CRACK INTERACTION MECHANISM OF PRE-SPLIT ROCK BLASTING

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ABSTRACT

The paper investigates and models the mechanism of pre-split cutting, a technique used in excavations in hard rock and based on creating large splits by simultaneous blasting or slow pressurising of closely placed holes. Only the case of initially intact rock (no discontinuities comparable with the dimension of pre-split fracture) is considered. The critical spacing between the holes is found separating the case of splitting from the case of bulk fracturing of the rock. The determination of the critical spacing is based on the comparison between the hole pressure required to start the pre-existing cracks with the pressure required to bring the cracks to the length at which the interaction between them will make their propagation unstable. If the initial cracks are relatively large such that the pressure of the crack start is less than the pressure of unstable growth, other cracks will appear fracturing the bulk of material. If the initial cracks are small enough, the starting pressure will be high, hence the cracks will propagate dynamically until the coalescence with the neighbours, which produces splitting. For the case of pre-splitting prepared parallel to a free boundary, the influence of the latter is minor, so the dominant mechanism of pre-splitting is the crack interaction.

INTRODUCTION

Pre-split or smooth blasting is used to produce a fine cut surface in hard rock by simultaneous blasting of usually small, closely placed blastholes, e.g., [1-4]. Currently the parameters of this method are chosen based on experience or physical modelling on rock samples or artificial materials, e.g.,[1], [5], rather than on an understanding of the fracture mechanics. A common belief in analysing this technology is that the splitting cracks are driven by gases penetrating into the crack.

Both the formation of the pre-split fracture and the rock damage near the blastholes are processes based on crack formation. The damage in this case mainly consists of radial cracks growing from the blastholes well beyond the initial crushed zone (e.g., [1], [6]). Therefore, it is necessary to address the fracture mechanics of the process in order to be able to optimise the technological parameters. The present paper attempts to investigate and model the fracture mechanics of pre-splitting in initially intact rocks when no discontinuities (comparable with the dimension of pre-split fracture) are present. The pressure holes will be assumed to be aligned. The aim is to determine the critical spacing between the pressure holes separating the case of splitting formation from the case of bulk fracturing of the material.

Since the pre-splitting occurs through the formation of fractures connecting the holes, it is natural to base the investigation of its mechanism on the consideration of crack growth form the pressurised holes. Following [6] the consideration will be quasi-static i.e. based on the equations of static fracture mechanics. This will provide a simple and reasonable approximation for the extent of crack growth. Also, this static modelling is important *per se*, since it is relevant to fracturing using the non-explosive rock breaking systems, e.g., [7].

An example of such a system is given by the expanding grout in which case the pre-splitting is formed slowly, over a few weeks time, e.g., [3].

MECHANISM OF FORMATION OF THE SPLITTING FRACTURE

Let a chain of holes of equal radius, r, be drilled at an equal distance, d, along a line. Each hole is subjected to internal pressure p. The influence of the in-situ stress will be neglected at this stage.

In the case of a single hole, the pressurising will create cracks initiating from pre-existing flaws near the hole surface and growing from the surface in different directions. When the influence of remote stress field is neglected, the only mechanism of the preferential direction of the crack growth and the formation of a single splitting fracture can be the interaction between the holes in the chain. It is also natural to assume that the formation of the splitting fracture is caused by the coalescence of cracks growing toward each other from the adjacent holes. The coalescence will occur in the form of overlapping due to the tendency of the tensile cracks to avoid each other [8]. This is consistent with the results of physical modelling of the pre-split blasting, e.g., [1].

Consider the case when the distance between the holes is considerably greater than their radius, $d \gg r$. Then the cracks forming the splitting fracture have to grow at the length much greater than the hole radius. Therefore, in order to investigate the crack interaction, the hole with collinear cracks will be modelled in 2-D as a single crack opened by a pair of concentrated forces at its centre. The magnitude of these forces will be taken equal to the force per unit length of the hole (in the direction perpendicular to the drawing) created by the internal pressure on the upper/lower half of the hole. This allows the following approximation for the mode I stress intensity factor (e.g., [9]):

$$K_I = \frac{P}{\sqrt{\pi l}}, \quad P = p\int_0^{\pi} r \sin\varphi d\varphi = 2pr \,, \tag{1}$$

The influence of the gas flow into the crack is neglected.

Figure 1 demonstrates the accuracy of such a modelling by comparison of the approximation presented by Eqn 1 with the numerical solution for two radial crack emanating from the hole [9]. It is seen that as long as the cracks become greater than the hole radius (l>2r) the representation becomes quite accurate. Therefore, this approximation is sufficient for the purpose of the present analysis. It is also seen that the growth of small cracks is unstable. It however becomes stable when the length of the sprouted cracks reaches half of the hole radius (l>1.5r). This approximation facilitates the analysis of the interaction of cracks originated from holes arranged in a periodical chain modelling pre-split blasting.

The modelling of crack interaction will be based upon the consideration of a periodic array of equally inclined cracks loaded by concentrated forces at their centres. The consideration of inclined cracks in the chain is necessary since the cracks from the holes can in principle, be initiated at arbitrary angle. The influence of a free surface is to be taken into account if the holes were drilled close to the surface. Thus the general problem to be considered can be formulated for the half-plane containing the array of parallel cracks as it is shown in the Figure 2. The following notations are in use: l is half length of the cracks, d is spacing between the centres of cracks, h is distance from the crack centre to the boundary of semi-plane and α is crack inclination to the boundary.

The problem has been reduced to solving the singular integral equation of a certain form [10] with respect to the density of the displacement discontinuity across the cracks. The solutions of the integral equations for both cases of periodical arrays in the plane and semi-plane have been found by the numerical method [11]. All calculations have been performed using the package MATHCAD 6PLUS. In the case of collinear cracks (α=0°) in entire plane, calculated K_I coincide with analytical results [9]. For parallel cracks (α=90°) K_I is in good agreement with an approximate analytical solution obtained in [10].

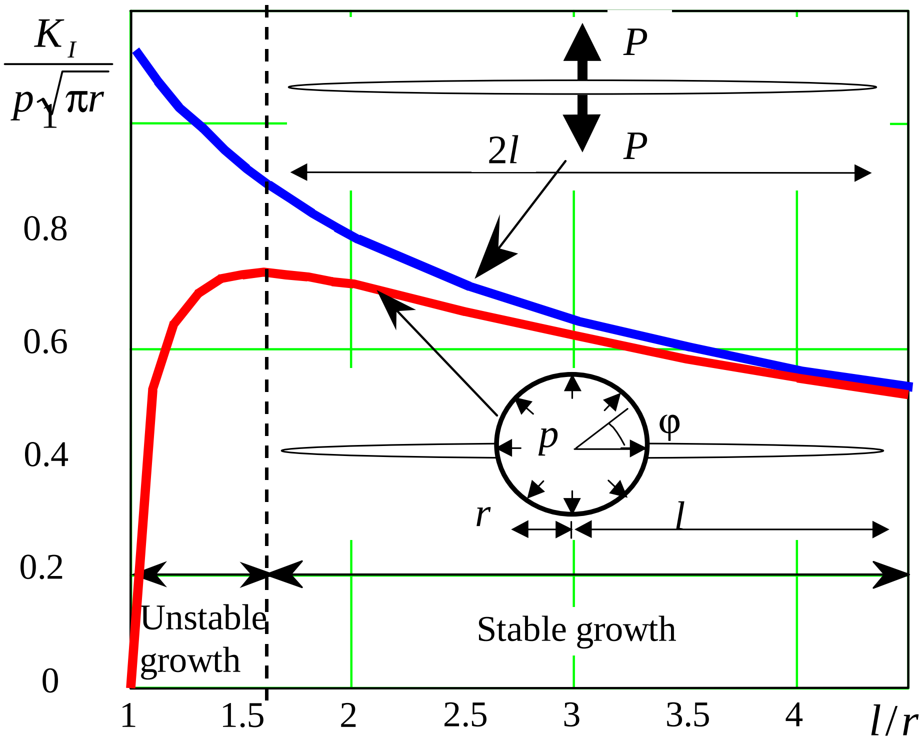

Figure 1. Comparison of the mode I stress intensity factor for radial cracks sprouted from the hole and for the approximation.

First the results for the entire plane will be discussed ($l<<h$, $d<<h$). The results of the calculations for K_I are shown in Figure 3. It is seen that for shallow crack inclinations there are points of minimum of K_I. A similar situation exists for the plots of the energy release rates. Therefore, regardless of the criterion of crack propagation the following conclusion can be made. Before the point of minimum of K_I, the crack growth is stable, that is every step of the crack elongation requires an increase in the load. After the point of minimum, the growth becomes unstable (dynamic), i.e., the crack elongation can be sustained even under decreasing load. Obviously, the existence of the regions of unstable crack growth underpins the mechanism of the splitting fracture formation.

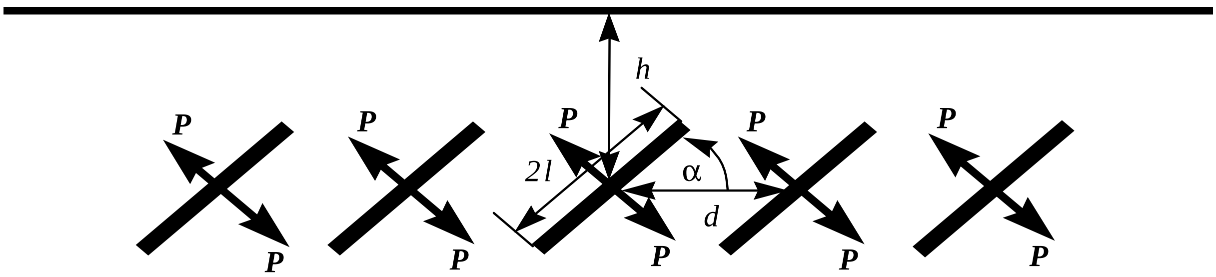

Figure 2. Periodic array of inclined cracks.

Another role the interaction plays is in straightening the crack trajectory. Indeed, regardless of the initial angle of crack inclinations, the mode II stress intensity factor is positive at the right tips of the cracks, Figure 4. This will turn the crack trajectories towards the array axis thus reducing the deviation form the collinear arrangement. Subsequently, the growth of interacting cracks ends up in forming the splitting fracture connecting the hole centres. Hence, the formation of the straight splitting fracture is a result of the interaction rather than the action of the *in-situ* compression directed parallel to the row of holes, as believed (e.g., [2]).

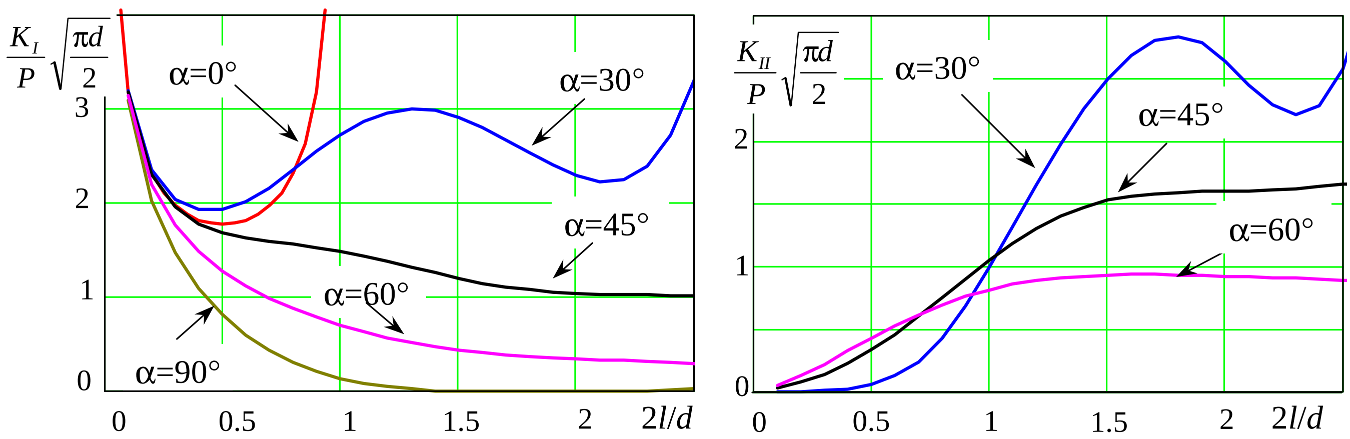

Figure 3. Normalised mode I and II stress intensity factors vs. length for different crack inclinations.

The presence of the second mode of the stress concentration requires the choice of a crack propagation criterion. It should be noted however, that for the purpose of the present analysis it suffices to concentrate only on the points separating the regions of stable and unstable crack propagation. In order to investigate whether the required qualitative analysis is sensitive to the choice of a particular criterion, it is shown in Figure 4 the dependence of the normalised energy release rate, $U=(K_I^2+K_{II}^2)Pd/2\pi^2$. Comparison with Figure 3 shows that both mode I stress intensity factor and the energy release rate produce the same regions of stable and unstable crack growth. For the further analysis, the criterion of crack propagation based on the mode I stress intensity factor is chosen $K_I=K_{ic}$, where K_{Ic} is the fracture toughness of the rock.

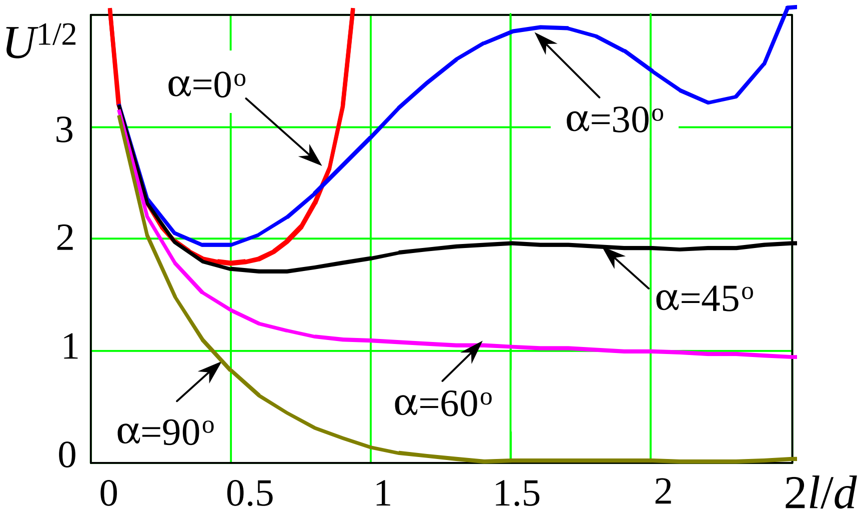

Figure 4. Normalised energy release rate vs. length for different crack inclinations.

For collinear cracks the expression for the stress intensity factor [9] and the derived expressions for the crack length, l_{cr}, and the stress intensity factor, $K_{I\min}$ at the point of minimum have the form

$$K_I = P\left(\frac{d}{2}\sin\frac{2\pi l}{d}\right)^{-1/2}, \quad l_{cr} = \frac{d}{4}, \quad K_{I,\min} = P\left(\frac{d}{2}\right)^{-1/2} \tag{2}$$

Using Eqn 1, one finds the pressure, p_f required to reach the unstable crack propagation and therefore the formation of the splitting fracture

$$p_f = \frac{K_{Ic}}{2r}\sqrt{\frac{d}{2}} \tag{3}$$

THE CRITERION OF SPLITTING

When a row of holes is pressurised two mechanisms are in competition. One of them is the formation of splitting fracture; this requires pressure p_f. Another mechanism is the growth of radial cracks from the hole contour. Let the pressure required to start the growth of a pre-existing surface flaw of length a_0 be p_{crack}. Obviously, if $p_{crack}<p_f$, the radial cracks will grow without formation of the splitting fracture. Thus the criterion of the transition from the radial cracks to the splitting fracture is $p_{crack}=p_f$.

To find p_{crack} one can consider a single hole with a radial flaw of length $a_0<<r$. The stress intensity factor is given by the following approximate formula [9] $K_I \approx 1.122 p_{crack}\sqrt{\pi a_0}$. The substitution of this into the criterion of crack propagation yields the value for p_{crack}. Then the criterion $p_{crack}=p_f$ gives the critical value for the distance between the holes

$$d_{cr}\approx 6.35 r^2(\pi a_0)^{-1} \qquad (4)$$

When the distance between the holes, $d<d_{cr}$, the splitting fracture will be formed, otherwise the radial cracks will grow and break the bulk of the material. It is interesting that the critical distance is inversely proportional to the size of initial flaws. This implies that the smoother (less damaged) the hole surface the higher the critical distance.

The critical pressure necessary to produce the splitting fracture from the holes placed at the critical distance can be obtained by substituting Eqn 4 into the criterion $K_I=K_{Ic}$, which gives $p_{cr}\approx 0.891 K_{Ic} r^2(\pi a_0)^{-1/2}$. The critical pressure does not depend on the radius of the holes. It is not surprising since p_{cr} is the pressure that is required to start a small crack at the hole contour (the distance between the holes is such that the interaction immediately promotes the small crack into a splitting fracture). Since the initial crack is much smaller than the hole radius, this pressure is practically independent of the hole radius.

When the applied pressure p_{appl} is less than the critical one then one has to reduce the spacing in order to ensure the splitting fracture formation. The necessary spacing is the one which ensures the crack growth under the given pressure to the distance sufficient for the interaction to make their growth unstable. The required crack half-length is $l=d/4$. Substituting this into the first equation from Eqn 2 and then into the criterion of crack propagation one has $d_{cr}=8(pr)^2 K_{Ic}^{-2}$.

THE INFLUENCE OF FREE SURFACE

In real situations the pre-splitting is performed parallel to an existing free surface, formed for instance at the previous stage of excavating. The presence of the free surface alone can make the growth of a single crack loaded at is centre unstable (e.g., [11]), that is why it is necessary to investigate its effect for the case under consideration. It should be taken into account that the action of the free surface is combined with the interaction of cracks in the chain.

Figure 5 shows the Mode I stress intensity factors for collinear cracks in semi-plane for different distances from the free boundary. For comparison, the Figure also presents the cases of collinear crack array in a plane and a single crack in a semi-plane. It is seen that for the distances from the free surface equal to the distance between the crack centres the values of the stress intensity factor coincide with the ones for collinear crack array in a plane. Also, for this distance, the crack length from which the unstable growth starts (the point of minimum of the stress intensity factor) is smaller than in the case of a single crack. Therefore, for practically interesting cases of the spacings between the pressure holes smaller than the distance from the boundary, the influence of the boundary on the Mode I stress intensity factor is minor.

Another role the free surface my play is in creating the Mode II stress concentrations which are potentially able to direct the cracks towards the surface (e.g., [12]) preventing the formation of the pre-split fracture. Figure 6 however shows that for the spacings smaller than the distance from the boundary the values of the Mode II stress intensity factors induced by the interaction with the free surface are negligible.

The above considerations lead to the conclusion that for practically interesting cases of the distances between the pressure holes smaller than the distance from the boundary the influence of the boundary on the pre-split fracture formation can be neglected. This conclusion is supported by the practical experience, e.g. [1]. Therefore, the results of the previous section can still be used for computing the spacing between the holes.

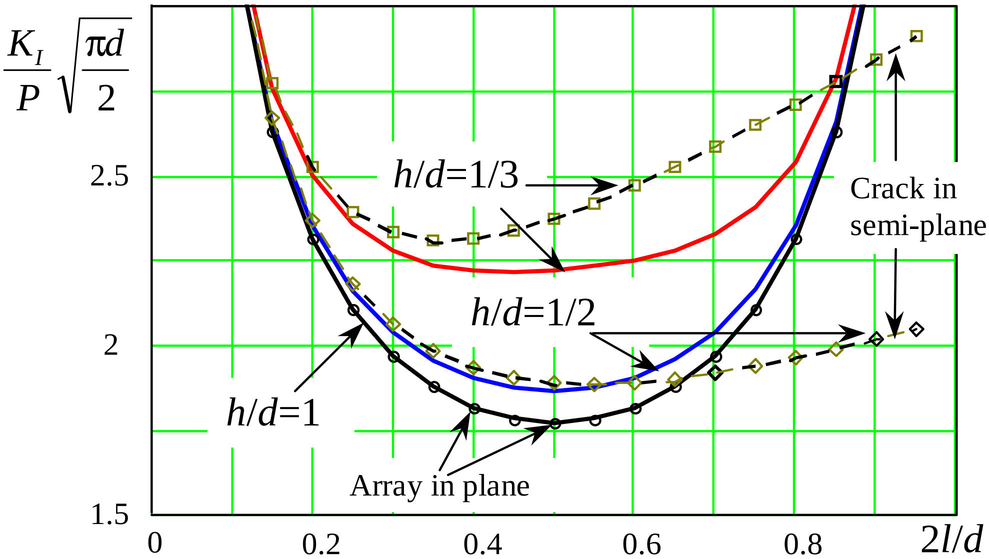

Figure 5. Mode I stress intensity factor for collinear cracks in semi-plane vs. crack length (solid lines) for different distances to the boundary. For comparison, data points show the case of collinear cracks in plane (circles) and for a single crack in semi-plane (boxes and diamonds).

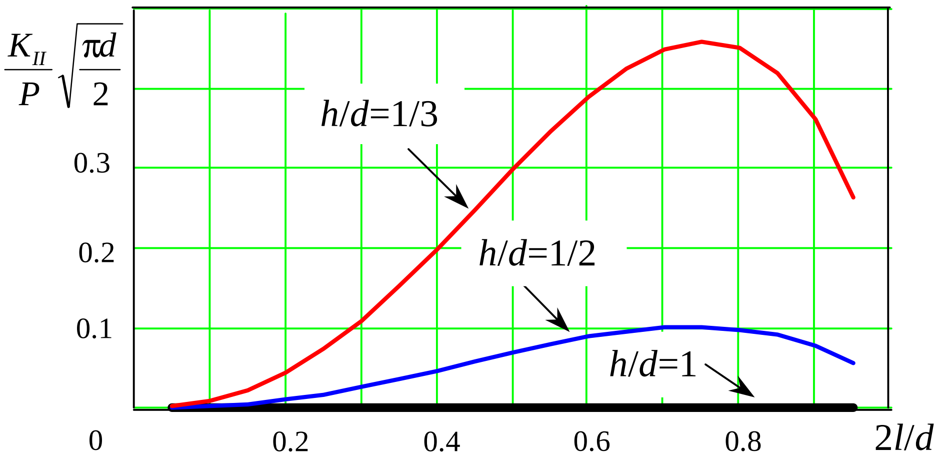

Figure 6. Mode II stress intensity factor for collinear cracks in semi-plane vs. crack length.

THE INFLUENCE OF *IN-SITU* PRESSURE ACTING NORMAL TO THE SPLITTING

In-situ pressure in the direction perpendicular the hole line will hamper the crack growth necessitating a reduction in the spacing necessary to produce the splitting fracture. The aim of this section is to investigate this effect and determine the required reduction in the spacing. The case of the absence of a free boundary will be investigated first, then the influence of the boundary will be considered.

Let q be the magnitude of the *in-situ* pressure in the direction perpendicular the hole line. For the crack length $2l$ taking into account Eqn 1 one has for the mode I stress intensity factor [9]:

$$K_I = 2rp\left(\frac{d}{2}\sin\frac{2\pi l}{d}\right)^{-1/2} - q\left(d\tan\frac{\pi l}{d}\right)^{-1/2} \tag{5}$$

Figure 7 shows this dependence for different values of dimensionless pressure $\lambda = qd(2pr)^{-1}$. It is seen that as the confining pressure increases the crack length starting from which the cracks grow unstable (small circles on the plots) increases tending to $d/2$, i.e. to the length at which they geometrically reach each other.

The crack length of the onset of unstable crack growth, l_{cr}, i.e. the point of minimum of the curves from Figure 7, is determined from the equation $dK_I/dl=0$. After differentiating Eqn 5 and substituting λ one has the following equation $\lambda\sin(\pi l_{cr}/d)+\cos(2\pi l_{cr}/d)=0$. From here and from Eqn 5, the value of the stress intensity factor at $l=l_{cr}$ can be obtained:

$$K_I\frac{\sqrt{d}}{2rp}=\frac{\left[4-\lambda\left(\lambda+\sqrt{\lambda^2+8}\right)\right]^{3/4}}{2^{1/4}\sqrt{\lambda+\sqrt{\lambda^2+8}}} \tag{6}$$

After using the criterion of crack growth, Eqn 6 becomes the equation for the determination of the pressure p_f of the splitting fracture formation. Then, after using the criterion $p_{crack}=p_f$ with p_{crack} determined from the $K_I\approx 1.122\,p_{crack}\sqrt{\pi a_0}$, one has the following equation for determining the critical (maximal) spacing between the holes yet allowing the splitting fracture formation

$$\frac{a_0}{r^2}d_{cr}=\frac{2.247}{\pi}\frac{\left[4-\lambda\left(\lambda+\sqrt{\lambda^2+8}\right)\right]^{3/2}}{\lambda+\sqrt{\lambda^2+8}},\qquad \lambda=\frac{qd_{cr}}{2p_{cr}r},\qquad p_{cr}=\frac{K_{Ic}}{1.122\sqrt{\pi a_0}} \tag{7}$$

where a_0 is the length of initial (pre-existing) flaws.

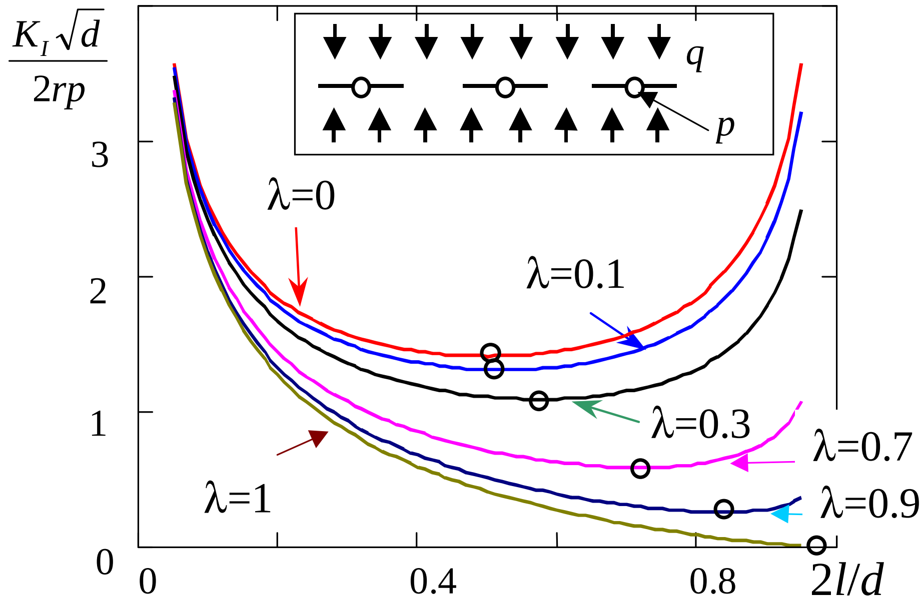

Figure 7. Mode I stress intensity factor for collinear cracks in plane under confining pressure for different values of the dimensionless confining pressure. The small circles mark the onset of unstable crack growth.

Figure 8 shows that the critical spacing reduces significantly as the *in situ* pressure increases.

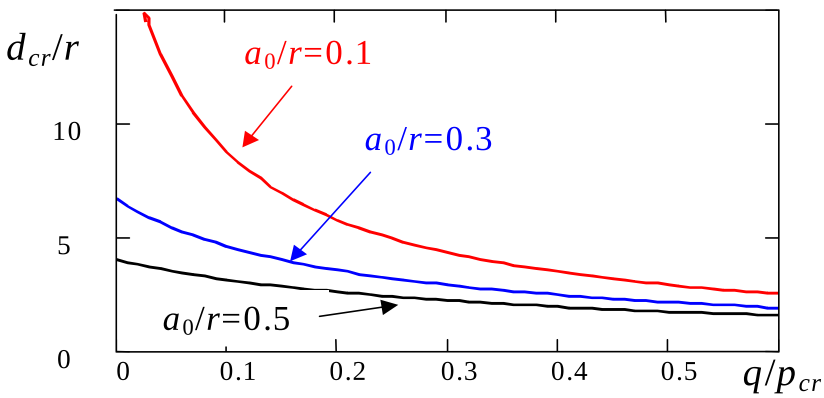

Figure 8. Critical spacing between the pressure holes under different values of confining pressures.

CONCLUSIONS

Critical spacing of the splitting fracture formation is determined by equating the pressure in the hole required to start the pre-existing cracks to the pressure required to drive the cracks to the length at which the interaction between cracks makes their propagation unstable. If the initial cracks are relatively large such that the pressure of the crack start is less than the pressure of unstable growth, other cracks will appear fracturing the bulk of material. If the initial cracks are small enough, the starting pressure will be high, hence the cracks will propagate dynamically until the coalescence with the neighbours, which produces splitting.

The analysis of the arrays of cracks at different inclinations has shown that the interaction create tendency to straighten the trajectories of growth of initially inclined cracks. Also the criterion of unstable crack propagation is not very sensitive to the crack inclination. These finding permitted a simplified analysis of the effects of interaction based on the model of collinear cracks. The considered mechanism is insensitive to moderate values of *in-situ* pressure in the direction of pre-splitting. *In-situ* pressure perpendicular to the direction of pre-splitting considerably reduces the maximum admissible spacing between the pressure holes.

For the case of pre-splitting prepared parallel to a free boundary, the analysis shows that the influence of the free surface is minor. Therefore, the mechanism of pre-splitting in this case is also the crack interaction.

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