第7卷第4期　　西北地震学报　　Vol.7, No.4
1985年12月　NORTHWESTERN SEISMOLOGICAL JOURNAL　Dec., 1985

VOLUMETRIC CHANGES IN ROCK SUBJECTED TO DIFFERENT STRESS PATHS

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ABSTRACT

The volumetric changes in Jinan gabbro and Changping granite subjected to three different stress paths have been studied. In all cases the rock was first loaded to a pre-determined stress state below that which would be conducive to fracture. This was then followed by three different cases of loading. Case A: The maximum principal stress was continuously increased to induce fracture. Case B: The minimum principal stress was decreased to induce fracture. Case C: The minimum principal stress was increased to prevent fracture. The experiments showed that for the same rock dilatant behaviour was different along different stress paths. When compared with the dilatant behaviour during case A experiments (i.e. the conventional triaxial experiments) the rocks were found to be in a superdense state for a case B stress path and in an ultra-dilatant state for a case C stress path.

1.INTRODUCTION

Inelastic volumetric dilatancy of rock preceding its fracture has been reported previously(1, 2). Since Brace et.al.(3) made detailed studies of dilatancy preceding fracture for various rocks, the concept of dilatancy has been used to study both the cause of earthquakes and their alleged precursory phenomena. The discovery of certain precursory phenomena in the field was presumed to be related to dilatancy(4, 5) and many models for earthquake generation have been proposed on the basis of this concept(6, 7). Although it is still too early to say definitely whether dilatancy models can explain earthquake occurrance or not, dilatant behaviour is undoubtedly an important phenomenon preceding fracture of rock under high pressure. It is related to acoustic emission, changes in elastic wave velocities and in electrical resistivity preceding the fracture of rocks. If one considers earthquakes to be caused by the fracture of rock under pressure in Earth's crust, then the influence of dilatancy must high be taken into accout in earthquake studies. Thus, further study of the dilatant behaviour of various rocks in the laboratory still has important significance. In the past many experiments have been preformed on rocks with different properties under different temperature, pressure and other conditions by investgators in several countries(8-10). These experiments have contributed to our understanding of various aspects of dilatancy. Brace(11) recently reviewed developments in the study of dilatancy during last decade.

All previous studies used the same loading path. Dilatant behaviour was studied by increasing the maximum principal stress until the rock fracture. This paper studies the volumetric changes in rock under three loading paths. Case A: Confining pressure was applied first, then the axial stress was increased until the rock sample failed (the conventional triaxal experiment). Case B: The confining pressure was applied first, then the axial stress was increased to about 80% of the strength of the rock and kept constant. Finally, the confining pressure was decreased until the rock sample failed. Case C: The confining pressure was apllied first, then the axial stress was increased to more than 90% of the strength of the rock and kept at that level. Then the confining pressure was increased. In this case the sample remained unruptured.

2. EXPERIMENTAL METHOD

A triaxial test machine was used for these experiments. The allowable maximum confining pressure was 150 MPa. Bonded foil resistance strain gages were used to measure strain. The relative error of the instrument was about 3%. A strain change of 1×10^{-5} can be read from the continuous records of these experiments. Both longitudinal and transverse strain was measured simultaneously in order to calculate the volumetric strain of the rock sample.

The rock samples were cylindrical in shape with a diameter of 50mm and a length of 110mm. The unevenness at two ends was less then 0.1mm. Before each experiment the sample was jacketed with a plastic tube which was further coated with an oil-proof plastic membrane. The strain rate was 10^{-6}/sec when the axial stress was increased and 10^{-8}/sec when the confining pressure was changed. The rock samples were taken from Jinan gabbro and Changping granite.

3. MAJOR RESULTS

(1) Case A.

Curve 1 in Figure 1 is the volumetric strain curve for gabbro obtained from case A experiments under 100 MPa confining pressure. Here the ordinate represents the differential stress between the maximum principal stress σ_1 and the minimum principal stress σ_3 ($\sigma_2=\sigma_3$). The abscissa represents the volumetric strain. From figure one we can see that initially the volume decreases almost linearly with increasing differential stress. The sample is gradually compacted. When the differential stress is increased further, the volumetric strain curve gradually deviates from a straight line. This results from the influence of dilatancy due to microfractures forming inside the rock sample. When the differential stress reaches a certain value, the dilatant effect become greater than the influence of compression and the rock volume actually increases with increasing differential stress. Thus the curve turns back toward the direction of increasing volumetric strain. For convenience the turning point will be called superior-dilatant point and designated by D* in the following discussion. It represents the maximum density state that can be abtained by a rock under a specific confining pressure. It also shows the starting point of significant dilatancy under this confining pressure. When the differential stress is raised above D*, the rock sample's volume increases rapidly with increasing differential stress until the rock fractures. The results for case A experiments agree with previous studies.

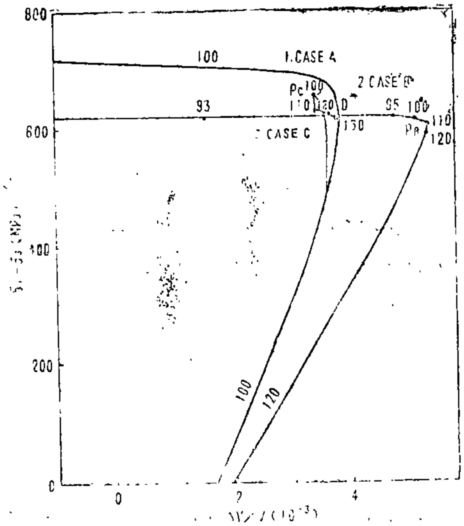


Fig.1 Volumetric strain curves of gabbro in the experiments of case A.B and C.

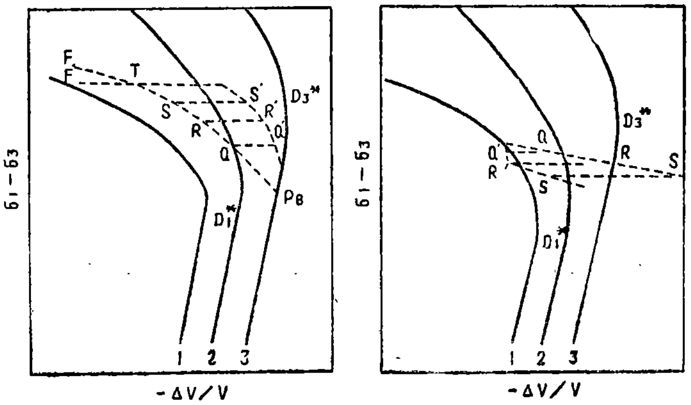
(2) Case B.

Curve 2 in Figure 1 shows the volumetric strain curve obtained from case B experiments. Below P_B the confining pressure was kept unchanged. The volumetric strain curve has the same shape as in case A experiments. Above point P_B the axial stress was kept unchanged and the differential stress was increased by decreasing the confining pressure. The corresponding confining pressure in MPa is given by the numbers at some points on the curves. It can be seen that the volumetric strain showed little change over the great part of the change in confining pressure (differential stress). The sample's volume drastically increased, however, over a small range of confining pressures (with a range of about 2 MPa) just before fracture. This is the main difference between the volumetric strain curves obtained in case A and case B experiments.

Figure 2(a) gives an explanation for this phenomenon. In the figure, solid curves 1,2,3 represent the volumetric strain variation in case A experiments in ascending order from low to high confining pressure. Supposing the sample is compressed under high confining pressure along curve 3 to point P_B, then the axial stress was kept constant and the differential stress continues to increase by decreasing the confining pressure. By doing so, the rock's state will move from point P_B toward curve 2 of low confining pressure when the confining pressure is decreased. On the other hand it will continue to increase along the volumetric strain curve with increasing differential stress. As a result, the rock's stress state should change along the dashed curve P_BQRSF until the fracture point F. However, the volumetric strain curve actually observed P_BQ′R′S′F′ clearly shows that at the beginning of decreasing confining pressure the rock state did not immediately move toward the curve of lower confining pressure. Instead, it continued to rise for a while along the original curve of higher confining pressure and then moved toward lower confining pressure very slowly, showing substantial lag behind the change in confining pressure. As the point of failure was approached the volumetric change quickened. In case B experiments the rock sample was compressed along curve 3 under high confining pressure up to point P_B. Failure occurred at some stage on curve 1 under a lower confining pressure. The corresponding differential stress at point P_B is below the point D^* with respect to curve 3 and above the point D^* with respect to curve 1. In case B experiments the density of rock before reaching fracture point T was greater than the density obtained under the same confining pressure and axial stress during case A experiments. The concept of a "super-dense state" of the rock is introduced at this point to name this phenomenon.

(3) Case C.

The existence of a super-dense state of rock in case B suggests the possibility that an opposite effect might occur, which could be called "ultra-dilatant state". The case C experiments mentioned above were designed specifically to identify this effect. From Figure 2 (b) one can see that if the sample was first compressed along curve 1 under lower confining pressure beyond point P_c and then the confining pressure was increased while the axial stress remained unchanged, the rock state would move to curve 2 of higher confining pressure. On the other hand, it would move downward along the volumetric strain curve with decreasing differential stress. Thus, the rock state might be considered to change along the path P_cQRS. However, one additional point must be considered. The point P_c was above the point D^* of curve 1, but was below the point D^* of curve 3. After the rock had experienced significant dilation under lower confining pressure, the microcracks inside the rock might not be closed completely when it was compressed to a higher confining pressure. The delayed effect of microcrack closure would probably keep the rock in an ultra-dilatant state, i. e. the volume of the rock would be greater than that obtained in case A experiments at the same stress state. After taking this into account, the change of rock state was more likely to follow the path $P_cQ'R'S'$. Curve 3 in Figure 1 shows that the volumetric strain curve observed in case C experiments confirmed the prediction regarding the ultra-dilatant state.



a. CASE B

b. CASE C

Fieure 2. Shematic explanation for the supei-dense state of case B experiments(a) and the ultra-dilatancy state of case C experiments(b)

4. DISCUSSION

Delayed effects are rather common phenomena in physics. Is it necessary here to introduce the concepts of super-dense state and ultra-dilatant state? The experiments show that the amounts of superdense and ultra-dilatant effects are larger than the delayed effect of dilatancy due purely to confining pressure changes by an order of magnitude. The observation of acoustic emission and P-wave velocity under different loading paths provided evidence for the existence of a super-dense state and an ultra-dilatant state (12, 13). In case B experiments the rocks were in a super-dense state, so that the dropping of P-wave velocity and the increase of acoustic emission appear much later. In case C experiments the rocks were in an ultra-dilatant state. Although the P-wave velocity remained at a low value and the acoustic emission were maintained a high level, no rupture was observed. The concepts of a super-dense state and an ultra-dilatant state for rocks may be useful in explaining the variety of earthquake precursors related to dilatant behaviour.

ACKNOWLEDGEMENTS

Prof. B. K. Atkinson made helpful suggestions for the manuscript.

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