1 Rock mechanics and mining engineering

1.1 General concepts

The engineering mechanics problem posed in all structural design is the prediction of the performance of the structure under the loads imposed on it during its prescribed functional operation. The subject of **engineering rock mechanics**, as applied in mining engineering practice, is concerned with the application of the principles of engineering mechanics to the design of the rock structures generated by mining activity. The discipline is closely related to the main streams of classical mechanics and continuum mechanics, but several specific factors identify it as a distinct and coherent field of engineering.

A widely accepted definition of **rock mechanics** is that first offered by the US National Committee on Rock Mechanics in 1964, and subsequently modified in 1974:

> Rock mechanics is the theoretical and applied science of the mechanical behaviour of rock and rock masses; it is that branch of mechanics concerned with the response of rock and rock masses to the force fields of their physical environment.

Clearly, the subject as defined is of fundamental relevance to mining engineering because the act of creating mining excavations changes the force fields of the rock's physical environment. As will be demonstrated throughout this text, the study of the response of the rock to these changes requires the application of analytical techniques developed specifically for the purpose, and which now form part of the corpus of the subject. Rock mechanics itself forms part of the broader subject of **geomechanics** which is concerned with the mechanical responses of all geological materials, including soils. The learned society for geomechanics in Australia, the Australian Geomechanics Society, defines geomechanics as "the application of engineering and geological principles to the behaviour of the ground and ground water and the use of these principles in civil, mining, offshore and environmental engineering in the widest sense".

This definition of geomechanics is almost synonymous with the term **geotechnical engineering**, which has been defined as "the application of the sciences of soil mechanics and rock mechanics, engineering geology and other related disciplines to civil engineering construction, the extractive industries and the preservation and enhancement of the environment" (Anon, 1999). The term geotechnical engineering and the adjective geotechnical will be used in this sense in this text.

Application of rock mechanics principles in underground mine engineering is based on simple and, perhaps, self-evident premises. First, it is postulated that a rock mass can be ascribed a set of mechanical properties which can be measured in standard tests or estimated using well-established techniques. Second, it is asserted that the process of underground mining generates a rock structure consisting of voids, support elements and abutments, and that the mechanical performance of the structure is amenable to analysis using the principles of classical mechanics. The third proposition

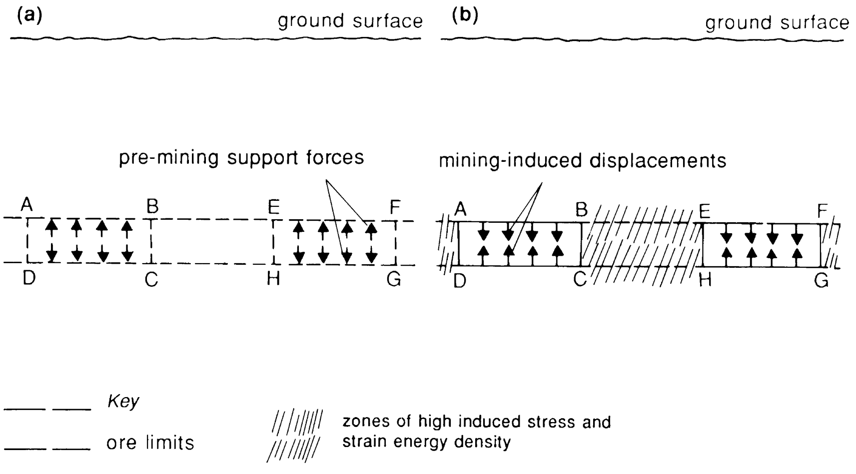


Figure 1.1 (a) Pre-mining conditions around an orebody, and (b) mechanical consequences of mining excavations in the orebody.

is that the capacity to predict and control the mechanical performance of the host rock mass in which mining proceeds can assure or enhance the safe and economic performance of the mine. These ideas may seem rather elementary. However, even limited application of the concepts of mechanics in mine excavation or mine structural design is a comparatively recent innovation (Hood and Brown, 1999).

It is instructive to consider briefly some of the mechanical processes which occur as rock is excavated during underground mining. Figure 1.1a represents a cross section through a flat-lying, uniform orebody. ABCD and EFGH represent blocks of ore that are to be mined. Prior to mining, the material within the surfaces ABCD and EFGH exerts a set of support forces on the surrounding rock. Excavation of the orebody rock to produce the rock configuration of Figure 1.1b eliminates the support forces; i.e. the process of mining is statically equivalent to introducing a set of forces on the surfaces ABCD and EFGH equal in magnitude but opposite in sense to those acting originally. Under the action of these mining-induced forces, the following mechanical perturbations are imposed in the rock medium. Displacements of the adjacent country rock occur into the mined void. Stresses and displacements are induced in the central pillar and abutments. Total, final stresses in the pillar and abutments are derived from both the induced stresses and the initial state of stress in the rock mass. Finally, the induced surface forces acting through the induced surface displacements result in an increase of strain energy in the rock mass. The strain energy is stored locally, in the zones of increased stress concentration.

The ultimate objective in the design of a mine structure, such as the simple one being considered here, is to control rock displacements into and around mine excavations. Elastic displacements around mine excavations are typically small. Rock displacements of engineering consequence may involve such processes as fracture of intact rock, slip on a geological feature such as a fault, excessive deflections of roof and floor rocks (due, for example, to their detachment from adjacent rock), or unstable failure in the system. The latter process is expressed physically as a sudden release of stored potential energy, and significant change in the equilibrium configuration of the structure. These potential modes of rock response immediately define some of the components of a methodology intended to provide a basis for geomechanically sound excavation design. The methodology includes the following elements. The strength and deformation properties of the orebody and adjacent country rock must be determined in some accurate and reproducible way. The geological structure of the rock mass, i.e. the location, persistence and mechanical properties of all faults and other fractures of geologic age, which occur in the zone of influence of mining activity, is to be defined, by suitable exploration and test procedures. Since the potential for slip on planes of weakness in the rock mass is related to fissure water pressure, the groundwater pressure distribution in the mine domain must be established. Finally, analytical techniques are required to evaluate each of the possible modes of response of the rock mass, for the given mine site conditions and proposed mining geometry.

The preceding brief discussion indicates that mining rock mechanics practice invokes quite conventional engineering concepts and logic. It is perhaps surprising, therefore, that implementation of recognisable and effective geomechanics programmes in mining operations is limited to the past 40 or so years. Prior to this period, there were, of course, isolated centres of research activity, and some attempts at translation of the results of applied research into mining practice. However, design by precedent appears to have had a predominant rôle in the design of mine structures. (A detailed account of the historical development of the discipline of mining rock mechanics is given by Hood and Brown (1999)). The relatively recent appearance and recognition of the specialist rock mechanics engineer have resulted from the industrial demonstration of the value and importance of the discipline in mining practice.

A number of factors have contributed to the relatively recent emergence of rock mechanics as a mining science. A major cause is the increased dimensions and production rates required of underground mining operations. These in turn are associated with pursuit of the economic goal of improved profitability with increased scale of production. Since increased capitalisation of a project requires greater assurance of its satisfactory performance in the long term, more formal and rigorous techniques are required in mine design, planning and scheduling practices.

The increasing physical scale of underground mining operations has also had a direct effect on the need for effective mine structural design, since the possibility of extensive failure can be reckoned as being in some way related to the size of the active mine domain. The need to exploit mineral resources in unfavourable mining environments has also provided a significant impetus to geomechanics research. In particular, the continually increasing depth of underground mining in most parts of the world, has stimulated research into several aspects of rock mass performance under high stress. Finally, more recent social concerns with resource conservation and industrial safety have been reflected in mining as attempts to maximise the recovery from any mineral reserve, and by closer study of practices and techniques required to maintain safe and secure work places underground. Both of these concerns have resulted in greater demands being placed on the engineering skills and capacities of mining corporations and their service organisations.

In the evolution of rock mechanics as a field of engineering science, there has been a tendency to regard the field as a derivative of, if not a subordinate discipline to, soil mechanics. In spite of the commonality of some basic principles, there are key issues which arise in rock mechanics distinguishing it from soil mechanics. The principal distinction between the two fields is that failure processes in intact rock involve fracture mechanisms such as crack generation and growth in a pseudo-continuum. In soils, failure of an element of the medium typically does not affect the mechanical integrity of the individual grains. In both diffuse and locally intense deformation modes, soil failure is associated with processes such as dilatation, particle rotation and alignment. This distinction between the different media has other consequences. For example, soils in their operating engineering environments are always subject to relatively low states of stress. The opposite is frequently true for rock. Further differences arise from the relatively high elastic moduli, and the relatively low material permeabilities of rocks compared with soils. The latter distinction is important. In most rock formations, fluid flow occurs via fissures and channels, while in soils fluid migration involves movement through the pore space of the particulate assembly. It appears, therefore, that rock and soil mechanics should be regarded as complementary rather than mutually inclusive disciplines.

Having suggested that rock mechanics is a distinct engineering discipline, it is clear that its effective practical application demands an appreciation of its philosophic integration with other areas of geomechanics. Rock mechanics, soil mechanics, groundwater hydrology and structural geology are, in the authors' opinions, the kernels of the scientific basis of mining engineering. Together, they constitute the conceptual and factual base from which procedures can be developed for the control and prediction of rock behaviour during mining activity.

1.2 Inherent complexities in rock mechanics

It has been observed that rock mechanics represents a set of principles, a body of knowledge and various analytical procedures related to the general field of applied mechanics. The question that arises is – what constituent problems arise in the mechanics of geologic media, sufficient to justify the formulation or recognition of a coherent, dedicated engineering discipline? The five issues to be discussed briefly below determine the nature and content of the discipline and illustrate the need for a dedicated research effort and for specialist functions and methodologies in mining applications.

1.2.1 Rock fracture

Fracture of conventional engineering material occurs in a tensile stress field, and sophisticated theories have been postulated to explain the pre-failure and post-failure performance of these media. The stress fields operating in rock structures are pervasively compressive, so that the established theories are not immediately applicable to the fracture of rock. A particular complication in rock subject to compression is associated with friction mobilised between the surfaces of the microcracks which are the sites for fracture initiation. This causes the strength of rock to be highly sensitive to confining stress, and introduces doubts concerning the relevance of such notions as the normality principle, associated flow and plasticity theories generally, in analysing the strength and post-failure deformation properties of rock. A related problem is the phenomenon of localisation, in which rupture in a rock medium is expressed as the generation of bands of intensive shear deformation, separating domains of apparently unaltered rock material.

1.2.2 Scale effects

The response of rock to imposed load shows a pronounced effect of the size or scale of the loaded volume. This effect is related in part to the discontinuous nature of a rock mass. Joints and other fractures of geological origin are ubiquitous features in a body of rock, and thus the strength and deformation properties of the mass are influenced by both the properties of the rock material (i.e. the continuous units of rock) and those of the various structural geological features. These effects may be appreciated by considering various scales of loading to which a rock mass is subjected in mining practice. The process of rock drilling will generally reflect the strength properties of the intact rock, since the process operates by inducing rock material fracture under the drilling tool. Mining a drive in jointed rock may reflect the properties of the joint system. In this case, the final cross section of the opening will be defined by the joint attitudes. The behaviour of the rock around the periphery of the drive may reflect the presence of discrete blocks of rock, whose stability is determined by frictional and other forces acting on their surfaces. On a larger scale, e.g. that of a mine pillar, the jointed mass may demonstrate the properties of a pseudo-continuum. Scale effects as described here are illustrated schematically in Figure 1.2.

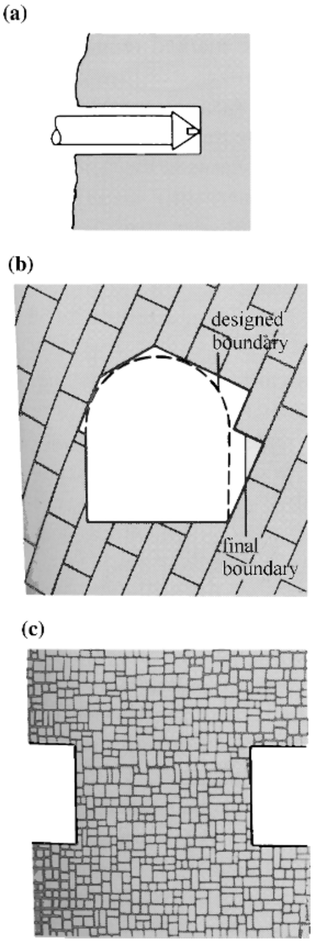


Figure 1.2 The effect of scale on rock response to imposed loads: (a) rock material failure in drilling; (b) discontinuities controlling the final shape of the excavation; (c) a mine pillar operating as a pseudo-continuum.

These considerations suggest that the specification of the mechanical properties of a rock mass is not a simple matter. In particular, the unlikely possibility of testing jointed rock specimens, at scales sufficient to represent the equivalent continuum satisfactorily, indicates that it is necessary to postulate and verify methods of synthesising rock mass properties from those of the constituent elements.

1.2.3 Tensile strength

Rock is distinguished from all other common engineering materials, except concrete, by its low tensile strength. Rock material specimens tested in uniaxial tension fail at stresses an order of magnitude lower than when tested in uniaxial compression. Since joints and other fractures in rock can offer little or no resistance to tensile stresses, the tensile strength of a rock mass can be assumed to be non-existent. Rock is therefore conventionally described as a ‘no-tension’ material, meaning that tensile stresses cannot be generated or sustained in a rock mass. The implication of this property for excavation design in rock is that any zone identified by analysis as being subject to tensile stress will, in practice, be de-stressed, and cause local stress redistribution. De-stressing may result in local instability in the rock, expressed as either episodic or progressive detachment of rock units from the host mass.

1.2.4 Effect of groundwater

Groundwater may affect the mechanical performance of a rock mass in two ways. The most obvious is through the operation of the effective stress law (section 4.2). Water under pressure in the joints defining rock blocks reduces the normal effective stress between the rock surfaces, and therefore reduces the potential shear resistance which can be mobilised by friction. In porous rocks, such as sandstones, the effective stress law is obeyed as in granular soils. In both cases, the effect of fissure or pore water under pressure is to reduce the ultimate strength of the mass, when compared with the drained condition.

A more subtle effect of groundwater on rock mechanical properties may arise from the deleterious action of water on particular rocks and minerals. For example, clay seams may soften in the presence of groundwater, reducing the strength and increasing the deformability of the rock mass. Argillaceous rocks, such as shales and argillitic sandstones, also demonstrate marked reductions in material strength following infusion with water.

The implications of the effect of groundwater on rock mass strength are considerable for mining practice. Since rock behaviour may be determined by its geohydrological environment, it may be essential in some cases to maintain close control of groundwater conditions in the mine area. Further, since backfill is an important element in many mining operations, the lithologies considered for stope filling operations must be considered carefully from the point of view of strength properties under variable groundwater conditions.

1.2.5 Weathering

Weathering may be defined as the chemical or physical alteration of rock at its surface by its reaction with atmospheric gas and aqueous solutions. The process is analogous to corrosion effects on conventional materials. The engineering interest in weathering arises because of its influence on the mechanical properties of the intact material, as well as the potential for significant effect on the coefficient of friction of the rock surface. It appears that whereas weathering causes a steady reduction in rock properties, the coefficient of friction of a surface may suffer a step reduction (Boyd, 1975).

Although physical processes such as thermal cycling and insolation may be important in surface mining, underground weathering processes are chiefly chemical in origin. These include dissolution and ion exchange phenomena, oxidation and hydration. Some weathering actions are readily appreciated, such as the dissolution of limestone in an altered groundwater environment, or softening of marl due to sulphate removal. In others, such as the oxidation of pyrrhotite, the susceptibility of some forms of the mineral to rapid chemical attack is not fully understood. A weathering problem of particular concern is presented by basic rocks containing minerals such as olivine and pyroxenes. A hydrolysis product is montmorillonite, which is a swelling clay with especially intractable mechanical behaviour.

This discussion does not identify all of the unique issues to be considered in rock mechanics. However, it is clear that the subject transcends the domain of traditional applied mechanics, and must include a number of topics that are not of concern in any other engineering discipline.

1.3 Underground mining

Ore extraction by an underground mining method involves the generation of different types of openings, with a considerable range of functions. The schematic cross section and longitudinal section through an operating mine, shown in Figure 1.3, illustrate the different rôles of various excavations. The main shaft, level drives and cross cuts, ore haulages, ventilation shafts and airways constitute the mine access and service openings. Their duty life is comparable with, or exceeds, the mining life of the orebody and they are usually developed in barren ground. Service and operating openings directly associated with ore recovery consist of the access cross cuts, drill headings, access raises, extraction headings and ore passes, from, or in which, various ore production operations are undertaken. These openings are developed in the orebody, or in country rock close to the orebody boundary, and their duty life is limited to the duration of mining activity in their immediate vicinity. Many openings are eliminated by the mining operation. The third type of excavation is the ore source. It may be a

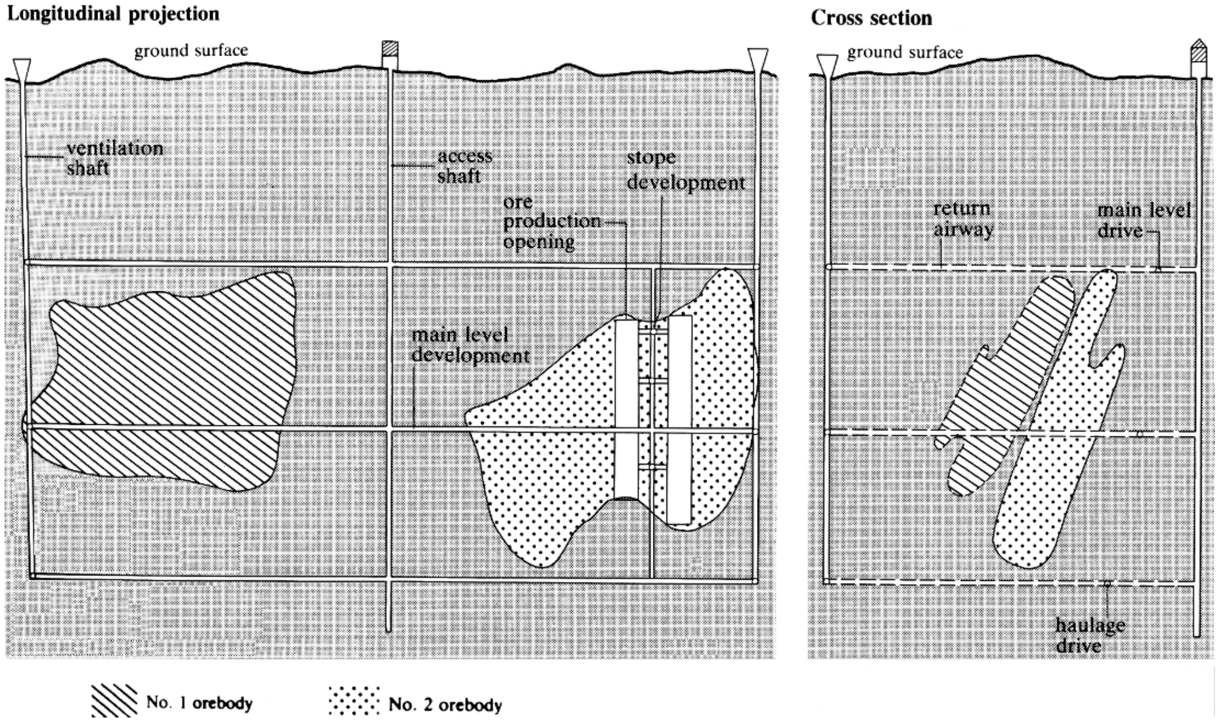


Figure 1.3 The principal types of excavation involved in underground mining by some stoping method.

stope, with well-defined, free-standing rock walls forming the geometric limits for the mined void, which increases in size with the progress of ore extraction. Alternatively, the ore source may be a rubble-filled space with fairly well-defined lower and lateral limits, usually coincident with the orebody boundaries. The rubble is generated by inducing disintegration of the rock above the crown of the orebody, which fills the mined space as extraction proceeds. The lifetime of these different types of ore source openings is defined by the duration of active ore extraction.

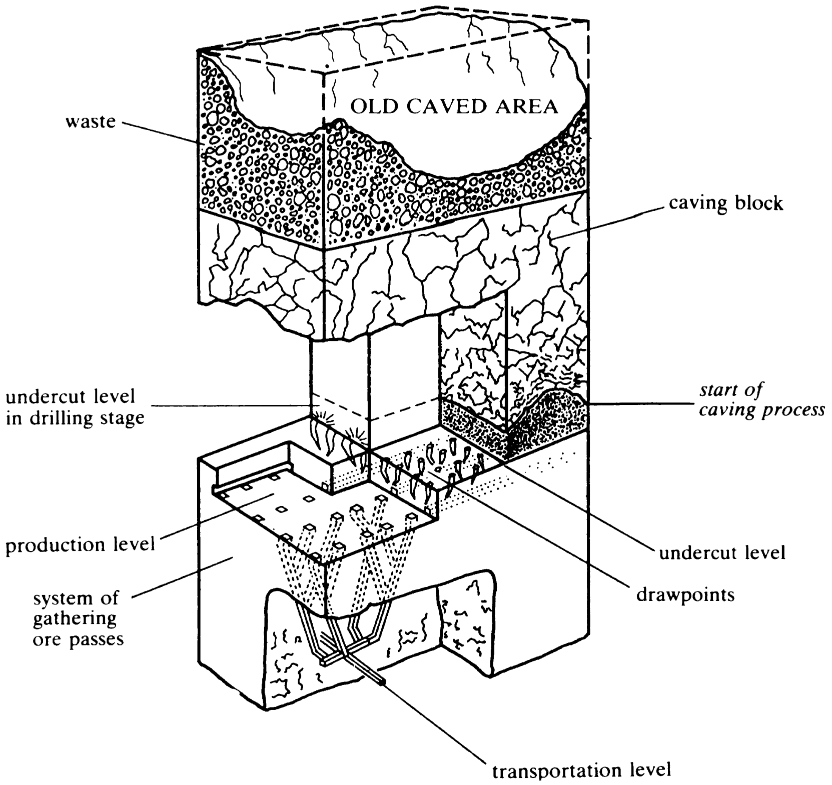
It is clear that there are two geomechanically distinct techniques for underground ore extraction. Each technique is represented in practice by a number of different mining methods. The particular method chosen for the exploitation of an orebody is determined by such factors as its size, shape and geometric disposition, the distribution of values within the orebody, and the geotechnical environment. The last factor takes account of such issues as the *in situ* mechanical properties of the orebody and country rocks, the geological structure of the rock mass, the ambient state of stress and the geohydrological conditions in the zone of potential mining influence.

Later chapters will be concerned with general details of mining methods, and the selection of a mining method to match the dominant orebody geometric, geological and geomechanical properties. It is sufficient to note here that mining methods may be classified on the basis of the type and degree of support provided in the mine structure created by ore extraction (Thomas, 1978). Supported mine structures are generated by methods such as open stoping and room-and-pillar mining, or cut-and-fill stoping and shrinkage stoping. In the former methods, natural support is provided in the structures by ore remnants located throughout the stoped region. In the latter methods, support for the walls of the mined void is provided by either introduced fill or by fractured ore temporarily retained in contact with mined stope walls. The second type of mine configuration recognised by Thomas is a caving structure, generated by mining methods such as block caving and sublevel caving. In these cases, no support is provided in the mined space, which fills spontaneously with fragmented and displaced orebody and cover rock.

From a rock mechanics point of view, discrimination between the two generic mining techniques, and the structures they generate, may be made on the basis of the displacements induced in the country rock and the energy redistribution which accompanies mining. In the technique of mining with support, the objective is to restrict displacements of the country rock to elastic orders of magnitude, and to maintain, as far as possible, the integrity of both the country rock and the unmined remnants within the orebody. This typically results in the accumulation of strain energy in the structure, and the mining problem is to ensure that unstable release of energy cannot occur. The caving technique is intended to induce large-scale, pseudo-rigid body displacements of rock above the crown of the orebody, with the displacement field propagating through the cover rock as mining progresses. The principle is illustrated schematically in Figure 1.4. The process results in energy dissipation in the caving rock mass, by slip, crushing and grinding. The mining requirement is to ensure that steady displacement of the caving mass occurs, so that the mined void is continuously self-filling, and unstable voids are not generated in the interior of the caving material.

This distinction between different mining techniques does not preclude a transition from one technique to the other in the life of an orebody. In fact, the distinction is

Figure 1.4 Principal features of a caving operation (after Borquez, 1981).



useful in that it conveys the major mechanical ramifications in any change of mining strategy.

Irrespective of the mining technique adopted for ore extraction, it is possible to specify four common rock mechanics objectives for the performance of a mine structure, and the three different types of mine openings described previously. These are:

(a) to ensure the overall stability of the complete mine structure, defined by the main ore sources and mined voids, ore remnants and adjacent country rock;
(b) to protect the major service openings throughout their designed duty life;
(c) to provide secure access to safe working places in and around the centres of ore production;
(d) to preserve the mineable condition of unmined ore reserves.

These objectives are not mutually independent. Also, the typical mine planning and design problem is to find a stope or ore block excavation sequence that satisfies these objectives simultaneously, as well as fulfilling other operational and economic requirements. The realisation of the rock mechanics objectives requires a knowledge of the geotechnical conditions in the mine area, and a capacity for analysis of the mechanical consequences of the various mining options. An appreciation is also required of the broad management policies, and general mining concepts, which have been adopted for the exploitation of the particular mineral resource.

It is instructive to define the significant difference in operational constraints between underground excavations designed for civil engineering purposes, and those types of excavations involved in mining engineering practice subject to entry by mine personnel. In the latter case, the use of any opening is entirely in the control of the mine operator, and during its active utilisation the surfaces of an excavation are subject to virtually continuous inspection by mine personnel. Work to maintain or reinstate secure conditions around an opening, ranging from surface scaling (barring down) to support and reinforcement emplacement, can be undertaken at any stage, at the direction of the mine management. These conditions rarely apply to excavations subject to civil engineering operating practice. Another major difference is that most mine excavations have duty lives that are significantly less than those of excavations used for civil purposes. It is not surprising, therefore, that mine excavation design reflects the degree of immediate control over opening utilisation, inspection, maintenance and support emplacement afforded the mine operator.

In addition to the different operating constraints for mining and civil excavations, there are marked differences in the nature of the structures generated and these directly affect the design philosophy. The principal difference is that a civil engineering rock structure is essentially fixed, whereas a mine structure continues to develop throughout the life of the mine. In the latter case, stope or ore block extraction sequences assume great importance. Decisions made early in the mine life can limit the options, and the success of mining, when seeking to establish an orderly and effective extraction strategy, or to recover remnant ore.

1.4 Functional interactions in mine engineering

The purpose of this section is to explore the roles of various engineering disciplines in the planning, design and operation of an underground mine. The particular concern

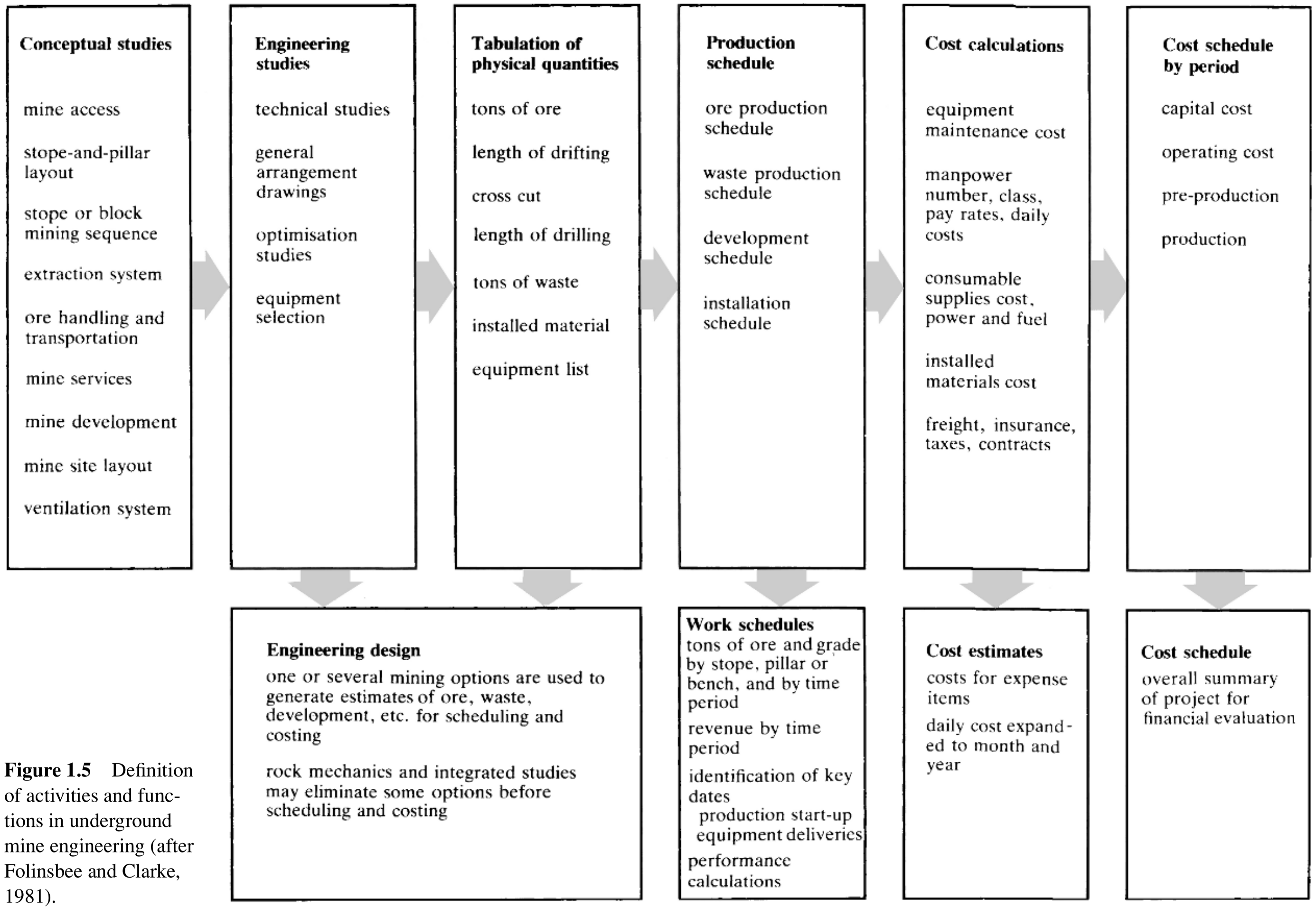


Figure 1.5 Definition of activities and functions in underground mine engineering (after Folinsbee and Clarke, 1981).

is to define the interaction of geologists and planning, production and rock mechanics engineers in the pre-production and operating phases of mining activity.

The scope of engineering activity to be undertaken preceding and during the productive life of a mine is illustrated in the design task definition chart shown in Figure 1.5. The overall aim of the various components of engineering activity (e.g. mine access design, ventilation system) is the development of sustainable production and cost schedules for the operation. The specific rock mechanics contributions to the mine engineering programme, and its interface with other planning functions, occur primarily in tasks related to mine access, mining method development and mine layout, mining sequence and ore extraction design. Mining method development, mine layout and sequencing, support and reinforcement design, and the development of responses to unanticipated events (e.g. falls of ground) occurring during operations, usually constitute the majority of the initial and continuing rock mechanics activity.

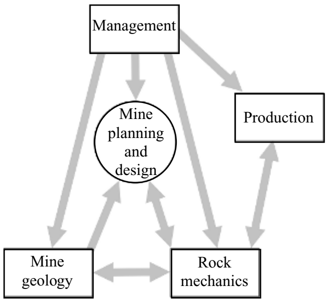


Figure 1.6 Interaction between technical groups involved in mine engineering.

Rock mechanics activities need to be conducted within an organisational framework that permits the exchange and integration of concepts, requirements, information and advice from and between management, geologists, planning engineers, production personnel and rock mechanics engineers. The logic of such an integrated mine engineering philosophy is illustrated in Figure 1.6. The principles implicit in this scheme are, first, the mutual dependence of each functional group on information provided by the others, and, second, that it is usually the mine planning engineers who transform the individual technical contributions into working drawings, production schedules and cost estimates for subsequent implementation by production personnel. The logic of Figure 1.6 is not intended to represent a mine site organisational structure. Whatever structure is used, it is essential that there be close working relationships between geology, planning, rock mechanics and production groups.

Considering Figure 1.6 from a rock mechanics perspective, it is useful to summarise the information that can be reasonably expected from the other functional groups and the information and advice that should be delivered by a rock mechanics group.

1.4.1 Management

Information from management is a key element which is frequently not available to rock mechanics specialists. The general requirement is that the broad framework of management policy and objectives for the exploitation of a particular resource be defined explicitly. This should include such details as the volume extraction ratio sought for the orebody and how this might change in response to changing product prices. The company investment strategy should be made known, if only to indicate the thinking underlying the decision to mine an orebody. Particular corporate constraints on mining technique, such as policy on disturbance of the local physical environment above the mine area, and restrictions on geohydrological disturbance, should be defined. Further, restrictions on operating practices, such as men working in vertical openings or under unsupported, temporary roof spans, need to be specified.

1.4.2 Geology

In defining the geomechanics role of exploration and engineering geologists in mine engineering, it is assumed that, at all stages of the geological exploration of an orebody, structural and geohydrological data will be logged and processed on a routine basis. A Geology Section can then provide information ranging from a general description of the regional geology, particularly the structural geology, to details of the dominant and pervasive structural features in the mine area. A comprehensive geological description would also include the distribution of lithologies in and around the orebody, the distribution of values throughout the orebody, and the groundwater hydrology of the mine area. In the last case, the primary need is to identify aquifers in the zone of possible influence of mining which might deliver groundwater into any part of the mining domain. Finally, specific geological investigations would identify sources of potential mining problems in the mine area. These include zones of shattered ground, leached zones, cavernous ground (vughs), rocks and minerals with adverse weathering properties, and major structural features such as faults and clay seams which transgress the orebody and are expressed on the ground surface.

It is clear, from this specification of duties, that mine geological activity should produce a major component of engineering geological data. It implies that successful execution of the engineering exploration of an orebody and environs requires the active co-operation of geologists and rock mechanics personnel. It may be necessary, for example, for the latter to propose drilling programmes and targets to clarify site conditions of particular mining consequence.

1.4.3 Planning

Mine planning and design engineers are responsible for the eventual definition of all components of an engineering study of a prospective mining operation. Their role is initiative as well as integrative. In their interaction with rock mechanics engineers, their function is to contribute information which can usefully delineate the scope of any geomechanical analysis. Thus they may be expected to define the general mining strategy, such as one-pass stoping (no pillar recovery), or stoping and subsequent pillar extraction, and other limitations on mining technique. Details of anticipated production rates, economic sizes of stopes, and the number of required sources of ore production, can be used to define the extent of the active mine structure at any time. The possibility of using backfills of various types in the production operation should be established. Finally, the constraints imposed on future mining by the current location of mine accesses, stoping activity, permanent openings and exploration drives should be specified.

1.4.4 Rock mechanics

It has been noted that the mine engineering contributions of a rock mechanics group relate to design tasks concerned principally with permanent mine openings, mine layout and sequencing, extraction design, support and reinforcement and operational responses. Specific activities associated with each of these tasks are now detailed. Design issues related to permanent mine openings include siting of service and ventilation shafts, siting, dimensioning and support specification of level main development, and detailed design of major excavations such as crusher excavations, interior shaft hoist chambers, shaft bottom facilities and workshop installations. The demand for these services is, of course, episodic, being mainly concentrated in the pre-production phase of mine operations.

The majority of rock mechanics activity in mining operations is devoted to resolution of questions concerned with the evolutionary design of the mine structure. These questions include: dimensions of stopes and pillars; layout of stopes and pillars within the orebody, taking due account of their location and orientation relative to the geological structure and the principal stress directions; the overall direction of mining advance through an orebody; the sequence of extraction of stope blocks and pillar remnants, simultaneously noting the need to protect service installations, maintain access and preserve mine structural stability; and the need for and specification of the strength parameters of any backfill in the various mined voids. In all of these design activities, effective interaction must be maintained with planning personnel, since geomechanics issues represent only part of the complete set of engineering information required to develop an operationally acceptable mining programme.

Extraction system design is concerned with the details of stope configuration and ore recovery from the stope. This involves, initially, consideration of the stability of stope boundaries throughout the stope working life, and requires close examination of the possibility of structurally controlled failures from stope and pillar surfaces. The preferred direction of stope retreat may be established from such studies. The design of the extraction horizon requires consideration of the probable performance of stope drawpoints, tramming drives and ore-flow control raises, during the stope life. Particular problems can occur on the extraction horizon due to the density of openings, resulting in stressed remnants, and the potential for damage by secondary breakage of oversize rock during ore recovery. A final issue in this segment of stope design is primary blast design. The issue here is blasting effects on remnant rock around the stope periphery, as well as the possibility of damage to access and adjacent service openings, under the transient loads associated with closely sequenced detonations of relatively large explosive charges.

A mine rock mechanics group also has a number of important rôles to play during production. It is good and common practice for a rock mechanics engineer to make regular inspections of production areas with the production engineer responsible for each area, and to make recommendations on local support and reinforcement requirements based on the mine's established support and reinforcement standards. Usually, these standards will have been developed by the rock mechanics engineers in consultation with production personnel. The rock mechanics group will also be responsible for monitoring the geomechanical performance of excavations and for making recommendations on any remedial actions or measures that may be required to manage unforeseen events such as falls of ground or the ingress of water. A close daily working relationship between production and rock mechanics engineers is required in order to ensure the safe and economic operation of the productive areas of the mine.

1.5 Implementation of a rock mechanics programme

It has been stated that an effective rock mechanics programme should be thoroughly integrated with other mine technical functions in the development and implementation of a coherent mining plan for an orebody. However, the successful accomplishment of the goals of the programme requires the commitment of sufficient resources, on a continuous basis, to allow rational analysis of the range of problems posed by the various phases of mining activity.

A methodology for the implementation of a rock mechanics programme is illustrated schematically in Figure 1.7. Five distinct components of the programme are identified, and they are postulated to be logically integrated, i.e. deletion of any component negates the overall operating philosophy. Another point to be observed from Figure 1.7 is that the methodology implies that the programme proceeds via a

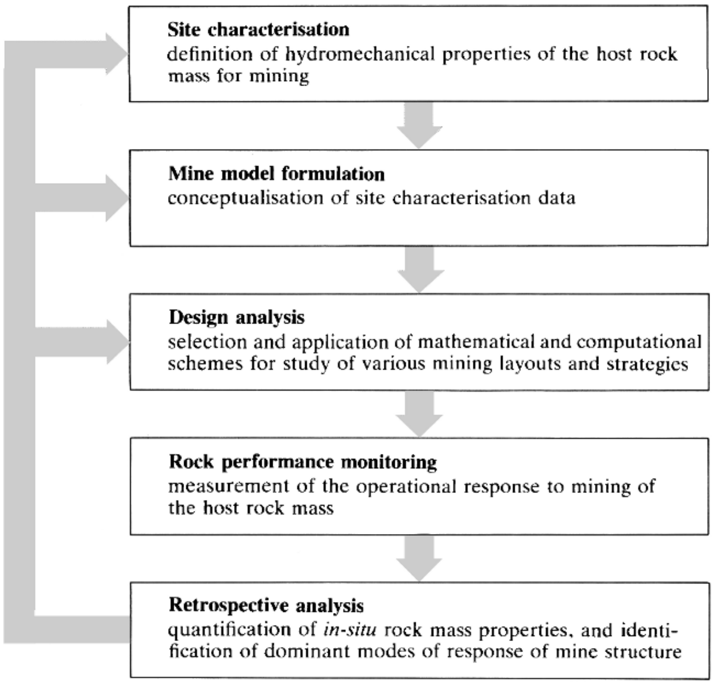


Figure 1.7 Components and logic of a rock mechanics programme.

multi-pass loop. There are two main reasons for this. First, the site characterisation phase never generates a sufficiently comprehensive data base from which to develop a unique plan for the complete life of the mine. Second, mine design is itself an evolutionary process in which engineering responses are formulated to reflect the observed performance of the mine structure under actual operating conditions. For these reasons, the process may not proceed in the linear manner implied by Figure 1.7. At times, some of the activities, or parts of those activities, may proceed in parallel. These issues are clarified in the following discussion of the component phases of the programme.

1.5.1 Site characterisation

The objective of this phase, in the first pass through the loop, is to define the mechanical properties and state of the medium in which mining is to occur. It involves determination of the strength and deformation properties of the various lithological units represented in and around the orebody, definition of the geometric and mechanical properties of pervasive jointing, and location and description of the properties of discrete structural features. An estimate of the *in situ* strength of the medium may then be made from the properties of the constituent elements of the mass. This phase also includes determination of the *in situ* state of stress in the mine area, and investigation of the hydrogeology of the orebody and environs.

The difficulty in site characterisation lies in achieving representative data defining geomechanical conditions throughout the rock medium. Under conditions of limited physical access, yielding small numbers of small rock specimens, with no unifying theory to relate the specimen properties with those of the host rock medium, a first-pass site characterisation is intrinsically deficient.

1.5.2 Mine model formulation

Formulation of a mine model represents the simplification and rationalisation of the data generated by the site characterisation. The aim is to account for the principal geomechanical features which will be expressed in the deformational behaviour of the prototype. For example, lithological units are ascribed average 'representative' strength and deformation properties, major structural features are assigned a regular geometry and average shear strength properties, and a representative specification is accepted for the pre-mining state of stress. The need for this phase arises from the limited details that can be accommodated in most of the analytical or computational methods used in design.

It is clear that significant discrepancies may be introduced at this stage, by failure to recognise the engineering significance of particular features of the mine geomechanical setting.

1.5.3 Design analysis

Having defined the prevailing conditions in the rock mass in an analytically tractable way, the mechanical performance of selected mining configurations and excavation geometries can be predicted using appropriate mathematical or numerical techniques. The analytical tools may be relatively primitive (e.g. the tributary area theory for pillar design) or advanced, employing, for example, computational schemes which may model quite complex constitutive behaviour for both the rock mass and various fabric elements. In any event, the design analyses represent the core of rock mechanics practice. Recent rapid development in the power of available computational schemes has been responsible for significant advances, and improved confidence, in the quality of rock structural design.

1.5.4 Rock performance monitoring

The objective of this phase of rock mechanics practice is to characterise the operational response of the rock mass to mining activity. The intention is to establish a comprehension of the rôles of the various elements of the rock mass in the load-deformational behaviour of the rock medium. The data required to generate this understanding are obtained by displacement and stress measurements made at key locations in the mine structure. These measurements include closures across pillars, slip on faults, and levelling and horizontal displacement measurements in and around the active mining zone. States of stress may be measured in pillars, abutments and in the interior of any rock units showing signs of excessive stress. Visual inspections must be undertaken regularly to locate any structurally controlled failures and areas of anomalous response, and these should be mapped routinely. Finally, data should be collected on the production performance of each stope, and the final configuration of each stope should be surveyed and mapped. The aim in this case is to seek any correlation between rock mass local performance and stope productivity.

1.5.5 Retrospective analysis

The process of quantitative analysis of data generated by monitoring activity is intended to reassess and improve knowledge of the *in situ* mechanical properties of the rock mass, as well as to review the adequacy of the postulated mine model. Review of the conceptualisation of the host rock mass involves analysis of the role of major structural features on the performance of the structures, and identification of the key geomechanical parameters determining the deformational response of the medium. Particularly valuable data are generated by the analysis of local failures in the system. These provide information about the orientations, and possibly relative magnitudes of the *in situ* field stresses, as well as high quality information on the *in situ* rock mass strength parameters. Subsequently, stope mechanical and production performance data can be assessed with a view to formulating detailed stope design and operating criteria. This might involve establishment of rules specifying, for example, stope shape relative to geological structure, stope blasting practice, and drawpoint layouts and designs for various types of structural and lithological conditions.

Figure 1.7 indicates that data generated by retrospective analysis are used to update the site characterisation data, mine model and design process, via the iterative loop. This procedure represents no more than a logical formalisation of the observational principle long used in soil mechanics practice (Peck, 1969). It is a natural engineering response to the problems posed by basic limitations in site characterisation and conceptualisation associated with excavation design in geologic media.