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# THE ROLE OF PORE PRESSURE IN DEFORMATION IN GEOLOGIC PROCESSES

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# THE ROLE OF PORE PRESSURE IN DEFORMATION IN GEOLOGIC PROCESSES

(A summary with a list of some pertinent references)

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## ABSTRACT

A Penrose Conference entitled, "The Role of Pore Pressure in Deformation in Geologic Processes" was convened by the authors at San Diego, California between November 9 and 13, 1979. The conference was sponsored by the Geological Society of America. This report is a summary of the highlights of the issues discussed during the conference. In addition, this report also includes a topical reference list relating to the different subject areas relevant to pore pressure and deformation. The references were compiled from a list suggested by the participants and were available for consultation during the conference. Although the list is far from complete, it should prove to be a good starting point for one who is looking for key papers in the field.

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# THE ROLE OF PORE PRESSURE IN DEFORMATION IN GEOLOGIC PROCESSES

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SUMMARY

Water is known to occur down to great depths in the earth's crust. Due to its slight compressibility as well as capillary action, water exerts fluid pressure on the pores containing it, thereby modifying the existing state of stresses on the rock matrix. The contrast that exists between the deformation properties of the rock and the fluid, the modification of the stress field by the fluid pressure and the continuous changes in fluid pressure induced by the dynamics of flowing groundwater contribute profoundly to the deformation behavior of the geologic systems. The importance of understanding the deformation behavior of fluid permeated geologic systems is readily apparent in more than one context: the development of oil, gas, water, and geothermal resources; the cause and the modification of earthquakes; the utilization of soil or rock masses to support engineering structures; the response of the earth's crust to electrical and mechanical waves; the formation of hydrothermal ore deposits, and others. Scientists and engineers in many disciplines are actively striving towards a better understanding of the physical mechanisms that govern the deformation behavior of geological systems subjected to the ubiquitous influence

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of water. With a view to bringing together the current ideas and observations on this important natural phenomenon, a Penrose Conference, sponsored by the Geological Society of America, was convened by the authors during November 9-13, 1979 at San Diego, California. This five-day conference was strongly interdisciplinary in nature and drew participants from the following fields: Structural Geology and Geophysics, Hydrogeology, Geotechnical Engineering, Geochemistry, Rock Mechanics, Applied Mechanics and Ocean Engineering. In keeping with the expectations of the Penrose ideals, the conference provided a forum for a free exchange of ideas among the participants, in addition to generating new research contacts.

This report is a brief summary of the highlights of the conference. During the conference, a collection of important reprints, textbooks and reports on the subject matter of the conference was assembled from lists suggested by the participants. In response to a suggestion by many of the participants, a list of these references has been prepared for distribution. Those interested in obtaining a free copy may contact the first author. Although the conference was essentially self supporting, partial financial support was provided by the Earth Sciences Division of the Lawrence Berkeley Laboratory. Five graduate students participated in the conference. Our thanks are due to Ms. Lois Elms for coordinating the conference and to the Geological Society of America for providing us an opportunity to convene the conference.

The discussions of the conference concentrated on the following general areas: Effective Stress Laws; Stress-Strain Relations; Seismicity and Pore Pressure; Hydraulic Fracturing and Geopressured Systems.

Most of the main points covered in the various sessions are discussed below.

Perhaps the most significant feature that sets apart a fluid-filled porous medium from a dry one, in so far as deformation is concerned, is that fluid pressures acting outward from within counter the external stresses acting inward. Inasmuch as matrix deformation is governed strictly by the stresses borne by the matrix and since the hydrodynamics of fluid flow is governed by fluid pressure, a constitutive relation is a priori imperative if one is to couple fluid flow and skeletal deformation in a general conceptual framework. The notion of an effective stress, originally proposed by Terzaghi over fifty years ago, provides the basis for such a constitutive relation. Although there is little dispute about the general concept of effective stress, there still appears to exist many a question about the specific, quantitative meaning of this parameter, as was evident from the deliberations of the first two sessions of the conference.

Consider the definition of effective stress. It varies from a simple heuristic statement, "effective stress equals total stress less the pore pressure", to a more physical definition, "....is the stress, if applied alone would have the same effect on some aspect of the fluid-saturated porous solid as some combination of total stress and pore-fluid pressure". In general, the mechanical response of a fully saturated porous medium is a function of the grain to grain stresses ($\bar{\bar{\sigma}}_{ij}$), the pressure of the fluid filling the voids (P), as well as the net electrical forces resulting from osmotic repulsions (R') and van der Waals attractions (A'). In this case one can define effective stress as

$$\sigma' = \sigma - p^* \quad (1)$$

where $\sigma$ is total stress, $p^* = P + (R' - A')$ is the effective pore-fluid pressure. Experimental as well as theoretical support (based on double-layer theory) is forthcoming for equation 1. When there is no net $(R' - A')$, $\sigma'$ can be expressed in terms of the intergranular stress, $\bar{\bar{\sigma}}$, as follows.

$$\sigma' = (\bar{\bar{\sigma}} - p)a_m \quad (2)$$

where $a_m$ is the normalized grain contact area. It can be seen from (2) that where point contacts exist between grains, as in granular materials, then $p << \bar{\bar{\sigma}}$ and $\sigma'$ essential equals $\bar{\bar{\sigma}}a_m$. Following the second definition for effective stress, namely, $\sigma'$ acting alone would have an equivalent response as some combination of $\sigma$ and p, one can write the following expression for a porous medium with compressible grains,

$$\sigma'_{ij} = \sigma_{ij} - \alpha\delta_{ij}P \quad (3)$$

where for bulk strain of the material skeleton $\alpha = (1 - K/K_s)$, with K as the bulk modulus and $K_s$ as the modulus of the solid grains and $\delta_{ij}$ is Kronecker Delta. For pore volume strain, by contrast, which depends also on porosity, $\phi$, $\alpha = [1 - (1-\phi)K/K_s]$. Attempts have been made to extend equation (3) to non-isotropic materials on theoretical grounds, giving consideration to the compliances of rock grains.

The relation between effective stress and pore pressures becomes considerably more complex when the pores are filled with more than one fluid phase, due to a combination of mechanical as well as thermodynamic effects. For a partially saturated, water-air-solid system, in which the intergranular contact area is extremely small, effective stress can be defined as total stress less an equivalent pore pressure defined as, $p^* = P_w a_w + P_a a_a$. In this case,

$$\sigma' = \sigma - P_a + \chi \, (P_a - P_w) \tag{4}$$

where $\chi \approx a_w$, and $a_w$ is the normalized area of contact between water and solid. Obviously $\chi$ should depend on pore-size distribution and saturation. Recent work suggests that $\chi$ should also be dependent on total stress.

It was pointed out that there is no unique effective stress law or relation satisfying all mechanical properties and that an effective stress law may not be needed if a given property is known for any combination of total stress and pore pressures. Some of the questions raised, relevant to the effective stress concept included: What are the limits of the simple effective stress relation proposed by Terzaghi, $\sigma' = \sigma - P$? How important are physico-chemical forces of interaction? Can the state of a soil be uniquely defined by void ratio, effective stress and overconsolidation ratio? What happens to effective stress when temperature changes or phase transformations occur? What is the correct relation when more than one fluid phase is present?

Following the discussions on effective stress relations, theoretical developments were presented for the elastic as well as non-elastic response of fluid-saturated porous media. The possibility of applying the theory to such problems as flow in abnormally pressured systems, suddenly pressurized cavities, growing tensile cracks and suddenly introduced dislocations were discussed. The derivations carried out for isotropic linearly elastic materials included undrained as well as drained responses and showed that the Terzaghi effective stress relation is strictly valid only for plastic deformation.

From a practical stand point, one of the most intriguing questions of fundamental interest is the maximum depth to which interconnected pore spaces exist, facilitating deep circulation of groundwater. Indirect evidence, based on electrical resistivity measurements seems to suggest that circulation may persist down to a depth of 20 km. Permeabilities of the order of a nano-Darcy or higher have been inferred to exist down to a depth of 10 km through earthquake, isotopes and heat flow studies.

A variety of experimental results were presented and discussed in relation to the stress-strain behavior of fluid-saturated rocks. Some of these experimental results suggested that in some rocks (e.g. Cosco Granite) the bulk modulus is sensitive to saturation while in some others (e.g. Solenhofen limestone) it may not be; in clayey sandstones permeability may be more sensitive to pore fluid pressure than applied stress; in certain fault gouge materials permeability is related to strain rate and this material may exhibit strain-hardening properties with increasing sand fraction. Pressure solution effects may be important in certain joints subjected to non-hydrostatic stresses.

The phenomenon of earthquake instability is basically related to frictional sliding along a fault plane. A large number of laboratory experiments have indicated that the shear strength of fractures is related to the normal stress by the approximate relation, $\tau \approx 0.85\sigma'$ when $\sigma' < 2$ kb and $\tau \approx 0.5 + 0.6\sigma'$, $\sigma' \geq 2$ kb. If, because of pore pressure rise, $\sigma'$ is so diminished that $\tau$ falls below the shear stress in situ, the resulting sliding should lead to seismicity. This appears to be an adequate model for seismicity provided that we can reasonably predict the time-dependent variation of pore pressures leading to a progressive decline in normal effective stresses. A principal concern is therefore the permeability of the in situ material and the factors that influence its change. Experimental evidence indicates that the presence of compressible clayey materials in fractures considerably influences the permeability versus effective stress relation. Thus, permeability is related generally to $(\tau - \alpha p)$ with $\alpha < 1$ for clean fractures and $\alpha > 1$ for fractures with clay. A knowledge of these properties at hypocentral depths is essential in order to predict induced seismicity.

That fault movement occurs as the pore pressure exceeds a critical value causing fractional sliding was demonstrated in the case of the Rangely earthquakes through the use of mathematical simulation of the hydrogeologic system. In this case there was a definite correlation between the frequency and location of the earthquakes and the local fluid pressures.

Considerable research activity is currently in progress in studying reservoir induced seismicity. Among the carefully collected data at these sites are included: the measurement of in situ stress, permeability and fracture characteristics; the monitoring of earthquake loci and magnitudes. Depending on the permeability of the in situ rocks, the time-lag between lake filling and seismicity may vary from a few months to as much as several years. It is quite probable that the migration of pore pressure transients is critical to induced seismicity. Is there a reasonable chance of modeling the phenomenon accurately enough to achieve reliable prediction? An outstanding problem still defying solution is that of predicting earthquake magnitudes.

It was also pointed out that induced seismicity generally occurs only in areas where the shear strengths are close to existing shear stresses. The fact that induced seismicity occurs is a direct evidence that in situ conditions are close to criticality.

Measurement of in situ stresses is therefore of paramount importance in areas of seismicity. It was suggested that through a careful analysis of the geomorphic history of a given region, one could decipher the effective stress evolution over the geological past and draw inferences about the current state.

While the factors that cause seismicity are important for earthquake prediction, it is equally essential to study those factors which help mitigate earthquake hazards. Over the past decade, geotechnical engineers have established that abnormal pore pressure generation in shallow, cohesionless soils leads to soil liquefaction. Indeed, the study of many earthen dams and foundations subjected to strong earth motions show that abnormal pore pressure generation commonly accompanies cyclic loading in alluvial soils and earth structures. Experimental study of pore pressure generation using shaking tables simulating cyclic loading is therefore a very active area of research. Theoretical studies as well as experimental results from shaking table experiments were presented and discussed.

It was shown that the liquefaction of a sand or silt deposit depends not only on the looseness of the deposit, but also upon the mode of seismic loading. Loading in which the direction of shearing is alternately reversed has been found to be more effective in bringing about liquefaction than is one-directional, pulsating loading.

It was also pointed out that looseness of a deposit is a relative term and that the tendency of a material to contract during shear increases not only with porosity, but also with the confining stress to which it is subjected prior to shearing.

Techniques were illustrated whereby the magnitude of pore pressure generated by seismic loading of a granular material can be estimated, if certain parameters and conditions of loading are known.

It was noted that in situ stress measurements are of great importance in delineating areas of potential seismicity. The technique of measuring stress in situ using hydraulic fracturing is extensively employed. In addition, hydraulic fracturing is also beneficially employed to stimulate low permeability reservoir rocks to augment production of oil, water and geothermal fluids.

The nature and disposition of hydraulic fractures depend on the orientation of the local principal stresses, the toughness of the rock and the fluid pressure gradient within the fracture. Assuming elastic properties for the crack, theoretical relations have been developed to distinguish conditions of stable and unstable fracture growth. Theoretical analysis has also been carried out to study the growth of long, elliptical cracks and the controlling parameters. Field and laboratory studies indicate that the rate of fluid pressurization is important in controlling fracture disposition. Rapid pressurization favors vertical fractures while slow pressurization leads to horizontal fractures.

A large amount of field data collected from throughout the United States and elsewhere were presented and discussed. Induced seismicity studies in Illinois appear to indicate a threshold pressure of 240 bars. These studies have also helped draw broad pictures about the global distribution of in situ stresses. Such data appear to indicate a northeasterly trending compressive axis over much of Wisconsin and Illinois. However, similar studies in Iceland showed many local variations.

The technique of hydraulic fracturing is continuing to undergo development both in terms of hardware and interpretive techniques. The interpretation of pressure transient data from hydraulic fracturing tests is particularly involved due to the presence of well compliance effects, as well as the time-dependent variations in fracture geometry, aperture and stiffness. The successful application of a numerical model towards interpreting an actual field test and the estimation of the minimum principal test was presented. Whether mathematical models can help improve the design of hydraulic fracturing tests appears to be a fruitful area of inquiry. Perhaps the most important field problem in hydraulic fracturing at the present time is that of determining the maximum principal stress, since it is the difference between the maximum and minimum stresses that governs frictional sliding.

In the foregoing discussions the main emphasis was placed on the mechanical aspects of pore pressure generation and the interaction between pore pressure and skeletal stresses. However, in certain geological environments, chemical effects can act in conjunction with mechanical effects and contribute greatly to the creation of anomalously high pore pressures. Such anomalously high pore pressures are known to exist in many deep, young sedimentary accumulations.

The following mechanisms are believed to contribute to abnormally high pressures: aquifer head due to natural recharge, "fossil" head due to exhumation and erosion, tectonic compression, rapid loading and compaction, influx of juvenile water, gas infiltration, mineral dissolution or precipitation, phase changes (gypsum ⟷ anhydrite, smectite ⟷ illite, heavy hydrocarbon to light hydrocarbon), expansivity to temperature changes, and osmotic (clay-membrane) phenomena. There were considerable discussions as to which of the aforesaid mechanisms was the most dominant in geopressured systems. The phenomenon of non-equilibrium compaction, that is rapid deposition without adequate time for drainage, is perhaps the most dominant of all the mechanisms. In this mechanism, the role of permeability is very important. If rapid burial is accompanied by reduction in permeability due to precipitation and related effects, abnormal pore pressures are augmented. Among the other mechanisms, mineral-phase transformations, aquathermal effects and osmotic effects are probably the most significant, in general.

A consequence of the existence of abnormal pore pressures in the shale beds in deep sedimentary basins is that they exist in a state of under-consolidation. As a result, they possess high bulk compressibilities. Any reduction in pore-fluid pressures in these horizons should be expected to lead to significant reduction in pore-volumes with accompanying ground subsidence and related earth displacements. Due to the paucity of reliable field data, only speculations can be made at present on the possibility of subsidence. One prevalent belief is that although large deformations may occur at depth, the thick sequence of overlying sediments will inhibit or modify the vertical migration of reservoir displacements to the surface.

## CONCLUSIONS

It became obvious from the lively discussions and the diversity of presentations that the role of pore pressure in geological deformation processes is not only an important area of investigation, but that it is emerging as a broad, all encompassing one. Many of the vital or critical problems society faces today -- resource exploration, evaluation, recovery, earthquake hazards, and ground stability to name the more important ones -- are linked to the role of pore pressure. Although our understanding of the intricate behavior of geological material and the interaction between physical and chemical processes in the presence of pore fluids is far from adequate, the conference did show that we are rapidly gaining understanding of what the important problems are -- a first step to solving them. We all agreed that a great deal of new active research in the area of pore pressure is to be expected and encouraged in the coming decade.

## Some References on Pore Pressure - Deformation Relationships

The following collection of references deals with the general topic area of the interaction between pore fluid pressures and deformation in geologic systems. The collection is basically a list of publications/ reports that were assembled for the use of the participants in the Penrose Conference on "The Role of Pore Pressure and Deformation in Geologic Processes," which took place in San Deigo, California, November 9-13, 1979. The references by no means claim complete coverage of all the important papers on the topics. However, the list does contain most of the major North American references. The topics have been classified into the following categories, within each of which the references are arranged alphabetically according to authors:

Abnormal Pore Pressures

Clay Behavior

Diffusion Equation for Deformable Media

Effective Stress Laws

Fracture Mechanics

Hydraulic Fracturing

Permeability

Physical Properties

Pore Pressure (General)

Pore Pressure Measurements

Pressure Solution Effects

Seismicity and Induced Seismicity

Stability, Failure, Liquefaction

Stress - Strain Relations

Subsidence and Related Effects

Wave Propagation

Abnormal Pore Pressures (Geopressures)


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