

Hitoshi Koide, Kazuo Hoshino, Shozaburo Nagumo (1970.08)
Microscopic mechanism of the development of rock failure, *Rock Mechanics in Japan*, vol.1, p.62-64.

ABSTRACT: Large earthquakes are triggered by the brittle fracturing of rocks at tips or asperities of large geological faults. The process and mechanism of formation of geological faults is the key to the earthquake prediction. The authors studied the process of nucleation and interaction of microfractures in the rocks and their development into larger faults under confining pressures. Under compression, the growing critical microfractures tend to approach to the direction of the maximum compression and then stops. Microfractures increase in number as deformation advances and the interaction between microfractures helps the formation of new microfractures. In this process, deformation bands are formed as narrow zones of high density of microfractures. The deformation band acts as a large weak inclusion. The en echelons array of tension fractures which often occur near of the earth's surface is comparable to the deformation band. A microscopic mechanism and process of rock failure is tentatively summarized in the Table. Three principal phases: micro-yielding, macro-yielding and macrofracturing, are distinguished. In the micro-yielding phase, microfractures begin to occur. The macroscopic mode of deformation is almost elastic in this phase. In the macro-yielding phase, microfractures develop into the deformation bands. The macroscopic mode of deformation is the flattening of the stress-strain curve. The macro-yielding phase is subdivided into active and passive phases. In the active macro-yielding phase, the deformation advances without the generation of micro-shocks. In the passive macro-yielding phase, however, the deformation is accompanied with the generation of micro-shocks. In this case, the speed of fracture propagation is slower than the applied strain rate and new production of microfractures is required for further deformation. The macro-yielding phase is the precursor of macrofracturing phase – generation of large earthquakes.

MICROSCOPIC MECHANISM OF THE DEVELOPMENT OF ROCK FAILURE

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Introduction: The authors studied the process of formation and development of microfractures in the rocks deformed under confining pressures (Koide, Hoshino and Nagumo, 1967, Hoshino and Koide, 1970). The mechanism of the development of microfractures will be discussed in the present paper.

Nucleation of microfractures: It is observed in the experiments that microfractures occur at very early stage of deformation. The Griffith's criterion for fracture is almost valid in the brittle and semi-brittle cases. In the criterion, the local normal stress must reach an ideal strength(T_m) for the formation of fracture. If the plane of weakness is assumed to be a penny shaped pore or inclusion, the theory of elasticity indicates that the maximum local tensile stress occurs at about its tip and is determined almost only by the macroscopic normal stress(σ) and tangential stress(τ) across the elongation of the plane of weakness at infinity. The condition for fracture from an individual plane of weakness, therefore, is:

$$\tau = \frac{2T_m}{b} \sqrt{1 + \frac{a}{T_m} \sigma} \quad \cdot \cdot \cdot (1)$$

where,

$$a = 8/\left\{\frac{2\pi}{s} + 4(1-\nu)\frac{K'}{G} + \frac{16}{3}(1-\nu)\frac{G'}{G}\right\}$$

$$b = 8/\left\{\frac{(2-\nu)\pi}{s} + 4(1-\nu)\frac{G'}{G}\right\}$$

s : shape ratio, ratio of length to width; ν , G : poisson's ratio and rigidity of the rock, respectively; G' , K' : rigidity and bulk modulus of the inclusion, respectively ($G'=K'=0$, in the case of pore). The very thin pores which cause high stress concentration are closed under the following compressive stress:

$$\sigma_c = -\frac{\pi G}{2(1-\nu)s} \quad \cdot \cdot \cdot (2)$$

In Fig.1, the curves P denote the conditions for fracture from Griffith's cracks of shape ratio s . The Griffith's cracks will be closed at the intersection with the line CL:

$$\tau = -\frac{(2-\nu)(1-\nu)T_m}{2G}\sigma\sqrt{1 + \frac{2G}{(1-\nu)T_m}} \quad \cdot \cdot \cdot (3)$$

The Mohr's circles A-F denote the maximum stress applied on the specimens of a sandstone in which microfractures are observed microscopically (Hoshino and Koide, 1970). The areas 1 and 3 denote the stress states under which many micro-shocks are generated (Fig.2). It is estimated that microfractures occur in spite of the closing of critical Griffith's cracks. The condition (1) suggests that the most favorable fracture loci are inclusions which are weak with shear and are not easily compressible. An example of such inclusions is the clay-like materials in grain boundaries. The curves (I) denote the conditions for fracture from a possible weak inclusion

in the rock ($G = 10^3$ kg/sq.cm, $K = 10^4$ kg/sq.cm).

Formation of the deformation band: Under compression, the growing critical microfractures tend to approach to the direction of the maximum compression and then stops (Brace and Bombolakis, 1963). Microfractures increase in number as deformation advances and the interaction between microfractures helps the formation of new microfractures. In this process, deformation bands are formed as narrow zones of high density of microfractures. The deformation band acts as a large weak inclusion. The en echelons array of tension fractures which often occur near of the earth's surface is comparable to the deformation band.

Microscopic mechanism of brittle-ductile transition: The confining pressure diminishes the tensile stress concentration at the tips of growing critical microfractures. The higher is the confining pressures, the shorter is the branch fracture. The width and spacing of deformation bands are reduced under higher confining pressures, as the length of consisting microfractures becomes shorter. The fine network of deformation bands observed under high confining pressures, apparently, makes the mode of deformation more ductile. On the other hand, the pore pressure (p) makes the branch fracture longer, because it adds to the tensile stress concentration at the fracture tip. The conditions (1)-(3) must be put σ as $\sigma - p$. The existence of pore pressure, therefore, makes the mode of deformation more brittle.

A microscopic mechanism and process of rock failure is tentatively summarized in the Table. Three principal phases: micro-yielding, macro-yielding and macrofracturing, are distinguished. In the micro-yielding phase, microfractures begin to occur. The macroscopic mode of deformation is almost elastic in

this phase. In the macro-yielding phase, microfractures develop into the deformation bands. The macroscopic mode of deformation is the flattening of the stress-strain curve. The macro-yielding phase is subdivided into active and passive phases. In the active macro-yielding phase, the deformation advances without the generation of micro-shocks. From an analogy to the dislocation theory(Nagumo and Hoshino, 1967), it was considered that the speed of fracture propagation is higher than the applied strain rate and the deformation flow by itself. In the passive macro-yielding phase, however, the deformation is accompanied with the generation of micro-shocks. In this case, the speed of fracture propagation is slower than the applied strain rate and new production of microfractures is required for further deformation.

References:

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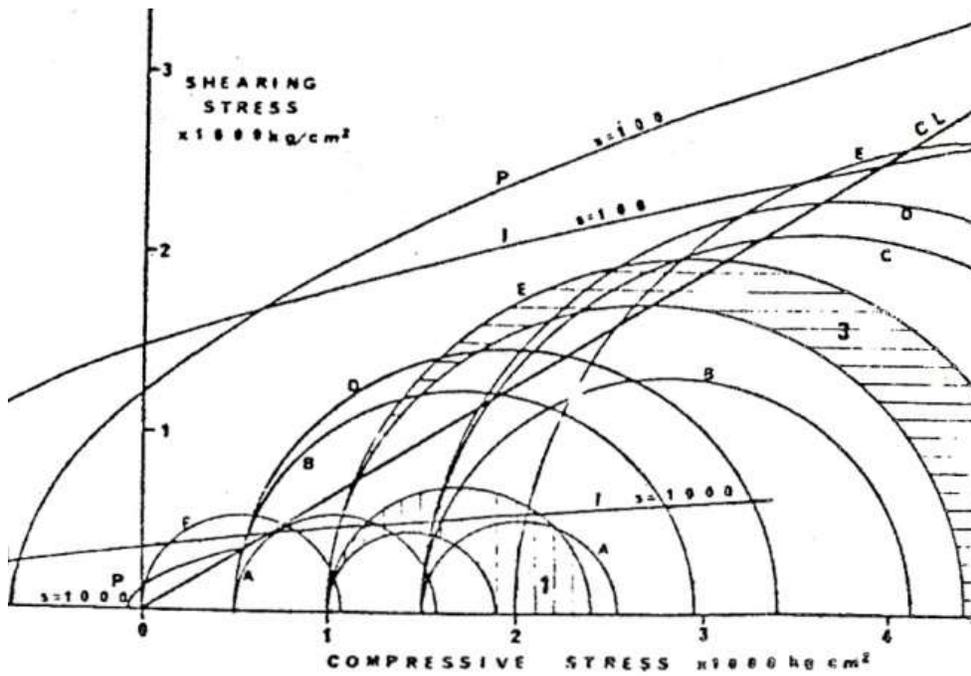


Fig.1 Failure criteria

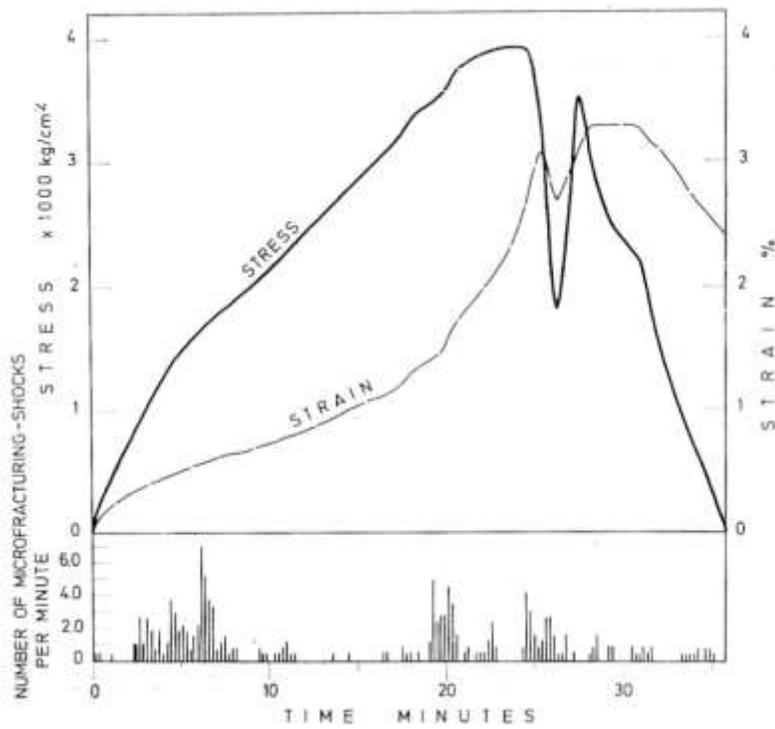


Fig.2 Generation of micro-shocks

Table. Microscopic Mechanism and process of rock failure

(Hitoshi Koide, Kazuo Hoshino, Shozaburo Nagumo, 1970)

Principal phases	Elemental process		Theoretical bases			Related phenomena		
	Microscopic fractures	Micro-shocks	Fracture density ρ	Fracture velocity v	Strain rate $\dot{\epsilon}$	Stress-strain relation	Geological structures	Earthquakes
Micro-yielding	Generation of fractures	With generation	$\Delta\rho \propto \Delta\epsilon$	$v=0$		Almost linear	Minor fractures	Micro-earthquakes
Maco-yielding Active	Growth of fractures (1) extension, opening (2) concentration, linkage, formation of deformation band	Without generation	$\Delta\rho \approx 0$	High speed	$\dot{\epsilon} \leq v$	Flattening	Fold	Swarm
		With generation	$\Delta\rho \propto \Delta\epsilon$	Low speed	$\dot{\epsilon} > v$			
Passive							Fractured zone	
Macro-fracturing	Bursting Linkage of deformation band	Principal shock		Unstable bursting		Stress drop	Fault	Main-shock

1970

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$$\tau = \frac{2 T_m}{b} \sqrt{1 - \frac{a}{T_m} \sigma} \quad \dots (1)$$

where, $a = 8 / \{ 2\pi / s + 4(1-\nu) K'/G + \frac{16}{3}(1-\nu) G'/G \}$
 $b = 8 / \{ (2-\nu) / s + 4(1-\nu) G'/G \}$

s : shape ratio, ratio of length to width; ν, G : poisson's ratio and rigidity of the rock, respectively; G', K' : rigidity and bulk modulus of the inclusion, respectively ($G' = K' = 0$, in the case of pore). The very thin pores which cause high stress concentration are closed under

the following compressive stress:

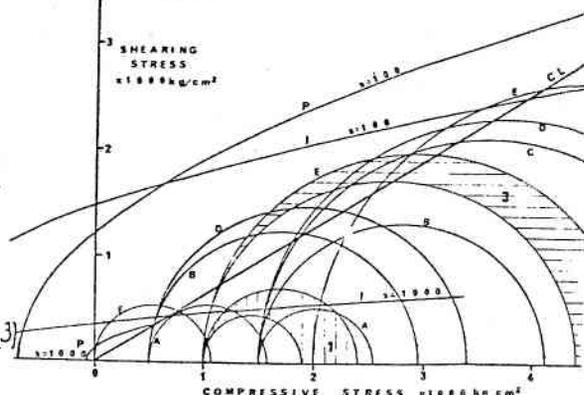
$$\sigma_c = - \frac{\pi G}{2(1-\nu) s} \quad \dots (2)$$

In Fig.1, the curves P denote the conditions for fracture from Griffith's cracks of shape ratio s . The Griffith's cracks will be closed at the intersection with the line CL:

$$\tau = - \frac{(2-\nu)(1-\nu) T_m}{2 G} \sigma \sqrt{1 + \frac{2 G}{(1-\nu) T_m}} \quad \dots (3)$$

The Mohr's circles A-F denote the maximum

Fig.1



stress applied on the specimens of a sandstone in which microfractures are observed microscopically (Hoshino and Koide, 1970). The areas 1 and 3 denote the stress states under which many micro-shocks are generated (Fig. 2). It is estimated that microfractures occur in spite of the closing of critical Griffith's cracks.

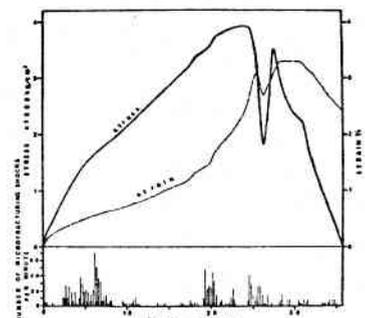
The condition (1) suggests that the most favorable fracture loci are inclusions which are weak with shear and are not easily compressible. An example of such inclusions is the clay-like materials in grain boundaries. The curves (I) denote the conditions for fracture from a possible weak inclusion in the rock ($C_f' = 10^3 \text{ kg/sq.cm}$, $K' = 10^4 \text{ kg/sq.cm}$).

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Fig. 2, Generation of micro-shocks



Table, Microscopic mechanism and process of rock failure

Principal phases	Elementally process		Theoretical bases			Related phenomena		
	Microscopic fractures	Micro-shocks	Fracture density ρ	Fracture velocity v	Strain rate $\dot{\epsilon}$	Stress-strain relation	Geological structure	Earthquake
micro-yielding	generation of fractures	with generation	$\rho \propto \dot{\epsilon}$	$v = 0$		slacet linear	minor fracture	micro-earthquake
macro-yielding	growth of fractures							
active	(1)extension, opening	without generation	$\rho \approx 0$	high speed	$\dot{\epsilon} \leq v$	flattening	fold	
passive	(2)concentration, linkage formation of deformation bands	with generation	$\rho \propto \dot{\epsilon}$	high speed	$\dot{\epsilon} > v$		fractured zone	swarm
macro-fracturing	bursting linkage of deformation bands	principal shock		unstable bursting		stress drop	fault	main-shock

advances without the generation of micro-shocks. From an analogy to the dislocation theory(Nagumo and Hoshino, 1967),it was considered that the speed of fracture propagation is higher than the applied strain rate and the deformation flow by itself . In the passive macro-yielding phase,however, the deformation is accompanied with the generation of micro-shocks. In this case, the speed of fracture propagation is slower than the applied strain rate and new production of microfractures is required for further deformation.

References

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