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VELOCITY ANOMALIES IN A CRACKED POROELASTIC REGION

M. D. SHARMA* AND T. N. SAINI**

**Department of Mathematics, Kurukshetra University, India* 136 119
***Govt College Kalka, Haryana, India*

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Elastic and dynamical parameters used in Biot's theory of wave propagation in poroelastic solids are modified for the introduction of cracks. The possible interconnection between cracks are also taken into account while modifying these parameters. During the process of stress accumulation, pores are assumed to be squeezing after draining their liquid to keep the cracks fully saturated. The effects of variations in crack density and increase in width of cracks on wave velocities are observed numerically. Variations in velocity ratio are also observed for different values of crack density, aspect ratio of cracks and for different regimes of connections between cracks. The velocity anomalies observed before an earthquake are linked with modifications in cracks. A hypothetical earthquake preparation process is suggested to explain these velocity anomalies.

Key Words : Crack Density; Aspect Ratio, Poroelastic, Precursor, Velocity Anomalies; Earthquake Prediction

INTRODUCTION

Recent studies suggest that there are liquids in distribution of cracks throughout at least top 10-20km of the crust. Every hydrocarbon field is also a reservoir of fluid filled cracks. Liquid is usually water but may be oil in hydrocarbon reservoirs. Existence of such cracks has wide implications for all dynamical processes in the crust. The effects of cracks on seismic waves are important since seismic experiments are one of the few geophysical techniques capable of examining the properties of rocks in the crust. It has applications to many currently important activities ranging from determining preferred direction of flow in hydrocarbon reservoirs to earthquake prediction.

Nersesov *et al.*[1] found that travel time ratio of shear and compressional waves varies prior to the occurrence of an earthquake in the Garm region of the then USSR. Nur[2] and Aggarwal *et al.*[3] explained the travel time variations prior to an earthquake in terms of the changes in dilatancy around the focal zone and saturation of dilatancy formed cracks. The wave velocities for the elastic solids containing dilute concentration of small cracks have been approximated by Garvin and Knopoff[4, 4a&b]. O'Connell and Budiansky[5] and Budiansky and O'Connell[6] calculated the effects of introduction of cracks on the elastic properties of an isotropic solid using self-consistent procedure. O'Connell and Budiansky[7] studied the viscoelastic properties of cracked solid and explained three separate regimes of connection between cracks. Attenuation of elastic waves in the cracked solids have been studied by Chatterjee *et al.*[8], Hudson[9] and Xu and King[10]. In recent years, Hudson[11] and Peacock and Hudson[12] studied the elastic properties of materials for different distributions of small cracks. Hudson[13] discussed the attenuation due to scattering in cracked materials.

For the last two decades Stuart Crampin is studying the effects of dilatancy formed cracks on the polarization of shear waves. Some of his important works are Crampin[14-17] and Crampin *et al*[18]. Crampin[16] suggested the widespread distribution of aligned water filled cracks in the top 10-20 km of the crust. According to him water enters into the pore space of sedimentary rocks when they are first deposited and attenuation of *S*-wave observed in the earth suggests that the cracks present in the crust are fully saturated. Following Crampin and Atkinson[19], healing processes may be comparatively fast whereas crack growth is extremely slow and only high pore fluid pressure can keep the cracks open. Cramping[17] explained that most direct effect of change of stress before an earthquake is the modifications of cracks present in and around the focal region. These modifications are common driving mechanism for the large variety of precursors observed before earthquakes.

The presence of internal cracks and pores in the crustal rocks have been recognized for some time. Recent important works also indicate the co-existence of water filled pores and cracks in the earth's crust and suggest a vital role of pore fluid in preparation and trigger of earthquakes. To define this co-existence Sharma[20] have modified the elastic and dynamical moduli of poroelastic solid, given by Biot[21 & 22] for introduction of isolated cracks. Surface wave propagation is also studied in such a medium.

In this paper author has made an attempt to define the elastic and dynamical parameters for a poroelastic medium containing a random distribution of fluid-filled cracks. Changes in wave velocities depending upon crack configuration are also studied. Velocity anomalies observed prior to an earthquake are linked with the modifications of cracks.

CRACKED ELASTIC SOLID

Studies discussed in previous section explain the modifications in elastic moduli and changes in wave velocities when small cracks were introduced in an elastic solid. Most of these studies assume very small value of crack density but O'Connell and Budiansky[5] assumes no restriction on the value of crack density but considers only random distribution of cracks. O'Connell and Budiansky[7] allows to consider interconnections between cracks.

In fact, the cracks in the earth are accepted to be vertically aligned and strictly isolated. A medium with such a distribution of cracks behaves anisotropic to wave propagation. According to Cramping and Atkinson[19], before an earthquake to occur, the local stresses may be large enough to promote crack growth sufficient to connect the micro cracks and permit water to flow into the region of greater dilatancy near the eventual fracture. Therefore, to consider the large values of crack density as well as interconnections between cracks, I preferred the effective elastic moduli derived by O'Connell and Budiansky[5]. They suggested elastic moduli derived by O'Connell and Budiansky[5]. They suggested that effects of cracks of any convex shape would be similar to those for circular cracks provided the crack density ε is expressed in terms of area and perimeter of the cracks. Therefore the results for circular cracks may be used for more general cases with negligible error.

Consider an elastic solid containing a random distribution of circular cracks ($\alpha = b >> c$) with very small aspect ratio c/α and saturated by a fluid of bulk modulus k_f. Elastic constants are modified according to the interconnection regime between the cracks. O'Connell and Budiansky[7] discussed three regimes of connections between cracks which are explained as follows.

a) *Saturated Isolated* — No fluid is able to flow out of (or into) any crack. Changes in fluid pressure due to application of external stress will be different in every crack. It represents a situation which arises for elastic waves of sufficiently high frequency. In such a situation moduli found are appropriate for stress changes that occur with sufficient rapidly to prevent communication of fluid pressure between the cracks. Following Budiansky and O'Connell[6], the elastic constants of the cracked solids are given by

$$\bar{k}/k = 1 - (16/9)\ \{(1-\bar{\nu}^2)/(1-2\bar{\nu})\}\ D\,\varepsilon \quad \text{... (1)}$$

and

$$\bar{\mu}/\mu = 1 - (32/45)\,(1-\bar{\nu})\ \{D + 3/(2-\bar{\nu})\}\ \varepsilon, \quad \text{... (2)}$$

where $k\,(=\lambda + 2\mu/3)$ is bulk modulus with λ and μ as Lame's constants. Poisson's ratio, ν, of the uncracked solid is $.5\lambda/(\lambda+\mu)$. The barred quantities represent corresponding elastic parameters for saturated cracked solid. Following Sharma[20], saturation prameter D is expressed in terms of elastic constants and crack density (ε) as

$$\varepsilon D\,(1-\bar{\nu}^2) = 45\,(\nu-\bar{\nu})/\{16(1+3\nu)\} + 2\varepsilon\,(1-2\nu)\,(1-\bar{\nu}^2)\;/\;\{(1+3\nu)\,(2-\bar{\nu})\}. \qquad \ldots (3)$$

Effective Poisson's ratio ($\bar{\nu}$) is computed numerically from

$$a_1\,\bar{\nu}^5 + a_2\,\bar{\nu}^4 + a_3\,\bar{\nu}^3 + a_4\,\bar{\nu}^2 + a_5\,\bar{\nu} + a_6 = 0, \qquad \ldots (4)$$

for given values of ε, ν and another saturation parameter Ω, defined by $\Omega = \frac{\alpha}{c}\,k_f/k$. The coefficients $a_j\,(j = 1, 2, \ldots, 6)$ are functions of ν, ε and Ω and are given by

$$a_1 = (1-2\nu)\,\varepsilon\;\{2\varepsilon'\,(1+3\nu)\} + (1+3\nu)\,(9\,\varepsilon/8 - 45\,\varepsilon'/16),$$

$$a_2 = (1-2\nu)\,\varepsilon\;\{4\varepsilon\,(1-2\nu) - 45/4 + (1+3\nu)\,(9/4 - 4\varepsilon') + 2025/256$$
$$+ (1+3\nu)\;\{45\,\varepsilon'\,(\nu+4)/16 - 405/128 - 81\,\varepsilon\,(1+3\nu)/16\},$$

$$a_3 = (1-2\nu)\,\varepsilon\;\{45\;(\nu+2)/4 + (1+3\nu)\,(-45/8 - 4\varepsilon')\} - 2025\;(\nu+2)/128$$
$$+ (1+3\nu)\;\{45\,\varepsilon'\,(3+4\nu)/16 + 405\,(9+2\nu)/256 + 45\varepsilon\,(1+3\nu)/8\},$$

$$a_4 = (1-2\nu)\,\varepsilon\;\{(1-2\nu)\,(-8\varepsilon + 45/4) + 8\,\varepsilon'\,(1+3\nu)\} + 2025\;(\nu^2 + 8\nu + 4)/256$$
$$+ (1+3\nu)\;\{-45\varepsilon'\,(4-3\nu)/16 - 1215\,(4+3\nu)/256 + 45\,\varepsilon\,(1+3\nu)/16\},$$

$$a_5 = (1-2\nu)\,\varepsilon\;\{-45\,(\nu+2)\;?\;4 + (1+3\nu)\,(45/8 + 2\varepsilon')\} - 2025\;\nu\,(\nu+2)/64$$
$$+ (1+3\nu)\;\{45\varepsilon'\,(1+\nu)/4 + (1+3\nu)\,(405/64 - 27\,\varepsilon/4)\}$$

and

$$a_6 = (1-2\nu)\,\varepsilon\,\{45\;\nu/2 + 4\varepsilon\,(1-2\nu) + (1+3\nu)\,(-9/4 - 4\varepsilon')\} + 2025\;\nu^2/64$$
$$+ (1+3\nu)\;\{-405\;\nu/64 - 45\;\nu\,\varepsilon'/4 + 9\varepsilon\,(1+\nu)/4\},$$

where

$$\varepsilon' = \varepsilon + 75\;\Omega/\pi.$$

For circular cracks (radius $=\alpha$), volume of a sample crack (thickness $= c$) is given by $\frac{4}{3}\,\pi\,\alpha^2\,c$. Crack porosity ($\beta_c$) measures the fraction of volume occupied by cracks and is related to crack density (ε) by

$$\beta_c = \frac{4}{3}\,\pi\,\frac{c}{\alpha}\,\varepsilon. \qquad \ldots (5)$$

The density of cracked solid ($\bar{\rho}$) is modified as

$$\bar{\rho} = (1 - \beta_c)\,\rho_s + \beta_c\,\rho_f, \qquad \dots (6)$$

where ρ_s denotes the density of solid in the absence of cracks and ρ_f is density of the fluid present in the cracks.

(*b*) *Saturated Isobaric* — All the cracks are in communication with each other but no fluid flow is permitted out of the bulk sample. Fluid pressure will be same in all the cracks. Effective Poisson's ratio ($\bar{\nu}$) is obtained from

$$\varepsilon = (45/16)\,(\nu - \bar{\nu})\,(2 - \bar{\nu})\,/\,\{(1 - \bar{\nu}^2)\,(10\,\nu - \bar{\nu} - 3\nu\,\bar{\nu})\}, \qquad \dots (7)$$

for given values of ν and ε. Effective elastic moduli are derived from the relations, given by

$$\bar{k}/k = 1 \qquad \dots (8)$$

$$\bar{\mu}/\mu = 1 - \{(32/45)\,(1 - \bar{\nu})\,(5 - \bar{\nu})/(2 - \bar{\nu})\}\,\varepsilon, \qquad \dots (9)$$

Density of the bulk material is given by (6).

c) *Drained* — The fluid in cracks is in communication with outside of sample. The saturated cracked solid will respond as if no fluid were there. The elastic behviour will be equivalent to the cracked solid with dry cracks. The effective Poisson's ratio ($\bar{\nu}$) is obtained from eq. (7). Using this value of $\bar{\nu}$, effective elastic moduli are obtained from (1) by substituting D = 1. Density is given by (6).

CRACKED POROELASTIC SOLID

Following Biot[23], in fluid saturated porous solids, velocities of propagation v_1, v_2, and v_3 of fast compressional (or p_f) wave, slow compressional (or p_s) wave and shear wave respectively, are defined as

$$v_j^2 = (\lambda + 2\mu)/\rho;\ (j = 1,\ 2),\ v_3^2 = \mu/\rho, \qquad \dots (10)$$

where λ, μ denote Lame's constants for the solid skeleton. The mass densities ρ_j (j = 1, 2, 3) are given by

$$\rho_j = \{B + (-1)^j\surd(B^2 - 4AC)\}/2M;\ (j = 1,\ 2),\ \rho_3 = C/m, \qquad \dots (11)$$

where
$$A = (\lambda + 2\mu)\,M,\ B = \rho M + mH - 2\rho_f\,\alpha M,\ C = \rho m - \rho_f^2 \qquad \dots (12)$$

and
$$H = \lambda + 2\mu + \alpha^2 M. \qquad \dots (13)$$

m is Biot's parameter depending upon the porosity β and fluid density ρ_f ($m = \rho_f/\beta$ for tube like pores); α and M are the elastic coefficients related to the coefficient of fluid content γ, bulk modulus k_s of solid grains and bulk modulus $k\,(= \lambda + 2\mu/3)$ of the porous solid skeleton (drained bulk modulus), by

$$\alpha = 1 - k/k_s,\ M = k_s/(\gamma k_s + \alpha). \qquad \dots (14)$$

The coefficient of fluid content can be expressed as

$$\gamma = \beta\,(1/k_f - 1/k_s) \qquad \text{... (15)}$$

where k_f denotes bulk modulus of the interstitial fluid.

Fluid filled pores are consumed to be the permanent constituents of sedimentary rocks since their formation and cracks appear later with the accumulation of tectonic stresses. Therefore, to define the co-existence of fluid-filled cracks and pores, the introduction of cracks in a fluid saturated porous solid is considered. Following Crampin and Atkinson[19], attenuation of S waves observed in the earth suggests that the cracks present in the crust are fully saturated. Therefore, it is assumed that with the increase of stress in focal region the liquid required to fill the newly formed or modified cracks is extracted from saturated pores present in the solid. Pores are small and interconnected. With the increase of stress these pores may squeeze after draining out their liquid to nearby cracks. In such a situation the density of the aggregate remains unchanged. The elastic constants and dynamical parameters used in Biopt's theory are modified in accordance with Budiansky and O'Connell[6]. Modified elastic and dynamical parameters in different interconnection regimes are explained as follows.

a) *Saturated Isolated Cracks*

The increase of stress in an elastic solid introduce new cracks or modify existing cracks[2]. The pores at the boundary of such a crack may squeeze shut. This may prevent the communication of fluid pressure between the cracks in a poroelastic solid and cracks can be treated as isolated. Modifications are explained as follows :

i) The term porosity in Biot's theory refers to the effective porosity that encompassing only inter-communicating void space. The sealed pores were considered as part of the solid. Hence, the introduction of isolated cracks by closing the pores of equal volume reduces the effective porosity ($\bar{\beta}$). We have

$$\bar{\beta} = \beta - \beta_c, \qquad \text{... (16)}$$

where crack porosity (β_c) is related to crack density (ε) by (5).

(*ii*) On introduction of isolated saturated cracks, the elastic constants for the poroelastic solid are modified as follows :

$$\bar{k}/k = 1 - (16/9)\ \{(1 - \bar{\nu}^2)/(1 - 2\bar{\nu})\}\ D\,\varepsilon, \qquad \text{... (17)}$$

$$\bar{\mu}/\mu = 1 - (32/45)\,(1 - \bar{\nu})\ \{D + 3/(2 - \bar{\nu})\}\ \varepsilon \qquad \text{... (18)}$$

and

$$\bar{\gamma}/\gamma = \bar{\beta}/\beta. \qquad \text{... (19)}$$

Bulk moduli of solid and fluid parts, i.e., k_s and k_f remain unchanged. Coefficient of fluid content, γ, characterising the volume of the fluid entering the pores depends upon the effective porosity and hence changes accordingly. Biot's parameter m is equal to $\rho_f/\bar{\beta}$. The constants α and M are also modified as given in (14).

b) *Saturated Isobaric Cracks* — Local stresses may be assumed enough to promote connections between cracks and allow flow of fluid between them. Hence all the cracks and pores are in communication with each other but no fluid flow is permitted out of the bulk sample. Porosity remain unchanged because fraction of volume occupied by fluid-filled cracks is same as that obtained by closing the pores. Modified elastic moduli are given by

$$\bar{k}/k = 1 \qquad \text{... (20)}$$

and $$\bar{\mu}/\mu = 1 - (32/45)\ \{(1-\bar{\nu})(5-\bar{\nu})/(2-\bar{\nu})\}\ \varepsilon. \qquad \ldots (21)$$

Coefficient of fluid content (γ), and elastic constants α, M remain unchanged. Modification in Biot's parameter (m) is negligible.

c) *Drained Cracks* — All the cracks and pores are interconnected and fluid in cracks is in communication with that at the surface of the earth. This stage may results in the precursors like emission of Radon gas or rise of water level in wells. The saturated cracked solid will respond as if no fluid were there. The elastic behaviour will be equivalent to the cracked solid with dry cracks. The effective porosity will remain the same, i.e., $\bar{\beta} = \beta$. The effective elastic moduli are obtained from (17) - (18) by substituting D =1. Other constants γ, α and M remain unaltered. Modifications in Biot's parameter (m) is negligible.

Seismic Velocities

Earthquake preparation process may be represented by continuous accumulation of stress around the focal region of eventual failure. Precursors observed are indirect effects of variation of stress in an earthquake preparation zone. Modifications of cracks are the most direct effect of accumulation of stress before an earthquake. With the change in stress field, the stressed rockmass may experience modifications in the configuration of cracks and therefore may alter seismic velocities. These velocity anomalies are used as a promising precursor for the prediction of earthquakes. Modifications in cracks are explained as follows :

i) *Crack orientation* may be modified by a variety of processes but it is expected that change in crack orientation may not affect the velocities of seismic waves, significantly.

ii) *Crack density* may be modified by promoting crack growth and by opening new cracks when accumulating stress increases half the fracture strength of rockmass. In lab conditions healing process may be comparatively fast, whereas subcritical crack growth is extremely slow. Therefore, in the absence of drainage of liquid, change in crack density is not generally expected. However, in the presence or drainage of liquid from pores to cracks, change in crack density may affect the seismic velocities.

iii) *Aspect ratio* of cracks may increase due to growth of cracks under sufficiently strong applied stress. Cracks may bow enough to develop interconnections and allow the flow of liquid into the dilatant region leading to eventual failure. The change in aspect ratio is considered to be the most likely change of cracks geometry in an earthquake preparation zone.

iv) When stresses are great the connections between cracks may develop enough to start flow of liquid to the surface of earth. This may happen just before an eventual failure takes palce. Changes experienced by the interstitial liquid are taken into account while discussing the regimes of connection between cracks.

So, to study the effects of accumulation of stress on seismic velocities, it is required to study the changes in wave velocities with the variations in ε, c/α, and crack interconnections leading to eventual failure.

Numerical Results

Similar to the Biot's theory, in the cracked poroelastic solids, two compressional (ρ_f and ρ_s) waves and one shear wave are propagated. To observe the effects of newly formed, modified and connected cracks on the velocities of these waves numerical study is made to a particular model. Following the experimental results of Yew and Jogi, assuming that the laboratory samples of water saturated sandstone contained no cracks, following values of relevant paramaters are taken

$k = 0.918 \times 10^{11}$ dynes/cm^2

$\mu = 0.922 \times 10^{11}$ dynes/cm^2

$k_s = 1.35 \times 10^{11}$ dynes/cm^2

$\rho_s = 2.17$gms./cm^3

$\rho_f = 1.0$gm./cm^3

$\beta = 0.268$

Bulk modulus of water $k_f = .214 \times 10^{11}$ dynes/cm^2 is used to calculated γ and Ω. Using these values of elastic and dynamical constants the velocities of ρ_f, ρ_s and S waves are calculated for assumed values of crack density (ε) and aspect ratio (c/a) of cracks present in the medium. These velocities are calculated only for fixed values of aspect ratio, given by, 0.0001, 0.001, 0.01, 0.02 and 0.03. Fig. 1 to 3 show the variations of wave velocities for three different regimes of intercrack connections. ρ_s wave is a slow wave of very small amplitude and, hence, is not much significant to be observed for velocity anomalies. Therefore, to check the anomalies in the velocity ratio, the ratio of the velocity of ρ_f wave to the velocity of S wave is considered. Variations of velocity ratio with crack density are presented in Fig. 4 and Fig. 5 exhibits velocity ratio variations with aspect ratio of cracks for $\varepsilon = 0.2$ and $\varepsilon = 0.4$.

Discussion of Numerical Results

Fig. 1 — Cracks are saturated isolated with no communication of liquid between them. Velocities of all the three waves decrease with the increase of crack density. These velocities also decrease with the increase in aspect ratio of cracks. However, for large crack density, velocity of ρ_f wave may increase with the increase of aspect ratio. Therefore, there may exist values of crack density where velocity of ρ_f wave is same for different values of aspect ratio. These particular values of crack density are different for different media.

Fig. 2 — Cracks are saturated isobaric and allow the flow of liquid between them but no liquid is permitted to flow out of the bulk sample. Wave velocities decrease with the increase of crack density. It was assumed that growth of cracks does not alter saturation and liquid required to fill the modified cracks may be squeezed from pores. Therefore, as expected, change in aspect ratio has negligible Poisson's ratio ($\bar{v}$) tends to zero as crack density assumes the values of 0.56 approximately. For crack density greater than 0.563 the $\bar{v}$ does not lie between 0 and 0.5.

Fig. 3 — Interconnected cracks are drained with liquid allowed to flow out of the bulk sample. Wave velocities decrease with increase in crack density. Change of aspect ratio have negligible effect on wave velocities. However, velocity of p_s wave shows a decrease with the increase of aspect ratio. The value of crack density increased beyond 0.56 indicates the disappearance of p_s and s waves. As in Fig. 2, $\bar{v}$ does not lie between 0 and 0.5 when ε is greater than 0.563.

Fig. 4 — Aspect ratio of cracks are fixed at 0.01. Velocity ratio of p_f to S wave increases with the increase of crack density. This increase is gradual when cracks are saturated isolated. When the cracks are connected the velocity ratio increases rapidly with the increase of crack density beyond 0.3. For the value of crack density less than 0.35 approximately, velocity ratio increases when the cracks develop interconnections and then decreases rapidly when liquid is allowed to flow out of

the sample. Otherwise, for crack density greater than 0.35, connections between cracks increase the velocity ratio steeply and drainage of liquid decreases it considerably.

Fig. 5 — For smaller values of crack density, i.e., less tan 0.35 approximately, velocity ratio is lowest when cracks are drained. Otherwise, for lowest value of velocity ratio cracks must be saturated isolated. With the increase of aspect ratio, velocity ratio increases very slowly when the cracks are interconnected and it decreases at a comparatively faster rate when cracks are isolated.

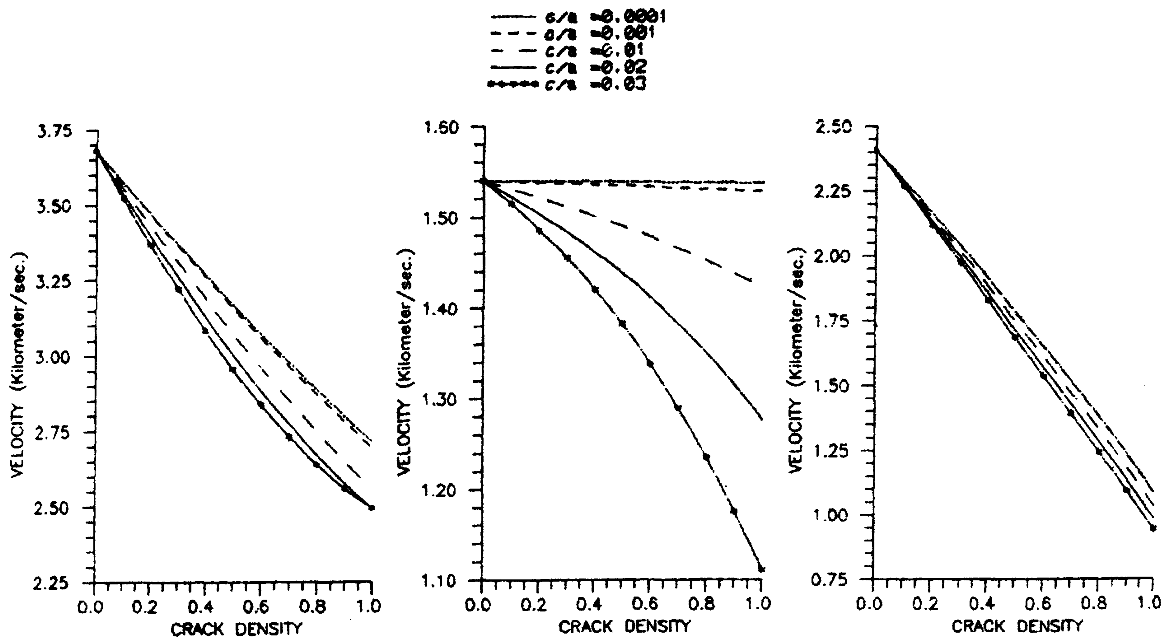

FIG. 1. Variations of velocity with crack density (saturated isolated cracks) (a) ρ_f wave, (b) ρ_s wave and (c) S wave.

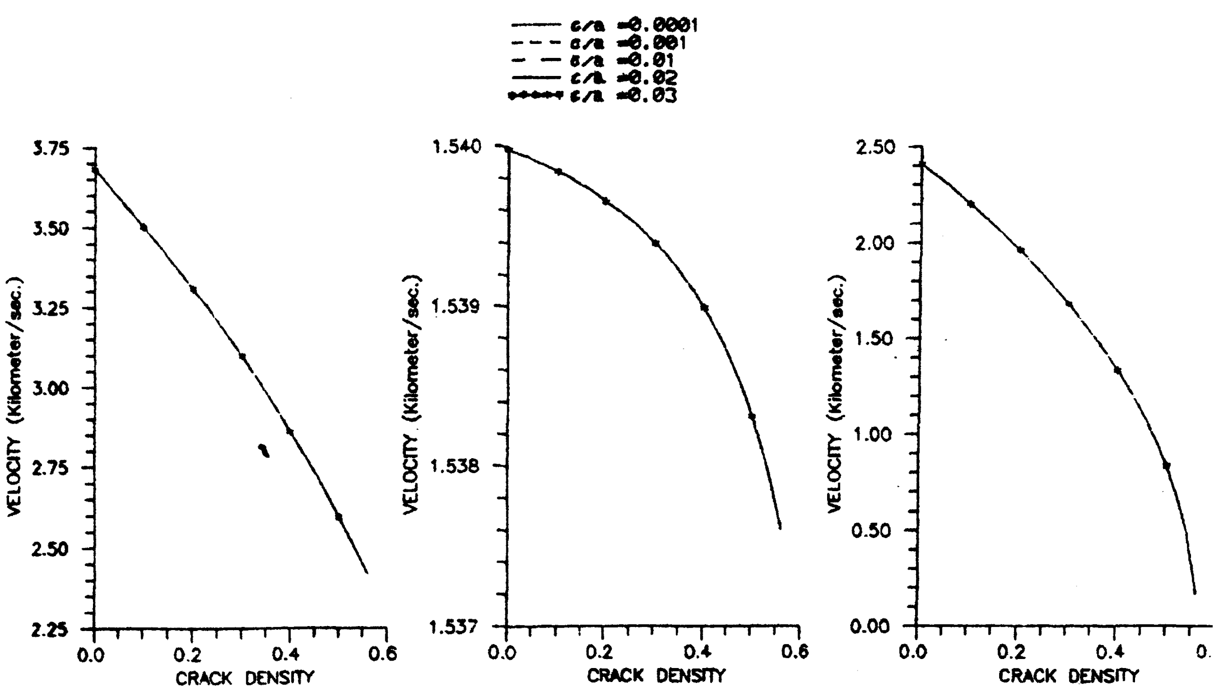

FIG. 2. Variations of velocity with crack density (saturated isobaric cracks) (a) ρ_f wave, (b) ρ_s wave and (c) S wave.

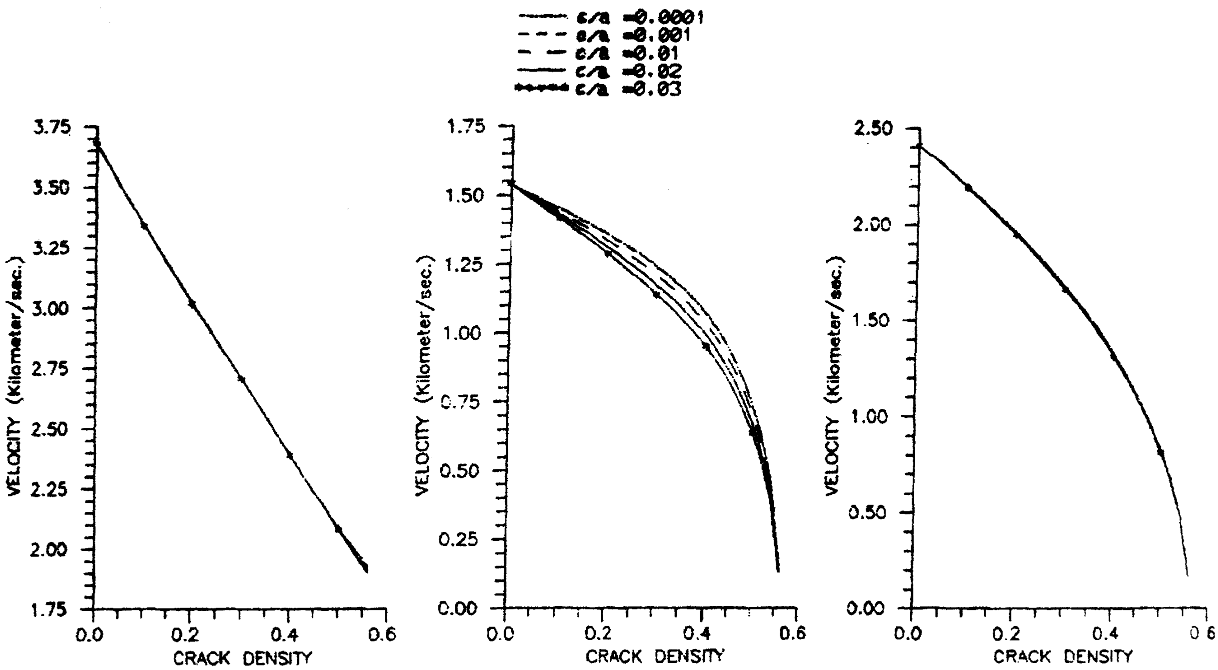

FIG. 3. Variations of velocity with crack density (drained cracks) (a) ρ_f wave, (b) ρ_s wave and (c) S wave.

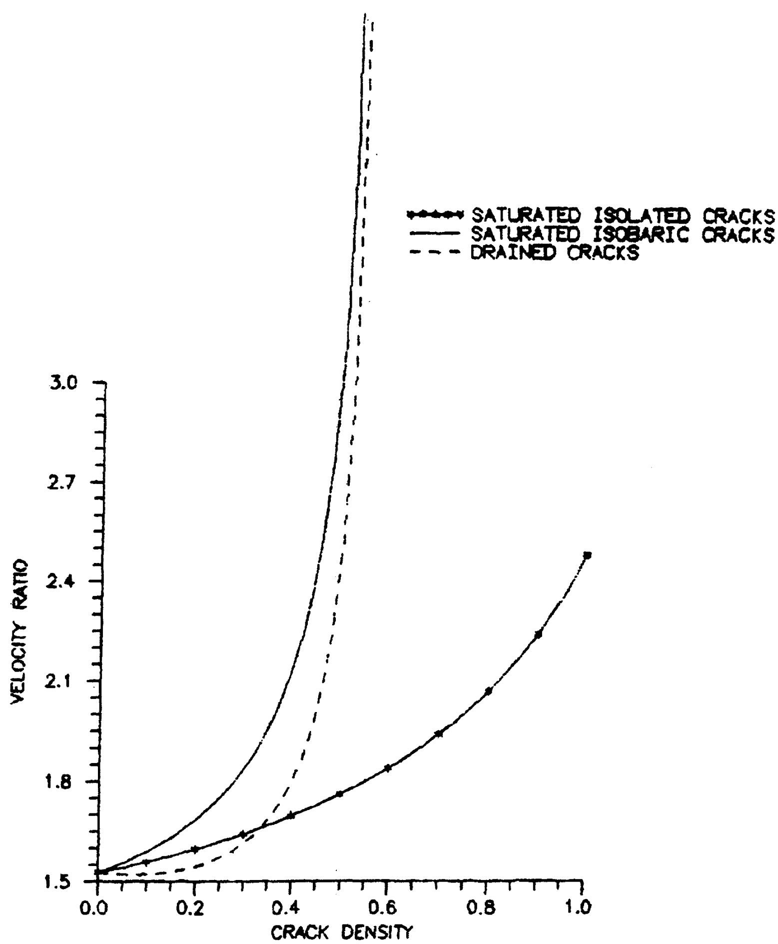

FIG. 4. Variations of velocity ratio with crack density (Aspect ratio of cracks = 0.01).

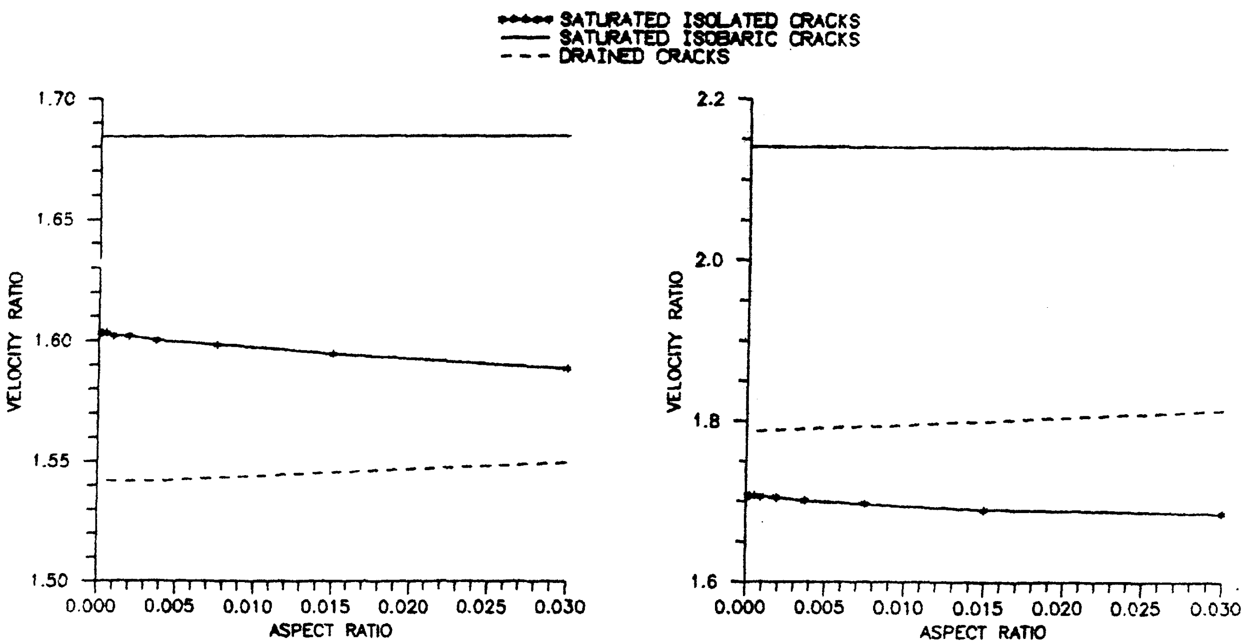

FIG. 5. Variations of velocity ratio with aspect ratio of cracks
(a) Crack density = 0.2 (b) Crack density = 0.4.

From the above discussion following conclusion can be drawn :

i) Although increase of crack density decreases the velocities of both compressional and shear waves but it increases their velocity ratio.

ii) There always exists a critical value of crack density at which rockmass loses its coherence. This critical value is larger when cracks are isolated.

iii) Although the change in aspect ratio is considered to be the most likely change of crack geometry in an earthquake preparation zone but its effect on velocity ratio is very small. Change in aspect ratio has a significant effect on wave velocities only when cracks are saturated isolated.

iv) If we summarise the general behaviour[3] of variations in velocity ratio, prior to an earthquake, stepwise, as

a) small increase from normal value of 1.75;

b) gradual decrease to lowest value 1.5 approximately;

c) recovery of velocity ratio to normal value and even greater value; and

d) return to normal value just before earthquake;

then, in equivalent steps, the earthquake preparation process can be explained with accumulation of stress as follows :

a) increases of crack density;

b) increase of aspect ratio of cracks but must, simultaneously, decrease the crack density near to value before step (*a*);

c) further increase of aspect ratio develops the isobaric intercrack connections and then again incrase the crack density;

d) growth of interconnected cracks to start flow of liquid to the surface of the earth just before the eventual failure; and

v) Increase in aspect ratio of cracks with the accumulation of stress must be accompanied by the decrease in crack density. In other words, growth of circular cracks must be represented by increase of width and decrease of radius of cracks, simultaneously.

An attempt has been made to define and study the presence of velocity anomalies observed prior to an earthquake. A realistic model of focal zone is defined where cracks are assumed fully saturated during the continuous accumulation of stress leading to eventual failure. A hypothetical earthquake preparation process, satisfying the general behavior of velocity anomalies, is also suggested. It is hoped that this piece of work may be useful in the theoretical and observational studies of earthquake prediction.

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