Chapter 16: Outlook for Rock Mechanics

THE PRINCIPLES of rock mechanics and rheology outlined here provide a basis for applications in structural geology and geotechnical engineering. The elementary theory also is essential for developing scaled model studies of rock stability and the formation of deformation structures. However, it is emphasized that successful integration of the theory with natural applications requires considerable practice. Some guidelines for further study and hints for avoiding major pitfalls are given in this chapter.

Contents: General application areas of rock mechanics are briefly outlined in section 16-1. The continued importance of geological field studies and site investigations is advocated in section 16-2. The complementary role of scaled model studies is introduced in section 16-3. Several noteworthy misconceptions and errors, persistently recurring in the geological literature, are summarized in section 16-4. Some limitations of the modern state-of-the-art in rock mechanics and a number of important topics in rock mechanics, urgently requiring further research, are suggested in section 16-5.

***Practical hint:* The rheology of anisotropic continua needs further study. The development of tectonite fabrics in deforming rocks is likely to have a profound effect on their mechanical behavior. Prepare a seminar discussing the significance of the anisotropy factor, as described in Weijermars (1992, see refs. p. 306).**

16-1 Where to apply your skills?

Rock mechanics provides knowledge about the behavior of rocks in response to forces. This knowledge is useful in determining the ground stability in tunneling, excavation, and building projects. Rock mechanics, also, helps to understand the deformation of the crust, involved in earthquakes, volcanism, and meteoritic impacts. Apart from the fast, elasto-plastic processes dominating in the above applications, other large-scale deformation patterns in the crust result from very slow creep of the rock. Understanding the formation of such patterns helps to unravel the tectonic history of the crust. This knowledge benefits the strategic planning of mining operations and hydrocarbon exploration.

Many of the applications of rock mechanics are too detailed and too complex to treat in a basic textbook like this one. This book was prepared to cover just one semester of teaching, and, thus, only basic principles and fundamental techniques are included. Much improved understanding of the topic can be fostered by applying fundamental knowledge, developed in this textbook, to advanced and practical situations. Perhaps three major application areas can be distinguished. These are (1) practical applications in field work and site investigations, (2) applications in dynamical modeling of complex deformation structures, and (3) applications in fundamental research on the deformation mechanisms and rheology of rocks. Each of these areas is briefly outlined in the following sections (i.e., sections 16-2, 16-3, and 16-5, respectively).

□Exercise 16-1: Write an essay of two pages, summarizing what rock mechanics is all about. Feel free to concentrate on a particular aspect which has interested you most.

16-2 Applications in fieldwork and site-investigations

Geoscientists and civil engineers need theoretical knowledge of rock mechanics. Of course, the theory cannot replace the fruitful experience of practical applications, but it provides a starting point to such venues. The theory complements practical knowledge on the stability and rheology of natural and man-made structures in rocks. Continued exposure to field geology and building sites is a most important and enjoyable activity (Fig. 16-1). It provides an excellent opportunity for developing a profound understanding of the variety of deformation structures in natural rocks. Teaching and studying geology and rock mechanics without field work is like educating a surgeon without practice on human bodies - How could any specialist ever become skillful without a carefully guided exposure to practical experience?

Figure 16-1: Students from King Fahd University of Petroleum and Minerals at work on the rocks of the Arabian Shield, Saudi Arabia.

Every new construction operation is likely to cause changes in the existing condition of the ground surface. Civil engineering works, involving ground movement, include: open excavations, drainage networks, trenches, tunnels, underground repositories, foundations of dams, bridges, buildings, road cuts, railways, airfields, harbors, land reclamation, and docks (Fig. 16-2). The chief aim of preliminary geological investigations is to provide accurate information about the subsurface conditions at the site of the proposed work and sometimes to identify possible locations for opening quarries, suitable for extracting some of the required construction materials. The geological conditions at the site of construction will determine the cost of the operation. It, also, may reveal the necessity of specific measures, needed to stabilize the foundations of the work and other rock faces nearby.

The geological information may further influence the engineering operation in that it may require possible alterations in design of the construction work, due to variations encountered in subsurface conditions. It usually, also, determines to some extent the method of construction to be adopted. It is, therefore, necessary to make a thorough geological survey of the area in which the works are to be situated. Before undertaking any design work for a project, a civil engineer must have full information on which rocks construction is to be founded. This will necessitate examination of the work site. The site study must always be considered in conjunction with, and is conditioned by, information available from previous geological studies of the area. Detailed study of the site itself, including full-scale tests of the rock *in-situ*, is a desirable means of further eliminating some of the uncertainties, arising from the preparatory studies in major rock-stability investigations. The geological conditions are best considered before any design or construction starts - to avoid major troubles and cost-escalation that may otherwise develop during or subsequent to the construction project.

For any major construction project, a close cooperation between engineers and geologists seems advisable. Engineers commonly have a strong background in rock mechanics, but they are sometimes less experienced in assessing the subsurface conditions of the construction site. On the other hand, geologists are experienced in abstracting information on the subsurface structure, using only a limited set of data available from rock outcrops, possibly supplemented by

□Exercise 16-2: One of the most common solutions for radioactive waste disposal comprises very long-term storage in underground repositories. Two major geological settings are popular: a) salt domes in intracontinental basins, and b) granite plutons in Precambrian shield areas. Discuss how the mechanics and rheology of the walls of any cavities in these rocks may jeopardize the stability and longevity of these repositories.

Figure 16-2: *Excavation at construction site with scaffolding of the walls in the foundation works.*

knowledge obtained from drill-cores. But their quantitative knowledge of rock mechanics is sometimes incomplete. Therefore, combining the skills of engineers and geologists provides the best guarantee for a proper evaluation of the geological conditions at the construction site.

16-3 Applications in model simulations

Further information on the behavior of rocks under special stress and boundary conditions is obtained in carefully scaled model studies of rock deformation. The purpose of model studies in fluid mechanics and aerodynamics is usually to avoid the expensive construction of real-size models. Down-scaled aircraft models are studied either in computer simulations or in wind tunnels. In rock modeling it is, also, common practice to down-scale the size of most instabilities observed over large length-scales in real rocks. The design of bridges, dams, and harbor infrastructure is carefully studied in miniature replicas at hydraulic laboratories. Stress and strain levels in the foundations are monitored and tested before building the complete structure.

The rate of deformation in natural rocks is usually extremely slow, so that we cannot observe any motion. Many tectonic experiments are aimed at speeding up the rate of deformation in a scale model, so that the kinematics of the deformation process can be studied (Fig. 16-3). Such scale models are useful for generating new concepts and for reconstructing the structural evolution of tectonic domains. For a concise introduction into the fundamental techniques of modeling rock deformation, the reader is referred to *Modeling of Rock Deformation*, a companion book in this lecture series (see page vi).

□Exercise 16-3: a) Which two physical quantities are commonly scaled in analog experiments, simulating natural rock deformation? b) Is there any relationship between these two quantities?

16-4 Avoiding common errors and misconceptions

Geologists and geotechnical engineers have a particularly difficult task in that the proper conduct of their profession requires them to tap a wide variety of skills. And the range is still expanding! They must be able to prepare and interpret geological maps under unpredictable field conditions. This requires physical fitness and sharpness of mind under all circumstances.

It must be emphasized that, perhaps due to the very wide range of skills required from geoscientists, inevitably some misconceptions have crept into the literature. Such misconceptions are particularly common in attempts to apply mathematics and physics to geological structures. Some of the erroneous assertions, recurring in the literature, are blacklisted below. References to the many works, from which these mistakes have been spotted, are not included, because the aim here is not to blackmark those who make and have made such mistakes. But the blacklist may help to stamp out or reduce the future occurrence of these misleading statements. Most of the misconceptions refer to concepts of either stress, strain, or rheology, and the statements of common misconceptions are listed accordingly below. Each numbered label, Mx, stands for a particular misconception and is included for your convenience. It may come in handy when pointing out mistakes in practical assignments.

Stress: M1) The orientations of the force vector and the major axis of principal stress are taken to be similar. However, this is the case only in progressive pure shear deformations. M2) The deviatoric stress is not distinguished from the total stress. The distinction is not always necessary, but it should not be overlooked in some applications, where it is of crucial importance. M3) Vector-decomposition rules are wrongly applied to obtain the components of normal and shear stress, thus violating its tensor property.

Strain: M4) The plane strain assumption is mistakenly not verified in field studies, applying

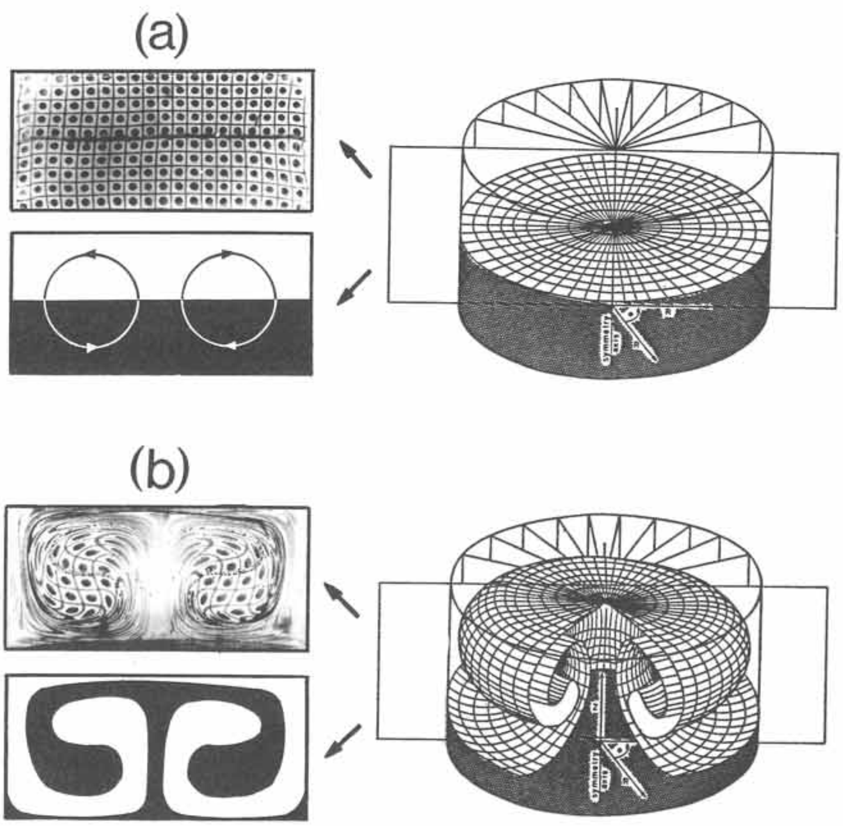

Figure 16-3: a) & b) Visualization of deformation within a vertical section of a convecting fluid: (a) Streamlines and deformation markers before the onset of flow. (b) Distortion inside the rising plume after convection for 14 minutes in the analog model at Rayleigh number of 10^4. The corresponding mantle time would be 650 million years.

practical techniques of strain analysis. M5) Strain is wrongly assumed to be synonymous with deformation or distortion, and the component of rotational distortion is neglected. M6) The rotational component of deformation is not accounted for in discussions of 3D deformation, using either the Flinn plot or the Hsu plot. Consequently, only the strain part of the deformation is accounted for. M7) The orientation of the incremental strain axes in simple shear deformations is not properly oriented at 45° to the direction of flow. M8) The major principal axis of finite strain in a unit simple shear is wrongly shown at 45° to the direction of shear. Explanatory note: For simple shear of unity this angle is about 32°. M9) Deformation is sometimes wrongly thought to be primarily due to the boundary displacement rather than the presence of a surface or body stress.

M10) Elongation and stretch are confused. M11) Quadratic elongation is mistakenly taken as the square of the elongation. Instead, it is the squared stretch (section 11-1). M12) The strain rate is multiplied with time to obtain the finite strain. This is increasingly inaccurate for large finite strains. The exact finite strain follows only from the time-integration of the velocity gradient equations and this yields an exponential function (section 13-5).

Rheology: M13) Anelastic response is mistaken for viscous behavior. M14) Frictional plasticity curves of rocks, deformed under cold press conditions, are confused with crystal plasticity curves of hot press conditions. Explanatory note: The graphs look similar, but the underlying deformation mechanisms are entirely different. M15) Non-Newtonian rheology of rocks is inadvertently considered important, despite the fact that the study concentrates on homogeneous deformations. Explanatory note: In such cases only an effective viscosity is relevant and the non-Newtonian nature of the rock becomes irrelevant.

□Exercise 16-4: Choose at least one of the mistakes listed above, and explain in detail why indeed they are mistakes.

16-5 Suggestions for further research

Some topics suitable for further investigation can be identified by pointing out limitations of the current state-of-the-art of rock mechanics. The suggestions below are just a few out of many topics, awaiting further research. But the ones outlined here may help to initiate you in directing your attention to some areas, which could benefit from further studies.

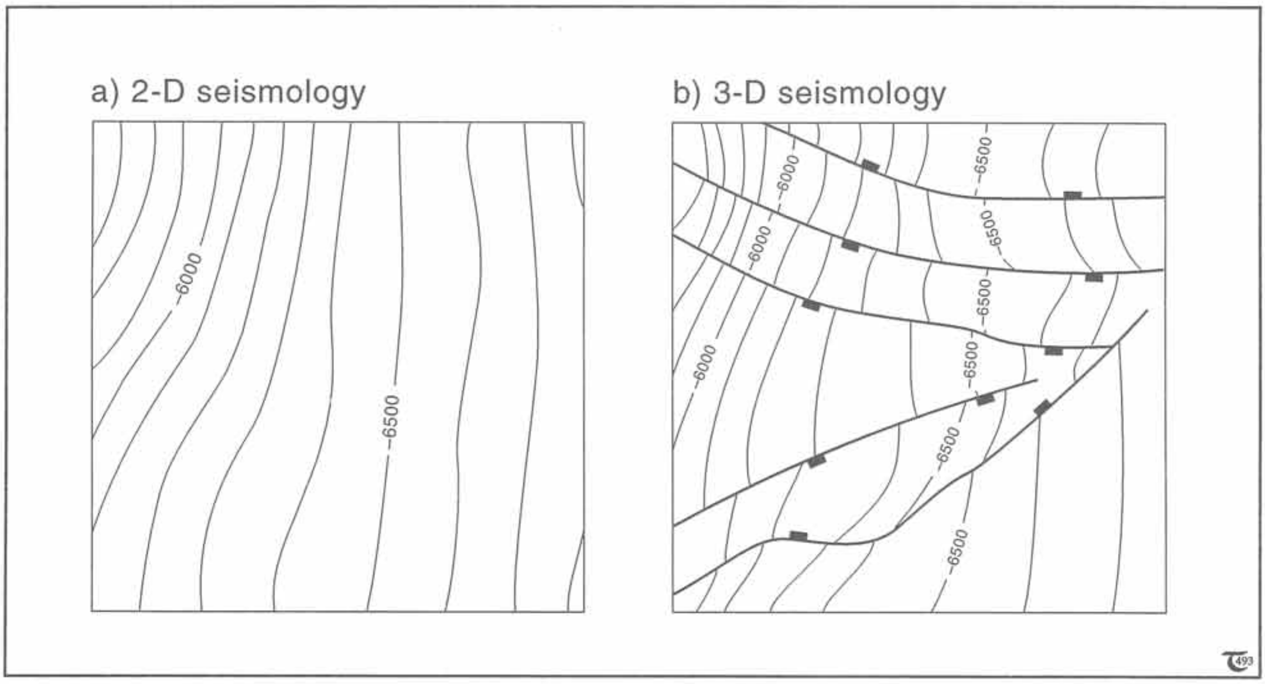

Figure 16-4: *a) & b) Structure contours, interpreted from 2D and 3D seismic surveys, respectively. This example of improved resolution is from the east flank of the Ghawar anticline, Arab hydrocarbon reservoir, Saudi Arabia. Depth is in feet.*

One of the starting principles in continuum mechanics is the continuum assumption. When transferred to the study of rocks, it is immediately obvious that rocks do not comply with the simple models usually assumed in the continuum approach. One of the features peculiar to crystalline flow is the proneness to develop an anisotropic viscosity. Compositional and textural anisotropy of rocks is well documented from field studies, but this phenomenon is still largely neglected in laboratory studies of rock flow. The presence of cleavage and linear fabrics in rocks is likely to have a significant effect on their mechanical behavior. The limited strain memory of rock fabrics, also, should be taken into account in more advanced continuum models of rock flow.

Additionally, volume changes may accompany the textural and compositional changes brought about during deformation. Initial volume reduction may result from simple compaction and dehydration. Further decrease of the volume upon burial may occur due to chemical reactions during metamorphism. Conversely, volume increase and drastic compositional change results from the injection of igneous dikes and hydrothermal veins. But continued volume reduction may take place in some rock types by chemical solution. For example, stylolites are found in many drillcores during hydrocarbon exploration of carbonate sequences. All of these phenomena for further research focus on time-dependent changes in the physical properties of the system, as well as the fact that deforming rocks are open and not closed systems. Material may be added and removed from the deforming rock volume in the course of the deformation. Theoretical studies and field surveys to investigate further any of these phenomena would be very useful indeed.

Deformation analysis typically concentrates primarily on the strain component of deforma-

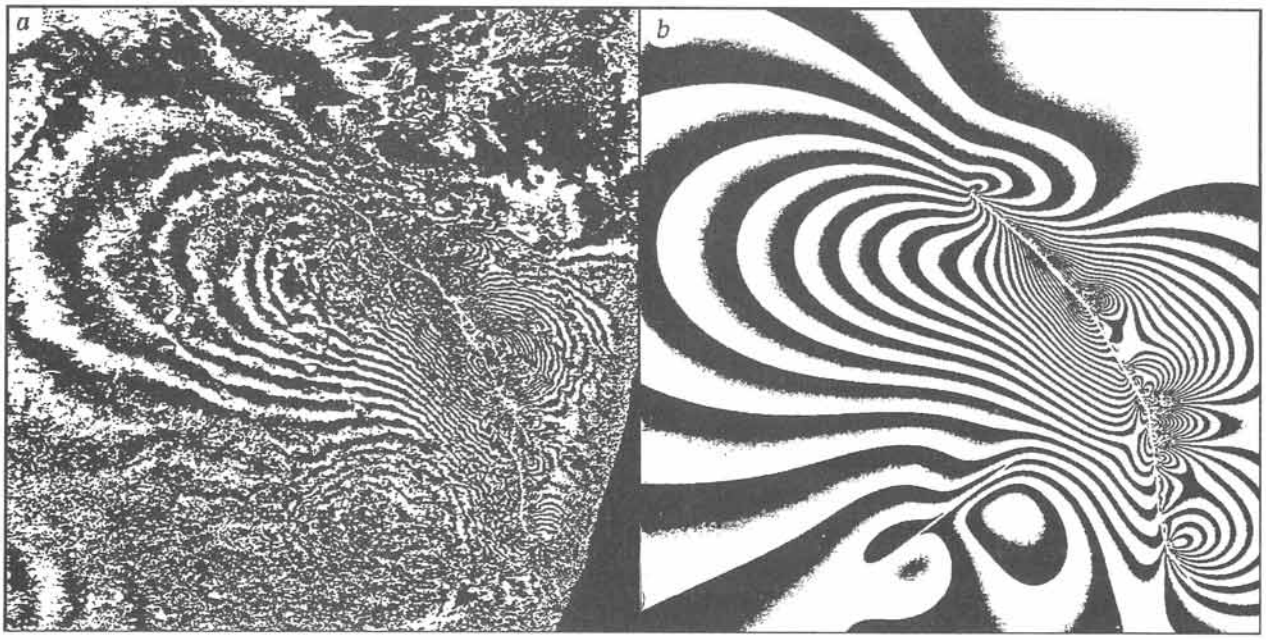

Figure 16-5: *a) Interferogram of ground surface displacements, associated with the 1992-Landers earthquake, California. Width of the image is 100 km. The pattern contours displacement vectors of the ground, pointing towards the ERS-1 satellite by comparing radar measurements before and after the quake. b) Displacement fringe pattern in an elastic halfspace-model, using the boundary conditions of the Homestead Valley fault, which generated the Landers quake.*

tion. This is because strain recovery can be done without the need to establish an external reference frame for the deformation path. However, for a complete understanding of the deformation history, it is necessary to recover not only the strain component, but also the rotation component of the deformation. Additionally, in many strain studies, the effect of sections oblique to the actual strain ellipsoid has been insufficiently considered. The question of the strain and rotation memory capacity of deformed marker objects needs to be explored in further detail.

It is important to take into account the role of new technological developments in rock deformation studies. Impressive results have been obtained by improving the resolution of several remote sensing techniques. For example, 3D seismics is now revealing the presence of very detailed fault patterns in many of the world's major hydrocarbon provinces (Fig. 16-4). In another development, interferometric processing of radar images of the ground surface reveals surface deformations in real time (Fig. 16-5). Such radar surveillances may ultimately lead us to predict earthquakes and volcanic eruptions with much greater precision than hitherto. It must be emphasized, however, that the proper interpretation of such new results requires a good understanding of rock mechanics.

This textbook aims to inspire a new generation of forward-thinking geoscientists and engineers, skillfull in, and favorable to, the practical application of mechanical principles to rock structures. Your efforts are needed in research and in applied science in order to help advance our field to further maturation. This will best succeed by careful study, hard work, and tedious calibration of your results. Stay true to the basic principles, do not compromise your knowledge, and you will get there, sooner or later!

□Exercise 16-5: Write a complete, and possibly detailed, proposal for a new research project, aimed at advancing our knowledge of any aspect of rock mechanics.

References

Articles

Peltzer, G. and Rosen, P. (1995, *Science*, volume 268, pages 1,333 to 1,336). Surface displacement of the 17 May 1993 Eureka Valley, California, earthquake, observed by SAR interferometry.

Weijermars, R. (1992, *Journal of Structural Geology*, volume 14, pages 723 to 742). Progressive deformation in anisotropic rocks.