on the combined action of stress waves and the quasistatic pressure generated by gas energy or on the quasistatic pressure.

Pain R S *et al*[1] have explained the creation of the presplitting in the following manner. When two adjacent charges in blast-holes are detonated simultaneously, the two peak stress waves generated by them will advance towards each other and meet at the point in the middle of the line connecting the centres of the two blast-holes. If the tangential stress at that point is stronger than the dynamic tensile strength of the rock, fracturing will take place at that point. Similarly, other stress waves coming from the opposite directions will help the fracture to grow and to connect between the two blast-holes. It is clear that the key requirement of this theory is the necessity for the simultaneous detonation of the two adjacent charges. In practice, however, it is very difficult to achieve this. Consequently, the two peak stress waves do not meet each other between the blast-holes. So far, there have been no reported experimental results which confirm the phenomenon described by them.

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Johansson C H, Persson P A[2] and Langefors U, Kihlstrom B[3] have believed that stress waves initially produce radial cracks around the blast-hole, then the high pressure hot gas enters the cracks causing them to extend further. However, this theory can not explain why there appears only one crack connecting the centres of the blast-holes in a presplit blast.

Sen G C and Ding Dexin[4, 5] have assumed that the quasistatic pressure plays an important role in the mechanism of rock presplitting. When charges are detonated, whether they are detonated simultaneously or not, the stress fields generated by quasisatic pressure resulted from the hot gases will interact to induce the circumferential tensile stress fields around the blast-holes. The circumferential tensile stresses at the points both on the walls of the blast-holes and on the line connecting their centres will first surpass the dynamic tensile strength of the rock. As a result, fracturing occures at these points. Then, the high pressure hot gases enter the fractures and make them connect between the holes. Furthermore, this theory has been verified with experiments.

The authors believe that quasistatic pressure is the driving force for generating a presplit in a presplit blast. Therefore, the present work is to use numerical modeling to predict, on the condition of simultaneous detonation, the appropriate quasistatic pressure for generating a presplit under a given set of conditions, investigate the influence of the detonation sequences on the predicted quasistatic pressure and check the validity of the simulation results.

2 NUMERICAL SIMULATION

The numerical simulation was conducted with the Fast Lagrangian Analysis of Continua (FLAC). FLAC is a very powerful finite difference program for solving rock and soil mechanics problems and has found wide application in civil and mining engineering all over the world[6, 7].

2.1 Model configuration

A plane strain finite difference model was constructed to simulate the rock presplitting at Shuangfeng marble quarry in Hunan Province. The model was 2 m in length by 2 m in width, and a hinge boundary was assumed along all sides of the grid. Three blast-holes were taken into account in the model, and they were 0.04 m in diameter and 0.4m apart. The model was discritized into 100 × 100 grids. A part of the mesh is illustrated in Fig. 1.

2.2 Model input parameters

The marble rock mass at the quarry has the following physical, deformation and strength parameters:

density, $\rho = 2\,850\ \mathrm{kg/m^3}$;

modulus of elasticity, $E = 19.5$ GPa;

Poisson's ratio, $\mu = 0.29$;

uniaxial tensile strength, $S_t = 6$ MPa;

uniaxial compressive strength, $S_c = 65$ MPa;

cohesion, $c = 1.19$ MPa;

internal frictional angle, $\varphi = 37.76°$

The initial stresses in the model are as follows:

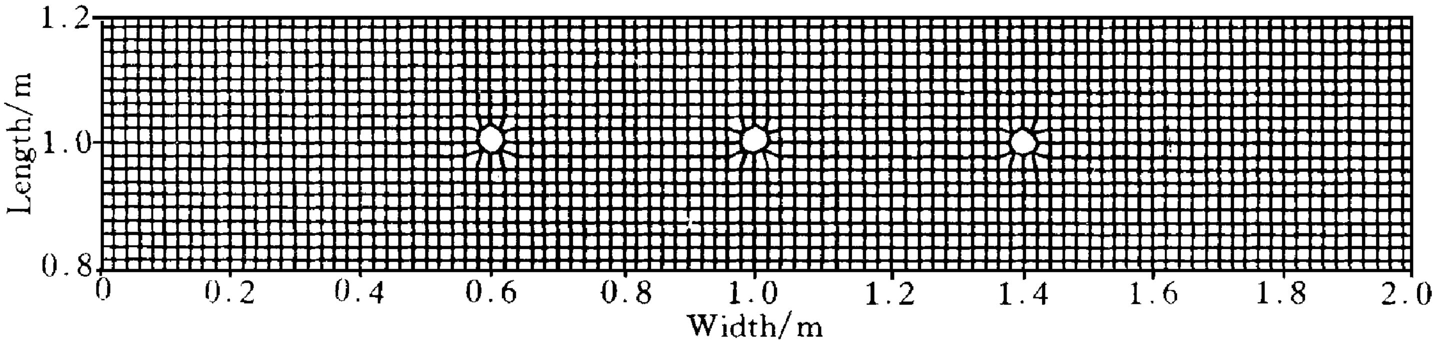

Fig. 1 A part of the mesh for simulating rock presplitting

σ_{π}= 1.221 × 10^4 Pa;

σ_y= 1.221 × 10^4 Pa;

σ_z= 2.85 × 10^4 Pa.

These stresses were determined from the initial stress state on the bottom plane of the blast-holes before they were drilled.

2.3 Simulation results

(1) Three charges were detonated simultaneously

In this case, three charges in the model were detonated without any time difference. In order to determine the appropriate quasistatic pressure for generating a presplit under the given set of the conditions, four different levels of quasistatic pressure (45 MPa, 50 MPa, 55 MPa and 60 MPa) were applied inside the blast-holes in the model respectively. Four kinds of failure states under these levels of quasistatic pressure were obtained. These numerical simulation results indicated that neither too low nor too high quasistatic pressure could result in an ideal presplit, and that, only when the quasistatic pressure was 55 MPa, did tensile failure occur along the line connecting the centres of the blast-holes and would an ideal presplit be created. This implies that there is an appropriate level of quasistatic pressure for generating a presplit under a given set of conditions. The failure state of the model for the quasistatic pressure of 55 MPa is illustrated in Fig. 2.

(2) Three charges were not detonated simultaneously

The above mentioned simulation results showed that, if all the charges were detonated simultaneously and when the explosion-induced quasistatic pressure in each blast-hole was 55 MPa, a satisfactory presplit would be formed. However, it is very difficult to accomplish simultaneous detonation in practice. Therefore, in this simulation, the main purpose is to investigate the influence of the detonation sequences on the predicted quasistatic pressure. The simulation was conducted on the following four application sequences.

Sequence Ⅰ: the hole in the left was first detonated the hole in the middle second and the hole in the right last.

Sequence Ⅱ: the hole in the middle was first detonated, the hole in the left second and the hole in the right last.

Sequence Ⅲ: the hole in the right was first detonated and the rest second.

Sequence Ⅳ: the hole in the middle was first detonated and the rest second.

The simulation results showed that, even though the application sequences were different, the failure states for them were quite similar. This indicates that detonation sequences do not have significant influence on the obtained appropriate quasistatic pressure for generating a presplit. The failure state of the model for sequence Ⅰ is illustrated in Fig. 3.

3 ESTIMATION OF AMOUNT OF EXPLOSIVE FOR EACH BLAST-HOLE

In order to acquire the predicted quasistatic pressure, the amount of explosive for each blast-hole had to be estimated. The estimation was made in the following way[8-10].

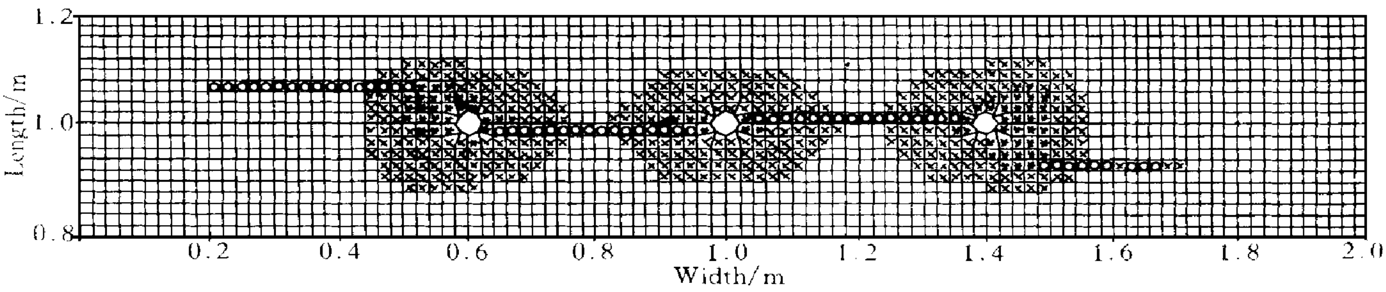

Fig. 2 Failure state of the model (quasistatic pressure= 55 MPa)

Plasticity Indicator: * —At yield in shear or volume; × —Elastic, at yield in past; ○—At yield in tension

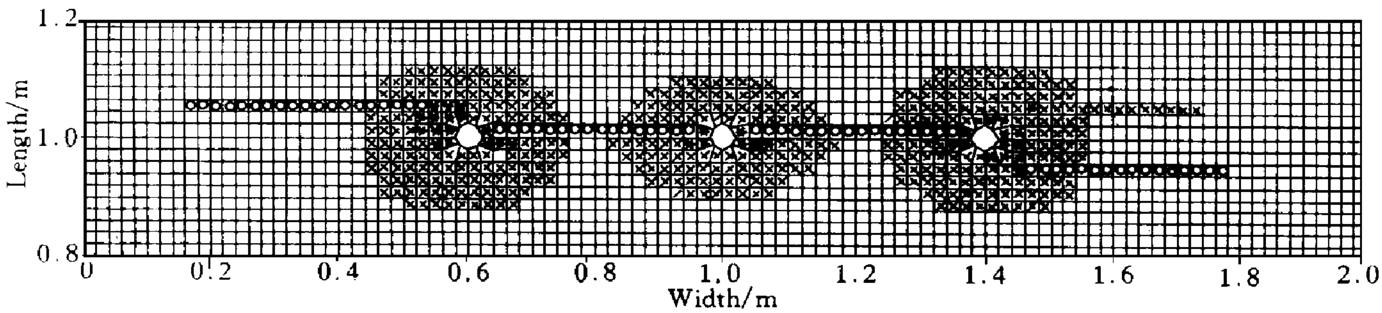

Fig. 3 Failure state of the model for sequence Ⅰ
Plasticity Indicator: * —At yield in shear or volume;
× —Elastic, at yield in past; ○—At yield in tension

Firstly, the gas pressure was calculated from the following:

$$p_g = \frac{\rho D^2}{2(K+1)} \quad (1)$$

where p_g is the gas pressure generated by a detonating charge in Pa; ρ, the density of the explosive in kg/m^3; D, the detonating velocity in m/s; K, the equivalent entropy coefficient of the explosive (typically 2).

Secondly, the quasistatic pressure was calculated from the following:

$$p = p_c\left(\frac{p_g}{p_c}\right)^{v/k}\left(\frac{\Delta}{\rho}\right)^v \quad (2)$$

$$\Delta = \frac{4Q}{\pi d^2 H} \quad (3)$$

where p is the quasistatic pressure in Pa; v, the gas expansion coefficient without any heat exchange (usually 1.4); p_c, the critical pressure in Pa generated by the detonation of the explosive in a blast-hole (generally 2×10^9 Pa); Δ, the volume density of explosive in a blast-hole; Q, the weight of explosive loaded in a blast-hole in kg; H, the depth of the blast-hole in m; d, the diameter of the hole in m.

Finally, the formula for calculating the amount of explosive for each blast-hole on the predicted quasistatic pressure was derived as follows:

$$Q = \frac{\pi}{4}\left[\frac{p}{p_c}\left(\frac{2(k+1)p_c}{\rho D^2}\right)^{v/k}\right]^{1/v}\rho H d^2 \quad (4)$$

4 EXPERIMENTS

Five tests were carried out at the marble quarry. Each test consisted of five vertical blast-holes. The properties of the marble rock mass have been described above. The explosive used was the No. 2 explosive for rock blasting, whose properties are listed in Table 1.

Table 1 Properties of No. 2 explosive for rock blasting

Density/(g·cm^{-3})	Detonating velocity/(m·s^{-1})
1.00	3000

The amount of explosive for each blast-hole was estimated by employing Eqn. (4). It was fabricated to a cartridge which was 20 mm in diameter and 300 mm in length, and a decoupling coefficient of Eqn. (2) was obtained.

An electric detonating system was employed. In order to achieve simultaneous detonation, all the detonators were instantaneous ones.

After each hole was loaded, it was stemmed. The test results are listed in Table 2. As can be seen from Table 2, No. 3 test did not produce a complete presplit. After careful investigation, it was found that the poor stemming caused this to happen. In fact, the stemming mud was pushed out of some blast-holes by blast.

5 CONCLUSIONS

The following conclusions have been obtained through the numerical and experimental studies.

(1) FLAC can be used to simulate rock

Table 2 Field test results

No. of test	Dia. of the hole/ m	Depth of the hole/ m	Spacing of the hole/ m	The amount of explosive per hole/ g	Results
1	0.04	1	0.4		A presplit was formed
2	0.04	1	0.4		A presplit was formed
3	0.04	1	0.4	95	Partial presplit was formed
4	0.04	1	0.4		A presplit was formed
5	0.04	1	0.4		A presplit was formed

presplitting. For a given set of conditions, it can be used to predict the proper quasistatic pressure for creating a complete presplit in a presplit blast.

(2) For the given set of conditions in this research, the quasistatic pressure for generating a presplit is predicted to be 55 MPa.

(3) The detonation sequences do not have significant influence on the predicted quasistatic pressure.

(4) The suggested formula can be used to calculate the amount of explosive for each blast-hole on the predicted quasistatic pressure. For this research, the amount of explosive for each blast-hole is estimated to be 95 grams.

(5) The field experiment results are consistent with the above conclusions.

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