Part One
Introduction to rock mechanics

1 The historical development of rock mechanics

1.1 The first attempts at rock mechanics

At the end of last century, geologists studying the formation of the Alps were realizing that tremendous forces were necessary to lift continents and form their mountain chains. Mining engineers and tunnel experts watching rock bursts and rock squeezing in tunnels and galleries, suggested that some 'residual forces' were still at work in rock at great depth. The German tunnel expert Rziha (1874) was probably the first to be concerned with the horizontal component of the forces acting in many tunnels. A few years later Heim (Professor at Zurich University and at Zurich Federal Institute of Technology) suggested that the horizontal force component must be of the same order of magnitude as the vertical component and he forcefully stressed this opinion in several papers (1878–1912). It took many decades for geologists and engineers to realize the importance of the ideas of Heim and Rziha.

In 1920, the Ritom tunnel, which had just been built south of the Alps by the Swiss Federal Railways, was severely damaged. Inspection showed many longitudinal fissures running along the tunnel. The rock strata had a general dip towards the valley and it was feared that water seepage could cause a rock slide. The tunnel was repaired.

At that time, the Swiss Federal Railways were also building the Amsteg tunnel north of the Alps. They decided to start pressure tests in this second tunnel. A dead end of the gallery was sealed off with a concrete plug provided with a manhole and steel cover and was filled with water under pressure. The tunnel diameters were measured by a spider with six branches and the length variations of the six radii versus time were recorded on a rotating disc. The varying water pressure was also recorded and strain-pressure diagrams traced. The bulk modulus of elasticity was estimated as a ratio of stress versus deformation. This was probably the first recording of the elastic deformations of rock masses.

A few years later J. Schmidt (1926*a*, *b*) published a thesis in which he cleverly combined Heim's ideas about residual stresses in rock, with the newly formulated ideas of rock elasticity to produce the first attempt at a theory of rock mechanics.

It was at this time that steel linings for tunnels and shafts were first introduced, and several authors (Jaeger, 1933), in different countries, produced papers estimating the stresses in the lining as a function of the relative elasticity of the steel and the rock. A few years later the Chilean geologist Fenner (1938) published a thesis which in many respects is similar to that by Schmidt. These two pioneering works were ignored by most engineers until many years later. Some of their theories were confirmed by Terzaghi & Richart (1952).

1.2 European and American efforts

Many engineers were astonished at the wealth of material Talobre was able to produce in 1957 in his excellent treatise *La Mécanique des Roches*. During the preceeding ten years, research in the field of rock mechanics had been slowly gaining momentum, and Talobre's treatise was most timely.

Important research had been going on on both sides of the Atlantic mainly in connection with the mining industry. As early as 1916, Young & Stock listed over a hundred papers dealing with mining problems and the mechanics of subsidence, mostly in relation to coalfields. American mining schools and the U.S. Bureau of Mines were very active and so too were their European counterparts. They were concerned with theoretical problems of stress around rectangular-shaped cavities but were also faced with many practical problems. Techniques were being developed for measuring strains and rock deformations, rock elasticity and convergence of the walls of galleries and cavities. A treatise by Obert & Duvall (1967) gives an extensive bibliography on the early efforts of American and European mining engineers.

Most American experts regard 1950 as the year in which systematic research into rock mechanics began in the USA. American mining schools and universities were increasingly active, mainly on the national level. Nation-wide symposia were organized; the U.S. Bureau of Reclamation at Denver was leading world research on the properties of rock material and rock masses; and an American Society of Engineering Geologists was created, one of its aims being the development of rock mechanics, which for many years was also the concern of the American Geophysical Society, the American Society for Testing and Materials and their research committees. In several American universities the teaching methods in engineering geology were modernized and adapted to the requirements of the petroleum and mining industries.

In Europe during the years 1950 to 1960, the most active centre of research outside the mining schools was probably the University of Vienna, where

Stini created an Austrian Society for Geophysics and Engineering Geology. This expanded rapidly and the 'Austrian School' became well known for its efforts in precisely describing and defining the faults and fissures in rock, far more exactly than is usual in engineering geology. Engineers from many European countries congregated in increasing numbers at the annual congress organized in Salzburg. After deciding against the possibility of linking its efforts with the International Conference on Soil Mechanics, the Salzburg group expanded on its own, forming the core of an independent International Society for Rock Mechanics. This body organized the First International Congress in Lisbon, Portugal, in 1966.

As early as 1951, dam designers started a parallel effort, when a suggestion was submitted by the author to the International Commission on Large Dams (ICOLD) to create a sub-committee on rock mechanics.

Up to this time geologists had been extremely careful in deciding where to build dams. Dams were of relatively moderate size and there were few problems on the stability of rock abutments. Isolated cases of dam rupture were explained by uplift forces or by failing shear strength of the rock. These two points initiated the development of techniques of dam foundation.

The demand for more and more electric power, led to larger dams and to the introduction of bold arch dams. The problems of the strength of rock abutments were becoming more pressing and more difficult. It became imperative to include the elasticity and plasticity of the rock abutments in the mathematical analysis of the arch dams and to consider with greater care the strain and stress distribution in the rock masses. The techniques of testing rock *in situ*, of analysing test results and of exploring rock abutments with galleries attained a high degree of precision. It was felt that dam designers and hydro-power engineers were fully responsible for the structures they were designing and that they could not leave the task of developing methods for rock testing, tunnel construction and dam foundation design to others.

In 1957, a small committee of experts, headed by G. Westerberg (Stockholm), submitted a report recommending the formation, within the organization of ICOLD, of a 'Committee on underground work' whose aim would be to solve the most urgent problems of rock foundation for large dams. The first official meeting of the new committee was at the Sixth Congress of ICOLD in New York, in 1958 (Guthrie-Brown, 1970).

On 3 December 1959, the dam of Malpasset burst, killing about 450 people. The Vajont disaster occurred during the night of 9 October 1963. Members of the 1961 ICOLD Congress (Rome) and the 1964 Edinburgh Congress were deeply shocked by these two disasters. There was no doubt that everybody considered the furthering of rock mechanics as the most urgent task for all dam designers.

1.3 Present trends

The Lisbon Congress (1966) was to show some important increase in the knowledge of physical and mechanical properties of rocks.

The present trends can be summarized as follows:

(1) Research on the structure and microstructure of rocks; causes of weakness and failure. This research mainly concerns universities.

(2) Laboratory testing of rock material; testing methods; standardization of tests, classification of rock material for engineering purposes.

(3) *In situ* tests of rock masses. Physical and mechanical characteristics of rock masses.

(4) The development of new methods of measuring strains, deformations and stresses. Mathematical theories of stresses and strains in homogeneous and non-homogeneous space or half-space and in fissured space. The introduction of new methods and the use of computers.

(5) Rock slopes, stability and safety of structures in rock; design of galleries and cavities, design of rock abutments for dams, consolidation of rock masses.

More recently, the efforts concentrated on:

(6) Research on the statics and dynamics of cleft water and water circulation in rock joints.

(7) The foundation of large dams on rock.

(8) The classification of jointed rock masses for engineering purposes.

(9) Practical applications of the new Austrian tunnelling method and similar methods. The design and construction of underground works.

2 Engineering geology and rock mechanics

2.1 The geologist's approach to rock mechanics

An American geologist, Professor Kiersch (1963), submitted to the annual Congress of the Austrian Society of Rock Mechanics in Salzburg (1962), a most interesting paper on the trends of engineering geology in the United States and on the modern teaching methods introduced at several American universities for training the new generation of engineering geologists. At the same meeting Professor Bjerrum, from Norway, speaking on behalf of A. Casagrande (President of the International Conference on Soil Mechanics) brilliantly explained how rock mechanics should be integrated into soil mechanics as a mere chapter of a wider, more advanced technical science. The Congress reacted by deciding to expand their own efforts and to form the nucleus of an International Society of Rock Mechanics.

Rock mechanics adopts many of the techniques developed in soil mechanics based on the simple law of Coulomb which related shear strength of elastic materials to the friction factor and the normal stress. But the behaviour of rocks is far more complex than the behaviour of soils, and in many cases rock mechanics uses techniques unknown in soil mechanics. The two are parallel but distinct chapters of the science of discontinuous spaces as opposed to the classical theory of strength of materials assuming a continuous space. The links between rock mechanics, engineering geology and classical geology are even more intricate and complex. It is not possible to think about rock mechanics without examining and discussing these links.

Geologic materials possess certain physical, chemical and mechanical characteristics which are a function of their mode of origin and of the subsequent geologic processes that have acted upon them. As stressed by Deere (1968, quoting Miller, 1965) in a lecture given at Swansea University: 'The sum total of these events in the geologic history of a given area lead to a particular lithology, to a particular set of geologic structures and to a particular *in situ* state of stress.' All this geological information is of fundamental importance to rock mechanics.

The geological classification of rocks (lithology) refers to the mineralogy, fabric, chemistry, crystallography and the texture of rocks. Even though rock mechanics has set up a completely different classification, based on strength, deformation and fissuration of rocks, an understanding of the geological classification is of paramount importance.