1. Preface

These notes were originally prepared during the period of 1987 to 1993 for graduate courses in rock engineering in the Department of Civil Engineering at the University of Toronto, where I was a Professor of Rock Engineering. From time to time, these notes were added to and updated, but they have remained in their original form for the past thirty years.

In 1996, the software company, RocScience Inc., was established for the development and marketing of geotechnical software for both educational purposes and for use in the design and analysis of civil and mining projects. These notes, with the title of Practical Rock Engineering, were placed online as one of the components of the RocScience website and they have always been freely accessible to anyone wishing to use them.

In 2020, I retired from all my consulting and academic activities and started the process of assembling material for a complete update and rewrite of these notes. In 2022 and 2023, I prepared several new chapters and re-wrote several of the original chapters to incorporate advances and practical applications in the field.

The original notes were prepared as a series of completely self-contained chapters each with its own page numbering and references. This proved to be a very effective presentation since the users could access a volume dealing with a particular topic of immediate interest to them. Wherever possible, case histories are included to illustrate the basic topics presented in the notes.

These notes are not a formal text and have not been, and will not be, published in any other format.

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Evert Hoek

Evert Hoek was born in 1933 in Southern Rhodesia, now Zimbabwe, Africa. He graduated in mechanical engineering from the University of Cape Town with a B.Sc. in 1955 and an M.Sc. in 1957.

He became involved in rock mechanics in 1958 when he was employed by the South African Council for Scientific and Industrial Research and worked on problems of rock fracture in very deep level gold mines. He was awarded a Ph.D. in 1965 by the University of Cape Town for his research on brittle rock failure.

In 1966, he was appointed Reader and, in 1970, Professor of Rock Mechanics in the Royal School of Mines at the Imperial College of Science and Technology in London. He was responsible for establishing an inter-departmental group for teaching and research in rock mechanics.

In 1974, he was awarded a Doctor of Science (Engineering) degree by the University of London based on his published works and research record. He ran two major research projects, sponsored by several international mining companies, that provided practical training for graduate students. These research projects also resulted in the publication of two books: *Rock Slope Engineering* (with J.W. Bray) in 1971 and *Underground Excavations in Rock* (with E.T. Brown) in 1980.

In 1975, he moved to Vancouver in Canada as a Principal in Golder Associates, an international geotechnical consulting organization. During his twelve years with Golder Associates he worked as a consultant on major civil and mining projects in more than twenty countries around the world.

In 1987, he returned to academia as a Professor of Rock Engineering in the Department of Civil Engineering at the University of Toronto. Here he was involved in another industry-sponsored research project which resulted in the publication of a book entitled, *Support of Underground Excavations in Hard Rock,* (with P.K. Kaiser and W.F. Bawden) in 1995. During this time, he continued to work as a member of consulting boards and panels of experts on several international projects.

In 1993, he returned to Vancouver to devote his full time to consulting as an independent specialist, working exclusively on consulting and review boards and on panels of experts on civil and mining projects around the world. He has maintained his research interests and has continued to write papers with friends and colleagues associated with these consulting projects. He retired from these activities in 2018.

His contributions to rock engineering have been recognized by the award of an honorary D.Sc. in Engineering from the University of Waterloo in 1994, an honorary D.Eng. in Engineering from the University of Toronto in 2004, an Honorary Doctorate from the Polytechnic University of Catalonia in Spain in 2019 and by his election as a Fellow of the Royal Academy of Engineering (UK) in 1982, a Fellow of the Canadian Academy of Engineering in 2001 and as an International Member of the US National Academy of Engineering in 2006.

He has also received many awards and presented several named lectures including the Consolidated Goldfields Gold Medal, UK (1970), the AIME Rock Mechanics Award, US (1975), the E. Burwell Award from the Geological Society of America (1979), the Sir Julius Werhner Memorial Lecture, UK (1982), the Rankine Lecture, British Geotechnical Society (1983), the Gold Medal of the Institution of Mining and Metallurgy, UK (1985), the Müller Award, International Society of Rock Mechanics (1991), the William Smith Medal, Geological Society, UK (1993), the Glossop Lecture, Geological Society, UK (1998), and the Terzaghi Lecturer, American Society of Civil Engineers (2000).

Rock engineering before computers

The contents of the chapters in Practical Rock Engineering have all been written during the past thirty years during which almost all our problem solutions utilize the power of modern computers. These were not available until the early 1980s and it is interesting to consider how stress analysis problems were dealt with during the early years of the development of rock mechanics and rock engineering. My own experience dates from 1957 when I started using the techniques which were then available for the solution of rock mechanics problems. Some of these techniques are discussed very briefly in the following pages.

I graduated with a degree in mechanical engineering from the University of Cape Town in 1955. I continued to a Master of Science degree, graduating in 1957, with research into the stress distribution in threaded connections (bolts and nuts) using three-dimensional photoelastic techniques, as shown in Figures 1 and 2. In those days all investigations into the stresses in mechanical components were done on physical models. Stresses were measured by means of strain gauges, bonded onto the models at appropriate locations or by using two- and three-dimensional photoelastic models.

In 1958, I applied for a position with the National Mechanical Engineering Research Institute of the South African Council for Scientific and Industrial Research (CSIR), located in the city of Pretoria. It turned out that I was lucky since a giant photoelastic polariscope, shown in Figure 3, had been constructed at this Institute. The designer of this instrument had resigned shortly before my application was received. Since none of the remaining staff knew how to operate this machine, or very much about photoelastic analysis, I was appointed as a research engineer, responsible for stress analysis and strength of materials projects.

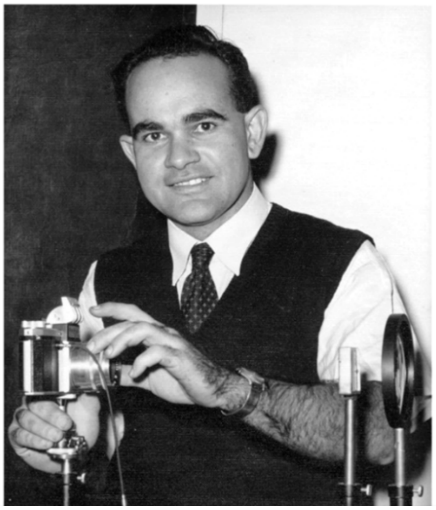


Figure 1: Evert Hoek working on a Photoelastic model, shown in Figure 2, in the Department of Mechanical Engineeriing in the University of Cape Town in 1957.

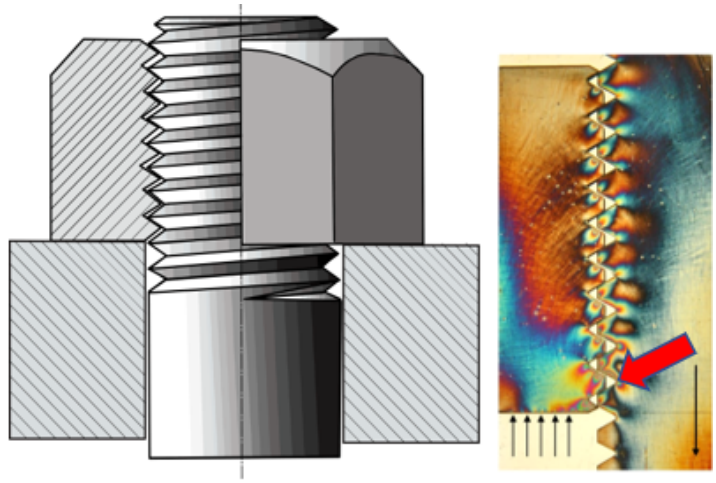


Figure 2: A sectioned bolt and nut and a slice cut from a three-dimensional epoxy resin model. The stress pattern, made visible by viewing the model in polarized light, was “frozen” into the resin by heating the loaded model to 150ºC and then cooling it slowly to room temperature. This model revealed that the highest stresses, shown by the red arrow, occurred in the first supported thread of the bolt, where the stress is about five times that of the stress in the bolt shank.

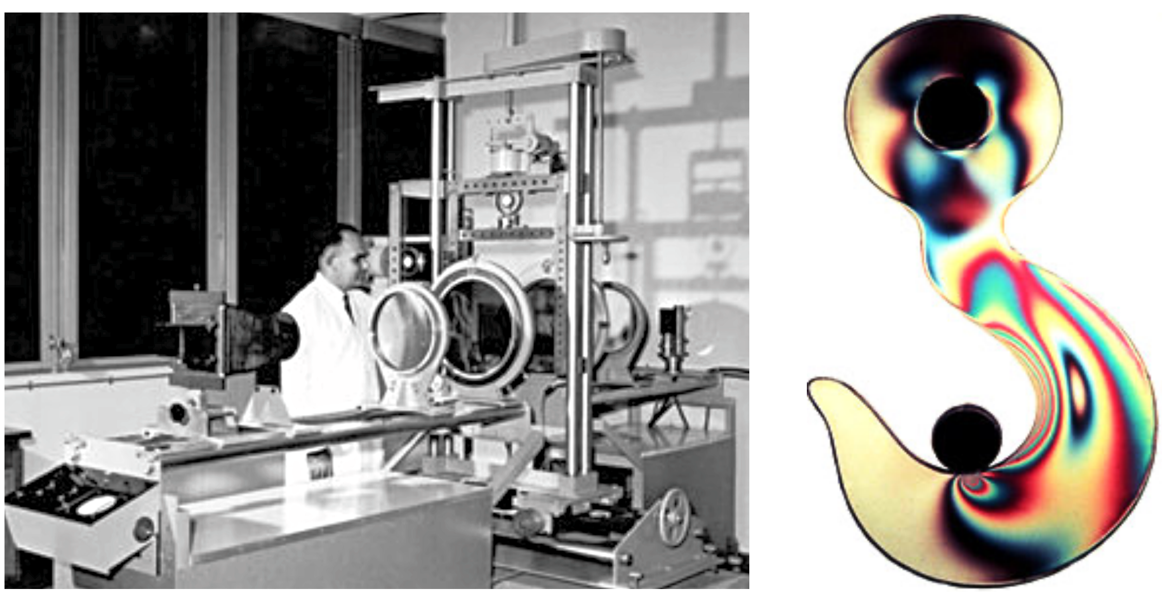


Figure 3: A large photoelastic polariscope and a photoelastic pattern in a loaded crane hook. Photographed in 1958 at the National Mechanical Engineering Research Institute in South Africa.

In addition to its work on mechanical engineering components, the CSIR also had a small rock mechanics department in which work on the measurement of in situ stresses in deep level gold mines was being carried out. I worked with this department on brittle fracture problems in the rock in these mines (Hoek, 1965). At mining depths of up to 3 km below surface, the high stress levels cause extensive fracturing in the rock, and, in some cases, these fractures took the form of very violent and dangerous rock bursts. I became a member of a team of researchers, from various universities and research organizations in South Africa, who were attempting to understand and to devise methods for minimizing the danger of rockbursts (Cook et al, 1966).

The Coalbrook Mine collapse was the worst mining disaster in the history of South Africa. It occurred in the Coalbrook coal mine of Clydesdale Colliery on 21 January 1960, when approximately 900 pillars caved in, almost 180 metres underground. About 1,000 miners were in the mine at the time and 437 died because of the collapse.

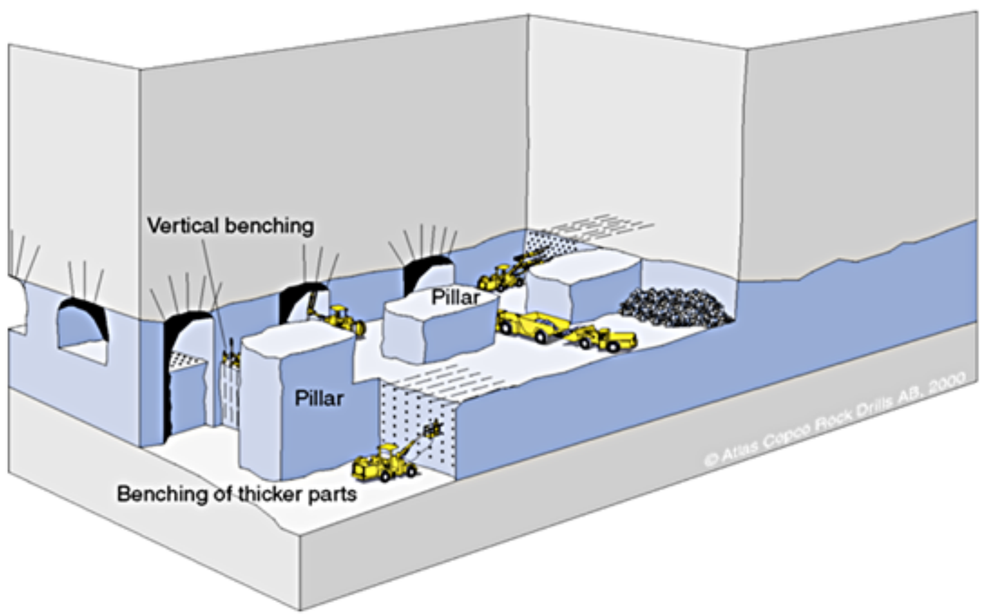


Figure 4: Simplified layout of a room and pillar mine (Image from Atlas Copco Rock Drills AB).

Following the disaster, the South African government established the Coal Mines Research Controlling Council to improve coal mine safety and to research pillar strength. It was supported by the Council for Scientific and Industrial Research and the Chamber of Mines Research Organization.

I was involved in the determination of the stress distribution and strength of coal mine pillars as part of the research program established after the Coalbrook disaster. This program existed for several years and resulted in the publication of several papers and guidelines for coal pillar design and the general safety of underground mines. The layout of an underground room and pillar mine is illustrated in Figure 4.

The three-dimensional photoelastic models used to study the stress distribution in the rock forming and surrounding pillars were constructed from blocks of epoxy resin, created by heating the component mix to 150ºC to induce the chemical reaction, followed by slow cooling to ensure that these blocks were free from locked-in stresses. The rooms between the pillars were machined from one of the two blocks used in each model. These blocks were then glued together with an epoxy adhesive to form the complete three-dimensional model. The model was loaded uniformly to simulate the gravitational load due to the weight of the overlying rock and, while still under load, the model was heated in an oven to a temperature of 150ºC and then cooled at 1.5ºC per hour until the temperature had fallen to below 70ºC. This process "froze" the three-dimensional stress field into the epoxy resin model which could then be cut into slices, approximately 3 mm thick, to allow the resulting photoelastic pattern to be viewed in polarized light.

A typical photoelastic image in one of these slices is reproduced in Figure 5. The colour fringes, illustrated below, represent the contours of principal stress difference ($\sigma_1 - \sigma_3$) in the model. To separate the principal stresses, an electrical analog model was used as illustrated in Figure 6. This model uses the voltage distribution in a sheet of uniformly conducting material to represent the distribution of the principal stress sum ($\sigma_1 + \sigma_3$). These two stress distribution patterns permit separation of the individual principal stresses σ_1 and σ_3 throughout the model.

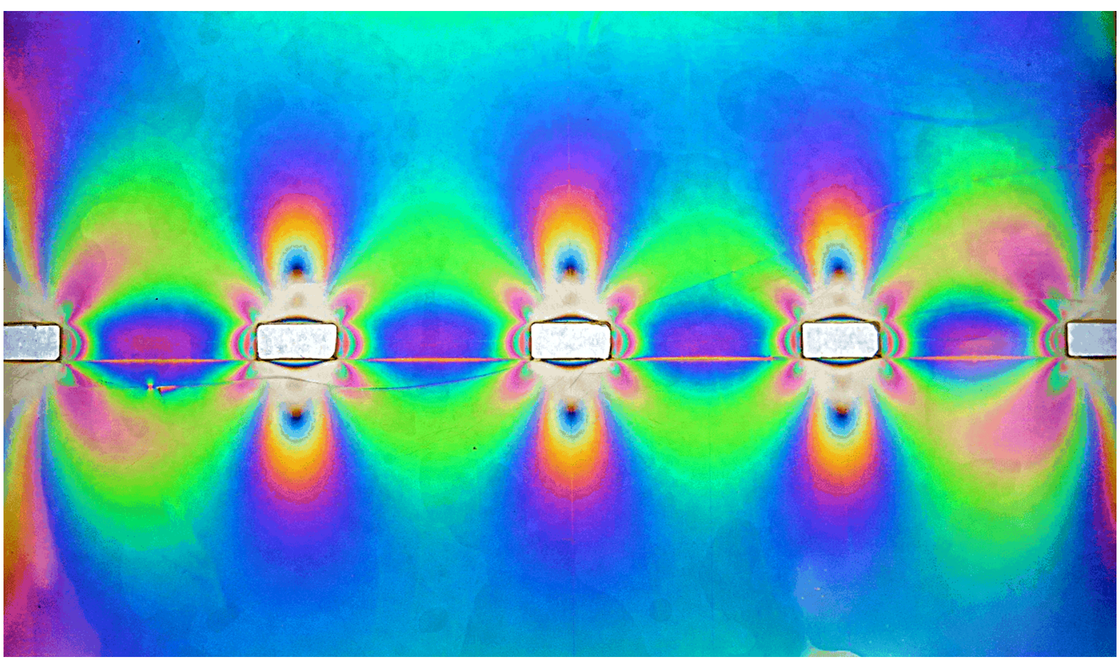


Figure 5: Photoelastic pattern in a slice from a three-dimensional frozen stress model representing a room and pillar coal mine. The fringes define the distribution of the principal stress difference ($\sigma_1 - \sigma_3$) in the model.

Figure 6: An electrical analog model in which the distribution of voltage in a sheet of uniformly conducting material defines the distribution of the principal stress sum ($\sigma_1 + \sigma_3$) in the model.

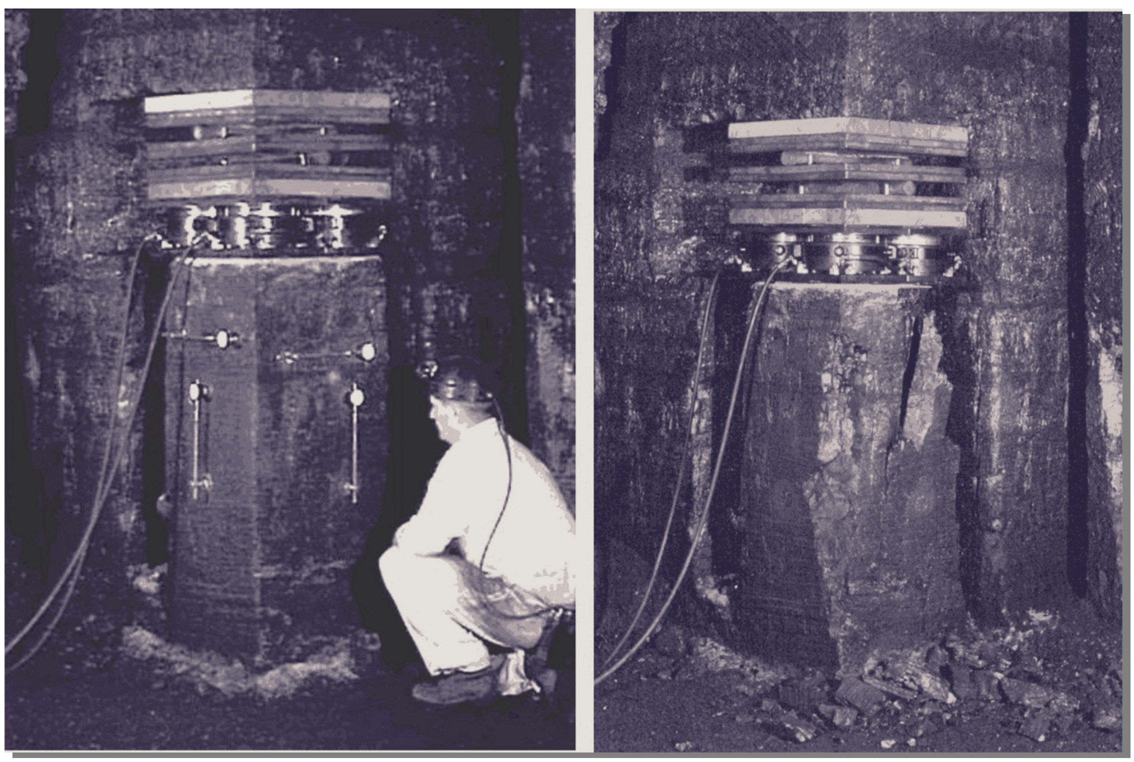
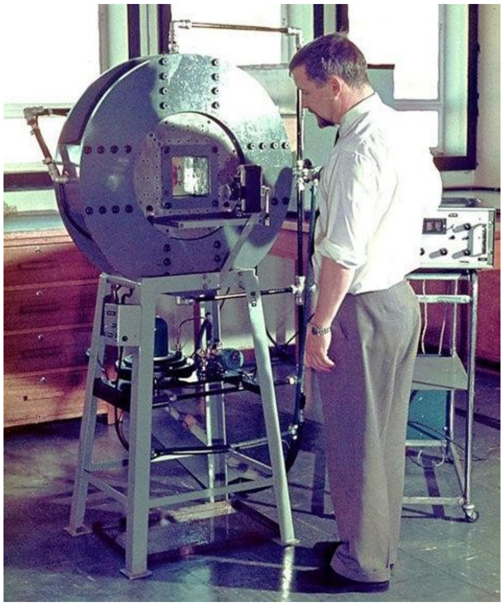
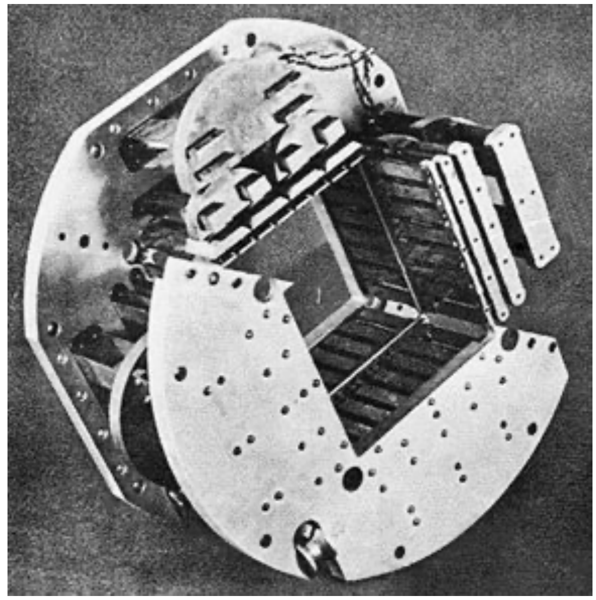


Figure 7: Uniaxial compressive strength test on a specimen cut from the corner of a coal pillar in an underground room and pillar mine.

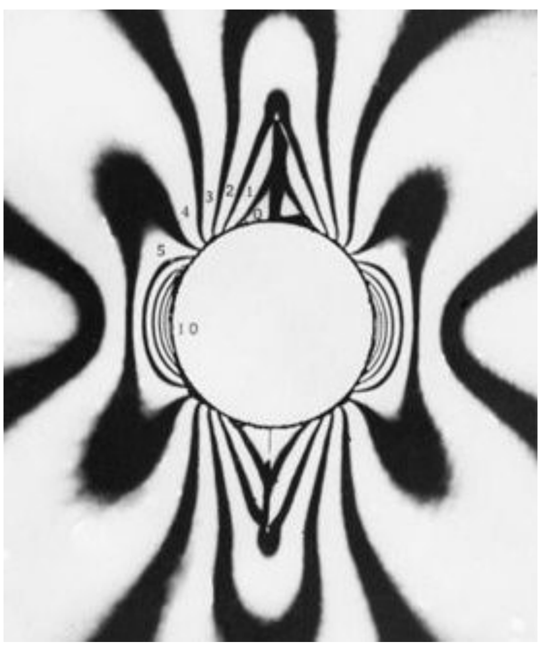
The design of pillars in a room and pillar mine requires a knowledge of both the stresses in the pillar and the strength of the rock mass forming the pillars. I was involved in designing and managing the first phase of a program to determine the strength of large specimens of coal in-situ. Testing of these specimens is illustrated in Figure 7. After my departure from the CSIR in 1966, this project was continued under the direction of Dr. Z.T. Bieniawski (Bieniawski and Van Zyl, 1975).



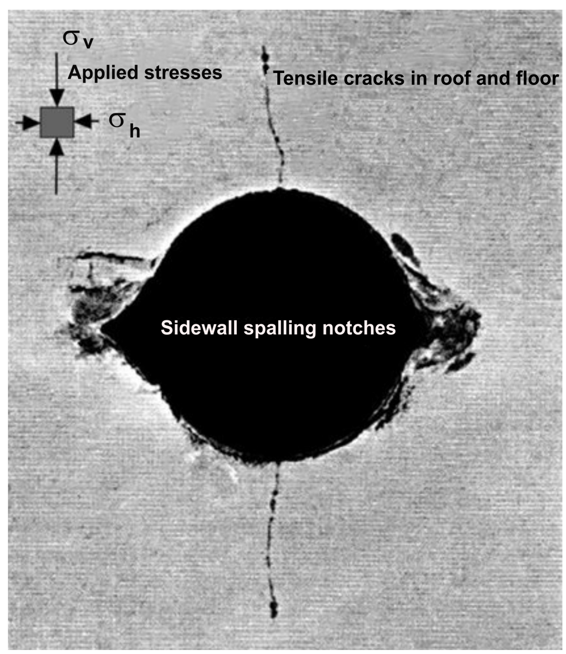
Model loading frame for 10 cm square glass or rock models.



Load distribution system to apply uniformly distributed loads on the model boundaries.



Photoelastic fringe pattern of principal stress differences in a glass plate model.



Vertical tension cracks and sidewall spalls induced in a stressed rock plate model.

Figure 8: Biaxial stress modelling to induce failure in glass and rock plate models.

One of the most sophisticated pieces of equipment that I designed and operated in the CSIR was a biaxial loading frame for the application of uniform biaxial stresses to the boundaries of 15 cm square glass or rock plates. These stresses, which could be different in vertical and horizontal directions, were applied to induce failure in the material surrounding excavations of various shapes.

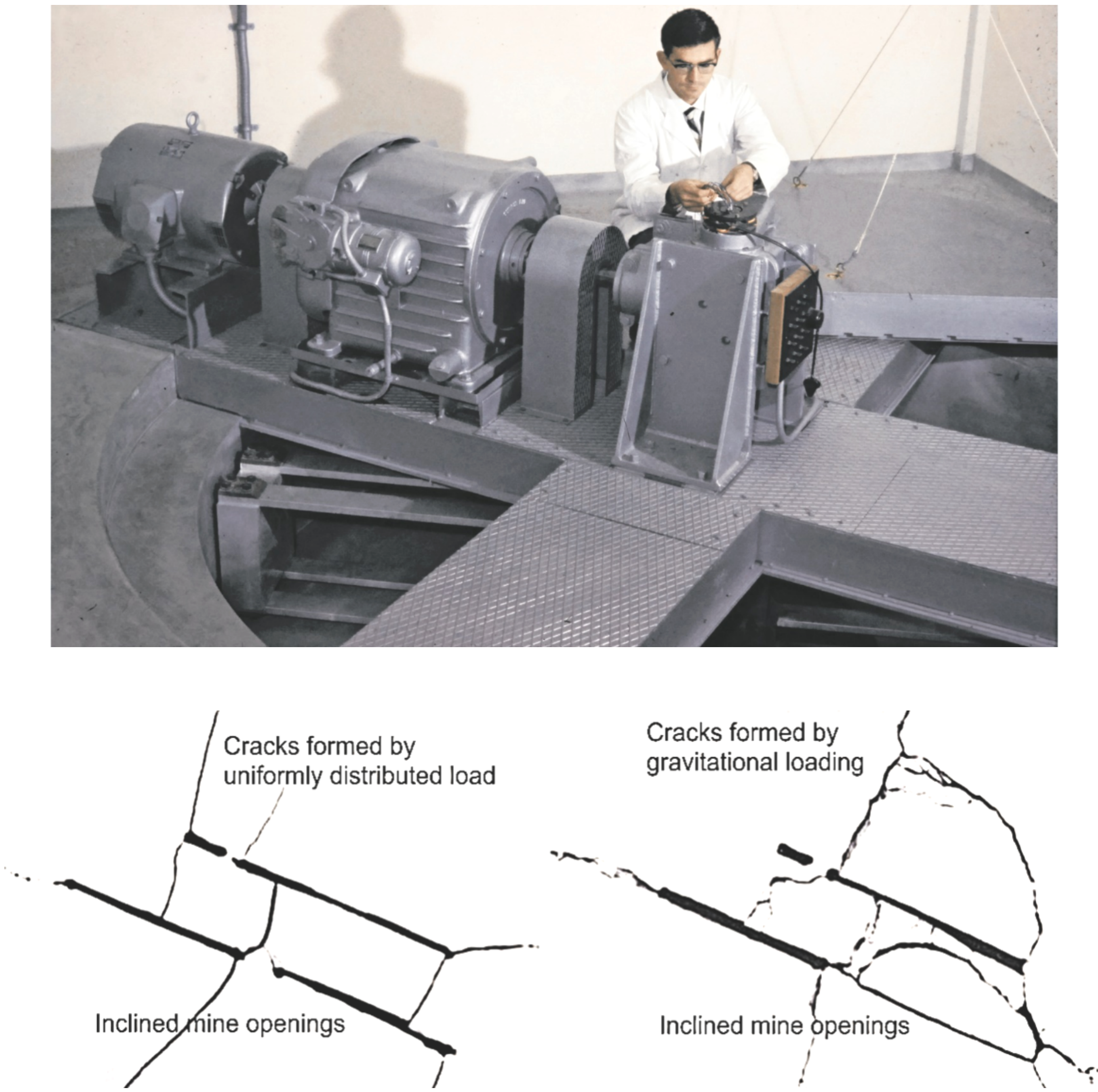


Figure 9: A three metre diameter centrifuge capable of accelerating models to 1000 times the normal gravitational acceleration.

In 1963, I designed the centrifuge, illustrated in Figure 9, to apply high gravitational loading to mine models. The photograph in the lower left-hand side shows cracks developed in a plaster mine model loaded with uniformly distributed vertical stresses. The lower right-hand photograph shows cracks in a similar model in which gravitational loading was simulated in the centrifuge. It will be seen that the crack

patterns are quite different, with the gravitationally loaded model giving roof failures and collapse which are much closer to reality than the uniformly loaded model.
The rapid development of computers, in the early 1960s, resulted in the availability of numerical models to which a wide variety of loads, including gravitation loading, could be applied. Numerical modelling soon rendered many of the traditional physical models obsolete. The centrifuge shown above was only used for a few tests before being moth-balled.

In 1966, I was appointed to the academic staff of the Imperial College of Science and Technology, one of the colleges of the London University in England. I worked in the Royal School of Mines, but I had close associations with the Departments of Civil Engineering and Geology. The Department of Civil Engineering had a strong soil mechanics division and the Department of Geology had a division of engineering geology. The purpose of my appointment was to establish a division of rock mechanics in the Royal School of Mines to offer introductory and graduate courses as well as research opportunities in this field.

My arrival at Imperial College in 1966 coincided with the creation of the post-graduate Centre for Computing and Automation. This centre incorporated work in computing by the Department of Mathematics which, in the early 1950s, had built a digital relay computer named the Imperial College Computing Engine. My post-graduate students had access to this new computing centre and were soon preparing their own punched cards and delivering stacks of these cards to the computing centre; returning the next day to receive the results. While this was a clumsy and time-consuming process, it played a critical role in the development of the powerful programs that we take for granted today. One of the first papers published on this work was by Peter Cundall (Cundall, 1971).

Figure 10: A model used to study slope failure in rock jointed rock masses.

This shift to numerical analysis also resulted in the decline of the use of physical models such as photoelasticity since problems could be analysed numerically in a fraction of the time and with a significantly higher level of accuracy. However, physical models, such as that illustrated in Figure 10, still played an important role in helping to understand some of the failure mechanisms in jointed rock masses. In this model, designed by Nick Barton (Barton, 1973) for his PhD studies on jointed rock masses, small pre-cast plaster blocks, representing the intact rock, were set in place on a large horizontal glass plate. Once the assembly of the model had been completed, a second parallel glass plate was added to keep the blocks in place. The frame was then rotated into the vertical position, thereby activating the gravitation load on each block. The resulting slope failures were important components in the development of our understanding of rock mass behaviour.

Another important development at Imperial College was the design of compact and robust testing equipment that could be used on the site of a construction project or in a site laboratory.

One of these tools is a triaxial test cell, illustrated in Figure 11, which is very compact and portable, but which can produce excellent results when used in a reliable compression testing machine. The design details of this cell were published by Hoek and Franklin (1968). These cells have been manufactured and used all over the world. A detailed discussion of the use of this cell, and the analysis of the results in terms of the Hoek-Brown failure criterion is presented in Hoek and Brown, 1980. A summary of some of the test results is presented in Figure 12.

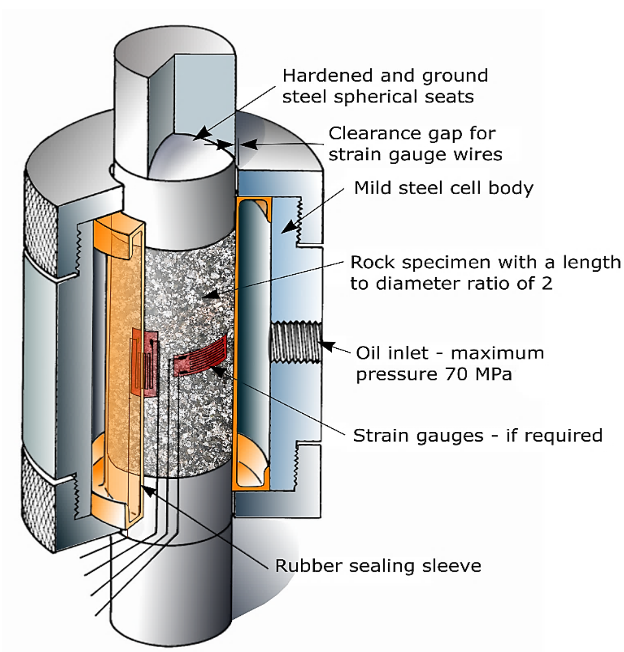


Figure 11: Triaxial testing cell designed by Hoek and Franklin at Imperial College.

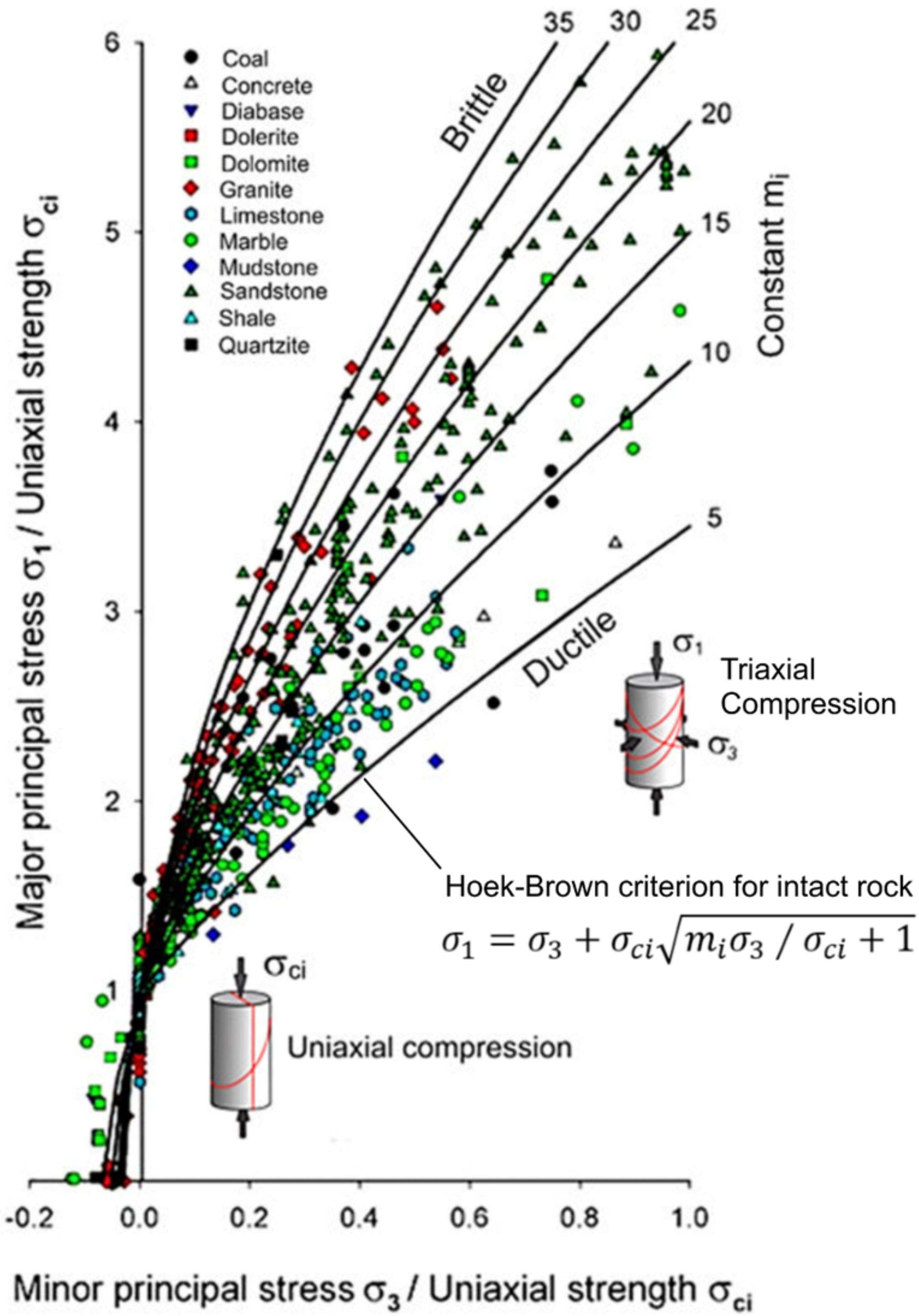


Figure 12: Plot of typical triaxial test results on intact rock specimens with an interpretation of these results in terms of the Hoek-Brown failure criterion.

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