Influence of pore pressure on the deformation behavior of saturated rocks

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INFLUENCE OF PORE PRESSURE ON THE DEFORMATION BEHAVIOR OF SATURATED ROCKS

INFLUENCE DE LA PRESSION DE PORE SUR LA DÉFORMATION DES ROCHES SATURÉES

DER EINFLUSS DES PORENDRUCKS AUF DIE VERFORMUNG VON GESÄTTIGTEN GESTEINEN

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ABSTRACT: This paper proposes a simple stress decomposition for the analysis of the influence of a pore fluid pressure on the deformation of saturated rocks. Using this approach, the change of pore pressure induced by external loads is derived for undrained conditions assuming a linear elastic behavior for both the solid matrix and the bulk material.

The applicability of the classical effective stress concept during the disintegration process is then discussed. With this respect, simultaneous measurements of both the interconnected pore space and the bulk volume variations during the controlled fracture of porous sedimentary rocks with various confining pressures indicate that dilatancy is not an intrinsic characteristic of rock disintegration but rather depends on the applied loads, the deformations and the deformation rates for a constant temperature.

Finally a detailed analysis of the mean axial force-mean deformations curves obtained in laboratory conditions is shown to provide a better comprehension of rock fracture mechanisms which ultimately could allow a more accurate analysis of rock mass deformations such as earthquakes.

RESUME: Cet article a pour but de proposer une décomposition simple de l'état de contrainte appliqué à une roche saturée pour étudier l'influence de la pression de pore. Il a été possible grace à cette méthode de déterminer rigoureusement la variation de pression poreuse induite, en conditions non-drainées, par des charges exterieures en supposant un comportement linéairement élastique pour la matrice solide et le matériau considéré.

D'autre part la validité du principe des contraintes effectives lors de la fracturation est également discutée. A ce sujet, des mesures simultanées des variations aussi bien du volume globale du materiau que du volume poreux interconnecté durant la désintegration controllée de deux types de roches sédimentaires poreuses, pour différentes pressions de confinement, indiquent que le phénomène de dilatance n'est possible que pour certaines conditions de charges, de déformations et de vitesses de déformations.

Finalement une analyse detaillée des courbes force axiale moyenne par unité de surface - déformation moyenne permet de mieux comprendre les mécanismes associés à la fracturation des roches. Celle-ci devrait permettre une analyse plus précise des déformations des masses rocheuses tel que les tremblements dè terre par example.

ZUSAMENFASSUNG: Dieses Heft zeigt eine einfache Spannungszergliederung für die Analyse des Porenflüssigkeitsdrucks auf die Verformung von gesättigten Gesteinen So wurde es möglich die durch äussere Ladungslasten herbeigeführte und unter nicht-entw sserten Bedingungen Veränderung des Porendrucks streng zu bestimmen, indem ein lineares elastisches Verhalten beider solider Naturböden und des ganzen Materials vorausgesetzt wird.

In wie weit das klassische Prinzip der wirksamen Spannungen während des Zusammenbruchsvorgangs gültig ist, wird auch umstritten. Daraufhin, während des gesteuerten Bruchs beider sedimentaren Felsen unter verschiedenen Manteldrücken, bezeigen gleichzeitige Messungen der Änderungen des ganzen Materialvolumens bezeichnungsweise des untereinander verbunden Porenvolumens, das der Ausdehnungsvorgang (dilatancy) nur unter bestimmten Zasts-, Verformungs-und Verformungs-geschwindigkeitsbestimmungen für eine steten Temperatur möglich ist.

Schliesslich wird eine detaillierte Analyse der mittleren axialen Belastungen bezogen auf die Ausgangsquerfläche in Bezug zu durchschnittlichen Verformungen ein besseres Verständnis für die Brucherscheinungen ermöglichen; es sollte eine genauere Felsmassensverformung analyse erleichtern.

Introduction

The role of fluids and fluid pressure on the deformation behavior of rock is often an important consideration in studies of rock mass stability. It is known, for example, that fluid pressure variations can exert a dominant influence on the occurrence of earthquakes [HUBBERT and RUBEY (1959), HANDIN and RALEIGH (1972)] or landslides [TERMINASSIAN et al. (1967), LANE (1969)].

Analysis of the mechanical effect of fluids on soil or rock is usually based on the concept of "effective stress" [TERZAGHI (1923), BIOT (1955), SKEMPTON (1960)], in which the 'total stress' tensor usually employed in mechanics is replaced by a stress tensor dependent on both the applied (solid) forces and the fluid pressure in the pores and interstices of the soil or rock. Some limitations in the effective stress approach have been noted, however. SKEMPTON (1960), discussing the effects of pore fluid pressure on the stresses generated at the points of contact of soil particles, concluded that, for the same total applied load, different effective stresses should be considered for the shear strength determination and for the analysis of the volumetric deformation. ROBIN (1973) has further shown that, even for volumetric deformation problems, the effective stress expression is not unique, i.e. the expression for a bulk volumetric change is not appropriate for the corresponding pore volume variation. He concluded that, since the effective stress tensor is not uniquely defined, the concept is of no real help in a study of the influence of pore fluid pressure on rock.

This paper outlines a different stress decomposition that is seen to yield interesting results in the study of pore pressure effects, both for the elastic domain and during the disintegration process. Results of laboratory experiments involving disintegration of fluid filled specimens are included, together with a discussion of some possible implications concerning earthquake mechanisms.

1. Effective Stresses and a Proposed Alternative

SKEMPTON (1954) noted that, in various problems involving the undrained strength of soils, the change in pore pressure occurring under changes in total stresses must be known, and that, for this purpose it was convenient to express the pore pressure variation Δu, due to changes $\Delta\sigma_1$, $\Delta\sigma_3$, in the two principal stresses, as follows:

$$\Delta u = B[\Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)]$$

where A and B are "pore pressure coefficients". Since these coefficients can be measured experimentally in the undrained triaxial test, where the change $\Delta\sigma_3$ is applied by the so-called 'confining pressure', he proposed that the application of the change in stresses $\Delta\sigma_1$ and $\Delta\sigma_3$ be considered as taking place in two stages: (1) an all-round increment $\Delta\sigma_3$ is applied and (2) the 'deviator stress" $(\Delta\sigma_1 - \Delta\sigma_3)$ is applied.

Accordingly, he derived expressions for A and B and discussed the influences of the degree of saturation and of the rheological characteristics of the soil on these two coefficients. This approach has been found very useful in solving problems of soils in undrained conditions.

However, it is important to note that the expressions for A and B were derived with the implicit assumption that the solid matrix compressibility is negligible. As will be shown in a subsequent paragraph, this assumption is not always permissible for rocks. In addition, it should be noted that SKEMPTON'S deviator stress $(\Delta\sigma_1 - \Delta\sigma_3)$ is not a deviator stress in the classical sense, since it does not correspond to a pure shear stress (a pure shear stress is a tensor in which the sum of the diagonal terms is identically 0).

Classically, the stress tensor $\underset{\sim}{\sigma}$ (the subscript $\sim$ is used to indicate a tensor, the unit tensor being denoted by $\underset{\sim}{1}$)can be decomposed into a mean normal stress and a deviator stress part, the latter corresponding to a pure shear stress.

Accordingly, the total state of stress acting on a saturated rock element [assumed to be large enough compared to the size of the pores that it is representative of the whole volume, but small enough so that it can be considered as infinitesimal in the mathematical analysis] may be decomposed analytically into three components as shown in Figure 1.

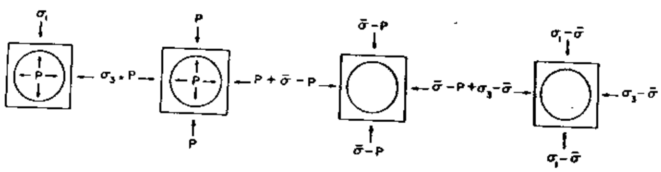


FIGURE 1 - PROPOSED STRESS DECOMPOSITION

Figure 1 - Décomposition de l'état de contrainte proposé dans le texte

Abb. 1 - Spennungszergliederung die im text vorgeschlagen wird

Component I corresponds to an equal internal and external hydrostatic pressure p1 ('internal' refers to the interconnected pore space).

Component II corresponds to an external hydrostatic stress

$$\bar{\sigma}\underset{\sim}{1} - p\underset{\sim}{1} \text{ where } \bar{\sigma} = \sigma_{ii}/3$$

Component III corresponds to an external deviator stress tensor

$$\tilde{\underset{\sim}{\sigma}} = \underset{\sim}{\sigma} - \bar{\sigma}\underset{\sim}{1},\ \tilde{\sigma}_{ij} = \sigma_{ij} - \bar{\sigma}\delta_{ij}$$

where δ_{ij} is the Kronecker delta symbol.

In such a stress decomposition component III corresponds to a pure shear. Its influence on rock deformation behavior is described more easily than in the usual "effective stress" decomposition, as is demonstrated below.

2. Elastic Behavior

Both the solid matrix and the bulk material are assumed to be linearly elastic. Following GEERTSMA (1957) and NUR and BYERLEE (1971) it can be shown that the bulk volumetric strain of a linear elastic body resulting from components I, II, and III is

$$\Delta V_b/V_b = (\bar{\sigma} - P)/K + P/K_i \tag{1}$$

where $\Delta V_b/V_b$ is the volumetric strain of the bulk material

$1/K$ is the compressibility of the bulk material

$1/K_i$ is the compressibility of the solid material.

For simplicity, the pore space is assumed to be fully interconnected; the validity of this assumption is discussed in a subsequent paragraph.

Applying Betti's reciprocal theorem it can be shown that the corresponding pore volume change is

$$\Delta V_p/V_p = 1/f(1/K - 1/K_i)(\bar{\sigma} - P) + P/K_i \tag{2}$$

where $f = V_p/V_b$ is the volume porosity

V_p is the initial pore volume.

The change of porosity is consequently easily obtained from Equations (1) and (2).

If ΔP is the pore pressure change under undrained conditions when a saturated rock element is submitted to the stress state $\underset{\sim}{\sigma}$, the pore volume change is:

$$\Delta V_p/V_p = \Delta P/K_i + (\bar{\sigma} - \Delta P)/k = \Delta P/K_e \tag{3}$$

where $1/K_e$ is the fluid compressibility

$1/k = 1/f(1/K - 1/K_i)$

Accordingly, the change of pore pressure in undrained conditions can be derived from Equation (3):

$$\Delta P = \frac{1/K - 1/K_i}{f(1/K_e - 1/K_i) + (1/K - 1/K_i)} \cdot \bar{\sigma} \tag{4}$$

and substituting Equation (4) in Equation (1) gives the bulk volumetric strain of a linearly-elastic saturated body deformed in undrained conditions.

The ratio $\Delta P/\bar{\sigma}$, which corresponds to SKEMPTON'S definition of his "B coefficient" can be derived from Equation (4), and is found to be dependent upon solid matrix compressibility $1/K_i$. This last quantity was neglected justifiably by SKEMPTON, since he was interested in the study of soils where pore pressures are relatively low and matrix compressibility of the soil is insignificant. However, it must be taken into account for certain rocks. Consider, for example, a fissured porous rock with a pore space in which the non-connected portion is significant while the interconnected part is filled by a fluid under pressure. The compressibility $1/K_i$ refers to that part of the body which is not occupied by fluid, and may have a value of the same order of magnitude as that of the fluid compressibility, so cannot be neglected. More generally, when the pore space is not fully interconnected, the complementary portion in the bulk volume of the interconnected pore space is considered as an 'equivalent homogeneous material'. Consequently, the volume porosity mentioned in Equations (2) and (3) refers only to the interconnected pore volume, and is called the 'interconnected volume porosity'. Similarly the 'solid matrix compressibility' becomes the "equivalent homogeneous material compressibility".

If the body does not behave elastically, the fluid pressure produced by a change in the stresses applied at the boundary must be determined by laboratory tests.

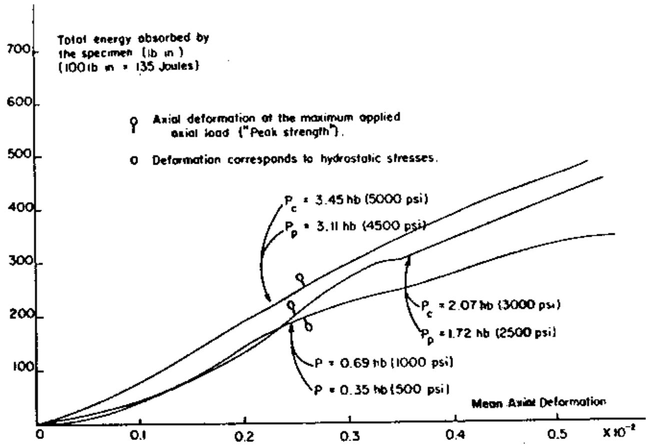


FIGURE 2 - TOTAL ENERGY ABSORBED VERSUS MEAN AXIAL DEFORMATION CURVES, FOR DIFFERENT COMBINATIONS OF PORE AND CONFINING PRESSURE, ON SATURATED CYLINDRICAL SPECIMENS OF INDIANA LIMESTONE. (50mm diam X 100mm long).

Figure 2 - Courbes déformation axiale moyenne - quantité d'énergie absorbée obtenues pour différentes combinaisons de pression de pore et pression de confinement avec des éprouvettes cylindinques (50mm x 100mm) de calcaire de l'Indiana.

3. The Disintegration Process

Here, disintegration has to be understood as post-elastic deformation. Since the mean axial force-mean deformations relations are no more linear, the stress decomposition is used, in this section, only to analyze the influence of each component during the fracture process. Its use to determine deformations should be considered with care.

3.1 The Classical Effective Stress Concept

While the classical effective stress concept is of little significance in analysis of the elastic behavior of rocks, it is a more fruitful approach when the disintegration process is considered.

HANDIN et al. (1963), and BRACE and MARTIN (1968), in triaxial tests on several rocks of different porosity, observed that the peak strength was constant for different combinations of pore and confining pressures, provided the difference between the two values remained constant.

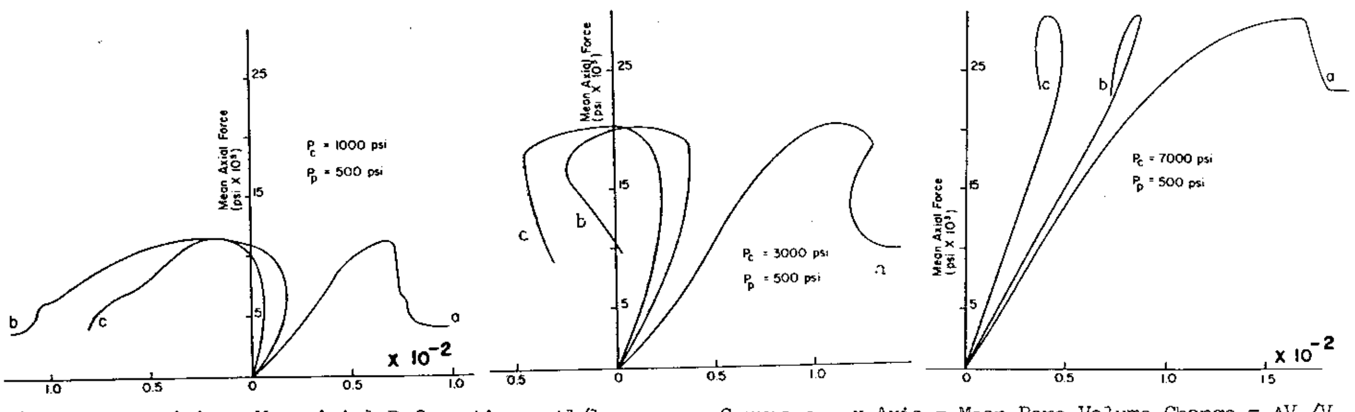
Similar results were observed by CORNET and FAIRHURST (1972) with respect to the elastic limit of Berea Sandstone specimens.

It is now generally recognized that no throughgoing shear plane exists in the rock specimen at the elastic limit [e.g. WAWERSIK (1968)], so that the conclusion that agreement between predicted and observed values of peak strength exists because the pore pressure is acting over the entire area of a throughgoing plane of fracture [LAUBSHER (1960), SERAFIM (1972)] must be rejected as incorrect.

An alternative explanation for such a good agreement can be provided by considering the stress decomposition proposed in Figure 1.

Component I represents the application of the same hydrostatic pressure to the element and to the saturating fluid. Thus, the stress state in the solid matrix is hydrostatic and equal to the applied pressure. The effect of this pressure depends on both the magnitude of the pressure, and the constitutive equation of the solid. In most cases, and more especially in those considered by the previously mentioned authors, this effect (of the hydrostatic pressure) is negligible, and the behavior of rock is affected by the stress (σ - PI) only, i.e. the effective stress concept provides a satisfactory explanation.

However, this pressure (P) has been shown for certain rocks to have a significant influence [GRIGGS (1936), McHENRY (1948)]. It may modify the behavior of the matrix, where the rock material has a tendency to behave plastically under high principal minimum stresses; as is the case for potash or calcite, for example. In addition it must be noted that the hydrostatic pressure induces an hydrostatic stress state in the matrix only if the pore space is fully intercon-



Curves a - x Axis = Mean Axial Deformation = $\Delta l/l$

Curves b - x Axis = Mean Volumetric Deformation = $\Delta V_b/V_b$

Curves c - x Axis = Mean Pore Volume Change = $\Delta V_p/V_b$

Average Lateral Deformation Rate: 10^{-5} sec^{-1}

Figure 3 - Drained Triaxial Tests on Saturated Cylindrical Specimens of Berea Sandstone [Specimens 50mm (2 in.) x 100mm (4 in.) long]

Figure 3 - Essais triaxiaux drainés effectués sur des éprouvettes saturées de grès de Berea (diamètre 50mm hauteur 100mm).

Abb. 3 - Dreiaxialversuchen an gesattigten Berea Sandstein Proben.

nected, i.e. so that the pressure is constant throughout the pore volume. For rocks in which a certain part of the pore space is not interconnected, the hydrostatic pressure P existing in the interconnected part may induce sufficiently high stresses in the matrix to provoke microfractures, which in turn will influence the overall behavior of the material. Experimental tests performed by the authors in triaxial conditions on unjacketed specimens of Indiana limestone, in which the pore and the confining pressure are equal, confirm this hypothesis. It was observed that, while the maximum load-bearing capacity was not affected significantly by an increase from 1.72hb* (2500 psi) to 3.45hb (5000 psi) in hydrostatic pressure, the post-peak slope of the ['mean axial force'/'mean axial deformation'] curve** was steeper for a 1.72hb (2500 psi) confining pressure than for that with 3.45hb (5000 psi).

In addition, drained triaxial tests were performed on the same rock with different combinations of pore and confining pressures, maintaining a constant difference between the two values. The strain rate ($0.8.10^{-6}$/sec) was chosen to insure uniform pore pressure throughout the specimen. It was found (Fig. 3) that more energy was needed to deform axially the specimen up to a certain amount at high values of pore pressure than at low values. This result confirms the above mentioned proposition. A more detailed analysis of this possible effect is in progress. Already it appears that curves of 'total absorbed energy' versus 'volumetric deformation' may yield very promising results.

It is generally recognized that a hydrostatic pressure applied to the exterior of a specimen (Component II of Fig. 1) greatly influences the pre-peak force behavior of specimen of porous rocks [WALSH (1965), BRACE (1965), KING (1969), GARG and NUR (1973)]. Therefore, the same effect will occur with equal internal and external pressures for porous rocks in which part of the pore space is not interconnected.

3.2 Pore Volume Changes

It has been shown above that, for fracture problems involving a pore pressure (P), the influence of the pressure in the interconnected pore space must first be determined; the analysis then can be carried out by simply considering the classical effective stresses. To accomplish this, it is thus essential to determine the pore fluid pressure.

In drained conditions, the pore fluid pressure remains constant with deformation; its influence is thus the same throughout the disintegration process.

In undrained conditions, no fluid is allowed to flow in or out of the material and the fluid pressure changes in accordance with its compressibility (see Equation 3) and the interconnected pore volume variation. The latter quantity consequently must be determined if the pore pressure is to be computed.

Actual loading conditions usually lie somewhere between these limits, depending on such factors as fluid viscosity, permeability, deformation rate, temperature, etc. Thus, the analysis of the influence of the pore pressure usually involves considerations of these two extremes.

*1hb - 1 'hectobar' = 1,454 psi

**Stress conditions in a laboratory rock specimen tested in compression are quite inhomogeneous and become even more inhomogeneous in the post-elastic deformation range. Consequently, it is not meaningful to reduce the force deformation diagrams to stress-strain curves. In fact, reference to such diagrams as stress-strain curves is misleading and their use should be discouraged.

Drained Conditions

In addition to the mechanical effect of the fluid pressure in the interconnected pore space, it is well known that fluids can chemically affect the rock by dissolution of the matrix (BARON et al. 1963), change of the free surface energy of the rock (REHBINDER and LIKHTMAN 1957), and modification of the internal friction coefficient (HORN and DEER 1962, COULSON 1971). Thus, any test designed to determine the saturated rock properties must be performed on the saturated, and not on the dry material. On the other hand, the pore volume of the rock changes with deformation (ROBINSON 1959). In particular, it increases during disintegration (BRACE et al. 1966) under low minimum principal stress. If no pressure is applied to the internal fluid, the pore pressure will decrease and even may become negative due to dilatancy. Thus, wherever possible, tests designed to determine the characteristics of wet rocks should be performed in drained conditions because of the simplicity of the analysis.

Simultaneous measurements of the bulk volumetric change and the pore volume variations during the rock disintegration process under drained conditions facilitates:

The determination of the volumetric deformation for that part of the body which is not occupied by the internal fluid, and

The analysis of the behavior for the bulk material in undrained conditions, since the change of pore pressure can be determined.

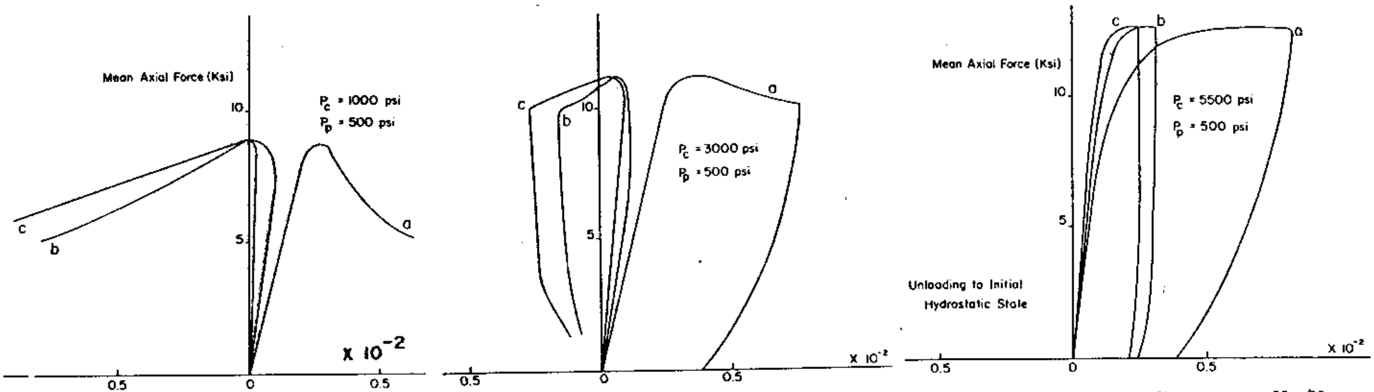
Figure 3 shows some results of drained tests on Berea Sandstone. It is seen that the increase in volume of the pores at 0.7hb (1000 psi) confining pressure is slightly smaller than the measured increase in the bulk volume; this is due to less than complete penetration of the fluid into the newly created cracks.

Conversely, in tests on Indiana limestone (Fig. 4) it appears that the pore volume variations are slightly greater than those measured for the rock volume. In this case, it is expected that the pore volume initially was not fully interconnected and that fractures, developed during loading, created links between the isolated pores and the interconnected pore space.

In either case it is seen that computation of pore pressure variations for undrained conditions in the post-elastic range on the assumption that the fluid filled pore space changed in direct proportion to the change in bulk volume, would give an incorrect result.

Figures 3 and 4 also reveal the influence of confining pressure on pore volume variations during the disintegration process for highly porous rocks (Berea sandstone 18% porosity, Indiana limestone 15% porosity). It is evident from the results of the tests on Indiana limestone at 3.79hb (5500 psi) confining pressure, and at 0.34hb (500 psi) pore pressure (Fig. 3, Curve C), that the pore volume can decrease continuously during post-elastic deformations. However, these tests were stopped at 0.9% mean axial deformation. Tests performed on the same rock under dry conditions and 3.45hb (5000 psi) confining pressure revealed a continuous decrease of the mean volumetric deformation up to a mean axial deformation of 1%, beyond which the volume increased continuously although remaining smaller than the original value. These tests were stopped at 2% mean axial deformation.

No increase in the bulk volume probably would be observed in tests on saturated specimens at larger confining pressure. A recent publication [SCHOCK et al. (1973)] indicating such a continuous decrease in



Curves a - x Axis = Mean Axial Deformation = $\Delta l/l$
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Curves c - x Axis = Mean Pore Volume Change = $\Delta V_p/V_b$
Average Lateral Deformation Rate: 5.10^{-5} min^{-1}

Figure 4 - Drained Triaxial Tests on Saturated Cylindrical Specimens of Indiana Limestone [Specimens 50mm (2 in.) x 100mm (4 in.) long].

Figure 4 - Essais triaxiaux drainés éffectués sur des éprouvettes saturées de calcaire de l'Indiana (diametre 5cm, hauteur 10cm).

Abb. 4 - Dreiaxialversuchen an gesattigten Indiana kalk stein Proben.

tests on dry sandstone at confining pressures up to 20 kb confirms this supposition. If high minimum principal stresses induce a behavior in the matrix that satisfies the Tresca criterion of plasticity, the material should flow with no volumetric change and it should then be possible to obtain large deformations with no pore volume change for such rocks.

In summary, the results shown in Figs. 3 and 4 indicate that for a certain domain of load, deformations, and deformation rates, under constant temperature conditions, the post-elastic behavior of rock is associated with pore volume decrease and that it is necessary to obtain a precise knowledge of this domain to explain pore pressure effects under load. Studies on the influence of the deformation rate are underway at the University of Minnesota.

Undrained Conditions

It was suggested in the previous section that, because of the simplicity of the analysis, pore volume changes during fracture should be determined experimentally by triaxial tests under drained conditions. Nevertheless, if in-situ conditions are known to be undrained, it might be simpler to perform, in the laboratory, triaxial tests in which the pore fluid is not allowed to flow, the variation of pore pressure being directly measured.

Also BRACE and MARTIN (1968) have observed that the pore pressure distribution in rocks is dependent on the deformation rate, due to the dilatancy phenomenon.

Consequently, since it is necessary, for the experimental study of the pore fluid influence on rock deformations, to use the saturated material - and since drained conditions cannot be achieved with deformation rates faster than a critical value, then for these higher rates, tests should be performed in undrained conditions. However, even this procedure is not fully satisfactory since local pressure gradients may still exist in the specimen at high deformation rates. Thus, although testing under undrained conditions enlarges the range of deformation rates over which direct experimentation is meaningful, a limit still is imposed by the rock permeability and the fluid viscosity.

Very little work has been carried out in the post-peak region with respect to the influence of dilatancy. In tests on a Berea sandstone specimen at 2.07hb (3000 psi) confining pressure, and 0.34hb (500 psi) pore pressure, CORNET and FAIRHURST observed that the development of a fault plane traversing the specimen was associated with a stress drop in the material, the effect of which was to close cracks that previously were opening up in the bulk of the material prior to the development of the through-going plane. This reduction of pore volume exceeds the increase associated with the formation of the fault plane. Thus fracture would have resulted in an overall pore-pressure increase, had undrained conditions been used.*

No such behavior was observed in similar tests on Indiana limestone specimens (for the .8 $10^{-6}sec^{-1}$ deformation rate used in the experiment). In fact, no significant dilatancy was observed in the pre-peak force region, but became significant only after the maximum load bearing capacity had been reached, for effective confining pressures up to 1.72hb (2500 psi). At higher confining pressures a continuous pore volume decrease was observed which, in undrained conditions, would have been associated with a reduction of the effective confining pressure ($P_c - P_p$) and thus would have yielded results opposite to those predicted by the BRACE and MARTIN'S dilatancy-hardening theory.

4. Mean Force - Mean Deformation Curves Interpretation

From the above experimental results, dilatancy is not a permanent feature of rock fracture but rather reflects only one energy dissipation process observed for low confining pressures and which corresponds simply to the creation and opening of microcracks. For intermediate confining pressure conditions, the development of microcracks allows a relative movement of the grains of the matrix and consequently is associated with an overall volume decrease; this fracture mechanism is described by EDMUND and PATERSON (1972) as cataclastic flow. Finally, at higher confining pressures, once the cataclastic flow has reduced the pore volume to nearly zero, intracrystaline plasticity may take place with virtually no volume changes (SCHOLZ 1968).

When dilatancy does occur, tests in which fracture development is controlled indicate that the fracture may develop in one of two ways: either the dilatancy monotonically increases (first mode) or, after

*This has been observed in tests for which fracture was not controlled. Since the collapse occurred very suddenly, the pore pressure could not be monitored. However, it was found to be larger after fracture than before.

an initial increase, the stress-drop associated with the development of a single fracture plane is followed by an overall pore volume decrease (second mode). The latter requires that the solid behaves elastically, a feature which is indicated in the mean-axial force/ mean-deformation curve [i.e. as obtained in experimental conditions] by a portion with a positive slope in the post-peak region (the first derivative of the function represented by the mean force-mean deformation curves is at first negative, then positive, and finally negative again for a continuous load decrease). In this case the elastic energy stored in the material is larger than that required for formation of the macrofracture plane; laboratory control of the unstable development of this plane is achieved by reducing the elastic energy of the testing system, i.e. by relieving the applied load (reversing the platens).

In some testing situations and with certain rocks no such instability is observed and energy has to be continuously supplied to the rock for its progressive disintegration. However, two kinds of energy-absorbing processes are still possible. The first is associated with an elastic behavior of the matrix, the increase of energy necessary for fracture extension arising from the fact that microcracks propagate toward a more stable configuration, so that more energy is required for the continued extension. This behavior is characterized by a large dilatancy. The second is associated with local plastic deformations or any other energy absorption mechanism (such as friction), involving no volume changes but absorbing a significant amount of energy.

5. Possible Application to Earthquakes Mechanisms

NUR (1972) described an interesting variation of the ratio $\zeta = t_s/t_p$ of the arrival times t_s over t_p for the P and S seismic waves observed before several earthquakes.

He proposed that the observed decrease in the ratio was probably attributable to dilatancy, while an increase observed just prior to the earthquake was probably due to percolation of fluid through the newly created cracks, the pore pressure increasing until the earthquake was triggered.

However, it usually is observed that dilatancy, when it occurs, is largest just before macrofracture develops. At least this is true for laboratory specimens. On the other hand, newly created cracks can be filled by a fluid only if dilatancy ceases, or at least if the dilatancy rate is sufficiently slow to allow fluid pressure build-up to take place.

WAWERSIK (1968) and SCHOLZ (1968) observed that cracks induced by compressive loading are more or less randomly distributed throughout a specimen for applied loads up to 85% of the peak strength. Just prior to fracture, however, the new cracks tend to be localized in the immediate vicinity of the region in which the fracture surface is to appear. In addition, the dilatancy rate accelerates as the applied load approaches the maximum load-bearing capacity.

If this mechanism occurs also under field conditions, (i.e. slip along a fault) fluid from the surrounding saturated rock mass can fill up the cracks in that part of the rock in which dilatancy has ceased (i.e. outside the fault region). But since dilatancy is likely to be accelerating in the region of the fault, it seems improbable that fluid pressure can build up in this region. If this is true, then the observed increase of the ratio ζ would be an indication that dilatancy is becoming a local phenomenon, and that fracture will soon occur. In such a case the influence of the pore fluid is only secondary and does not trigger the earthquake.

An alternative explanation can be offered if slip along the fault is not assumed to occur as a single event. Indeed it is most probable that some regions along the fault are more highly stressed than others and, consequently, that local fracture develops before overall slip. [This hypothesis is strongly supported by the occurrence of foreshocks often described in the literature].

Now, let us assume that these local fractures occur in accordance with the second mode of fracture as this was previously defined.
In this case the stress drop in the masses on each side of the local slip will be accompanied by local pore pressure increases, forcing the saturating fluid into the regions of lowest pore pressure, i.e. along the fault where dilatancy is highest. The fact, as observed by NUR, that dilatancy takes place long before the earthquakes occur, and that the minimum principal stress is in the range of 1 to 2 kilobars, appear to be similar to the conditions necessary for the second mode as described in the previous paragraph.

This proposed mechanism seems to be in good agreement with most observed facts. It provides an explanation for the pore pressure increase that does not require dilatancy to cease.

In such a mechanism, (i.e. localized fracturing, inducing pore pressure increase, which consequently triggers the earthquake) the pore pressure acts merely as an added factor promoting instability. The question may arise as to whether it is desirable to increase this pressure so that the earthquake is triggered earlier, with possibly lower elastic strain energy release, or if complete cancellation of pore pressure would induce a more stable fracture process such as creep. The authors do not feel ready to answer such a question; but propose that such parameters as in-situ stress conditions, pore pressure magnitude, and influence of the minimum principal stress on the fracture process, will affect the situation and need to be considered.

Conclusion

The deformation behavior of saturated rocks can be analyzed in two steps:

1. Examine the influence of hydrostatice pressure on that part of the material not occupied by the interconnected pore space. This is achieved experimentally by performing tests on saturated, unjacketed specimens using a classical pressure vessel. The influence of the hydrostatic pressure on the elastic deformation now is generally recognized but usually is considered to be negligible for post-elastic deformations. The validity of such an assumption depends on the nature of the rock and the magnitude of the pressure.

2. Investigation of the influence of the classical "effective stresses" on the bulk material (fluids and solids) appears to be simpler, at least in the elastic domain, if the effective stress tensor is decomposed into the mean normal component, and its deviatoric component. Experimentally, investigation of the effective stress is achieved by performing drained triaxial tests (in which influence of the pore fluid remains, mechanically and physicochemically, constant throughout the experiment). However, for deformation rates faster than a critical value, drained conditions cannot be attained and undrained tests must be performed. For such conditions the pore pressure changes in accordance with its compressibility and the interconnected pore volume variations.

In the elastic domain variation of the interconnected pore volume has been shown to depend on (i) the compressibility of the fluid, (ii) the compressibility of that part of the bulk volume which is complementary to the interconnected pore space, (iii) the compressibility of the bulk material, and (iv) the interconnected volume porosity.

In the post-elastic domain the variation of the interconnected pore volume is dependent on the applied loads, the deformation, and the deformation rate. This variation, while following a similar trend to that of the dilatancy, is not always equal to this last quantity and, consequently, should be determined, if possible, independently of it (the dilatancy). Thus, the interconnected pore space has been shown to decrease during fracture for some values of the confining pressure, especially with very brittle materials. Such a variation has been proposed as a possible factor of instability during earthquakes.

REFERENCES

References in common in this text and in the General Report of Theme 2 will be referred to General Report: (see G.R.).

BARON, G., Y. CASTEL and P.HABIB (1963) "Influence de la pression interstitielle sur les caractéristiques mécaniques des roches en condition de fond" revue de l'I.F.P. vol. XVIII n° hors série décembre.

BIOT, M.A. (1955) "Theory of elasticity and consolidation for a porous anisotropic solid" J. App. Phy. vol. 26, p. 182.

BRACE, W.F. (1965) "Some new measurements of linear compressibility of rocks", Jour. Geoph. Res. vol. 70 nb 2, pps. 391-398.

BRACE, W.F., B.W. PAULDING and C. SCHOLZ (1966) (see G. R.).

BRACE, W.F. and R.J. MARTIN III (1968) "A test of effective stress law for crystalline rocks of low porosity", Int. J. Rock Mech. & Min. Sc. vol. 5, p. 415.

CORNET, F. H. and C. FAIRHURST (1972) "Variations of pore volume in disintegrating rocks" Percolation through fissured rocks - a symp., Int. Soc. Roch Mech. Stuttgart.

COULSON, J.H. (1971) "Shear strength of flat surfaces in rock" 13th Symp. Rock Mech. Urbana-Champaign, Ill. A.S.C.E.

EDMUND, J.M. and M.S. PATERSON (1972) "Volume change during the deformation of rocks at high pressure" Int. J. Rock Mech. vol. 9, p. 161.

GARG, S.K. and A. NUR (1973) "Effective stress law for fluid saturated porous rocks" J. Geophy. Res. vol. 78, no. 26, p. 5911.

GEERTSMA, J. (1957) (see G.R.).

GRIGGS, D.T. (1936) "Deformation of rock under high confining pressures" Journ. of Geol., vol. 44, pps. 541-577.

HANDIN, J., R.V. HAGER, M. FRIEDMAN and J.N. FEATHER (1963) (see G.R.).

HANDIN, J. and C.B. RALEIGH (1972) "Man-made earthquakes and earthquake control" Percolation through fissured rocks symp. Int. Soc. Rock Mech. Stuttgart, published by Deutsche Gesellscheft fur Erd und Grundbau, edited by Wittke.

HODGE, P.G. (1972) Plasticity lectures, U. of Minnesota Unpublished.

HORN, H.M. and D.H. DEER (1962) "Frictional characteristics of minerals" Geotechnique, vol. 12, p. 319.

HUBBERT, M.K. and M.W. RUBEY (1959) (see G.R.).

HUDSON, J.A., S.L. CROUCH, and C. FAIRHURST (1972) "Soft, stiff, and servo-controlled testing machines" Eng. Geol., vol. 6, no. 3.

KING, M.S. (1969) "Static and dynamic elastic moduli of rocks under pressure" 11th Symp. Rock Mech., Berkeley, p. 329, A.I.M.E.

LANE, K.S. (1969) "Engineering problems due to fluid pressure in rocks" 11th Symp. Rock Mech. Berkeley, p. 501, A.I.M.E.

LAUBSCHER, H. (1960) "Mechanics of fluid filled porous solids and its application to overthrust faulting: a discussion", Bul. Geol. Soc. Am., vol. 71, no. 5.

McHENRY, D. (1948) "The effect of uplift pressure on the shearing strength of concrete". Proc. 6th Congr. Large Dams. Paper 48.

NUR, A. and J.D. BYERLEE (1971) (see G.R.).

NUR, A. (1972) (See G.R.).

REHBINDER, D.A. and V. LICHTMAN (1957) "Effect of surface active media on strains and ruptures in solids", Proc. Sec. Int. Con. Surface Activity, vol. III, p.563.

ROBIN, P.Y.F. (1973) "Note on effective pressure", J. Geophy, Res., vol. 78, no. 4, p. 2434.

ROBINSON, L.A. (1959) "The effect of pore and confining pressure on the failure process in sedimentary rocks" Col. School Mines Quart., vol. 54, no. 3, p. 177.

SCHOCK, R.N., H.C. HEARD and D.R. STEPHENS (1973) "Stress-strain behavior of a granodiorite and two graywackes on compression to 20 kilobars", J. Geophy. Res., vol. 78, no. 26, p. 5922.

SCHOLZ, C.M. (1968) "Experimental study of the fracturing process in brittle rock", J. Geophy. Res., Vol. 73, no. 4, pps. 1447-1554.

SERAFIM, J.L. (1972) General report on theme 4, percolation through fissured rocks, Symp. Int. Soc. Rock Mech., Stuttgart.

SKEMPTON, A.W. (1954) "The pore pressure coefficients A and B", Geotechnique, Dec., p. 143.

SKEMPTON, A.W. (1960) (See G.R.).

TER MINASSIAN, W., F. SABARLY, P. LONDE (1967) "Comment proteger les barrage-voutes contre la pression de l'eau dans les appuis" 9th Cong. Large Dams, Q32, R12.

TERZAGHI, K. (1923) (See G.R.)

WALSH, J.B. (1965) "The effect of cracks on the compressibility of rocks", J. Geophy. Res., vol. 70, no. 2, p. 381.

WAWERSIK, W. (1968) "Detailed analysis of rock failure in laboratory compression tests" Ph.D. thesis, University of Minnesota. (Unpublished).