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SECTION A

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Contents

Excavation design for bench stoping at Mount Isa mine, Queensland, Australia
E. Villaescusa A1

Comparative analysis of toppling behaviour at Chuquicamata open-pit mine, Chile
Mark Board *et al.* A11

Application of distinct-element modelling to assess slope stability at Delabole slate quarry, Cornwall, England
J. S. Coggan and R. J. Pine A22

Bayesian approach to slope stability assessment by updating probability of failure treated as a random variable
N. Powell and R. J. Pine A31

Modelling slope behaviour for open-pits
S. R. Hencher, Q.-H. Liao and B. G. Monaghan A37

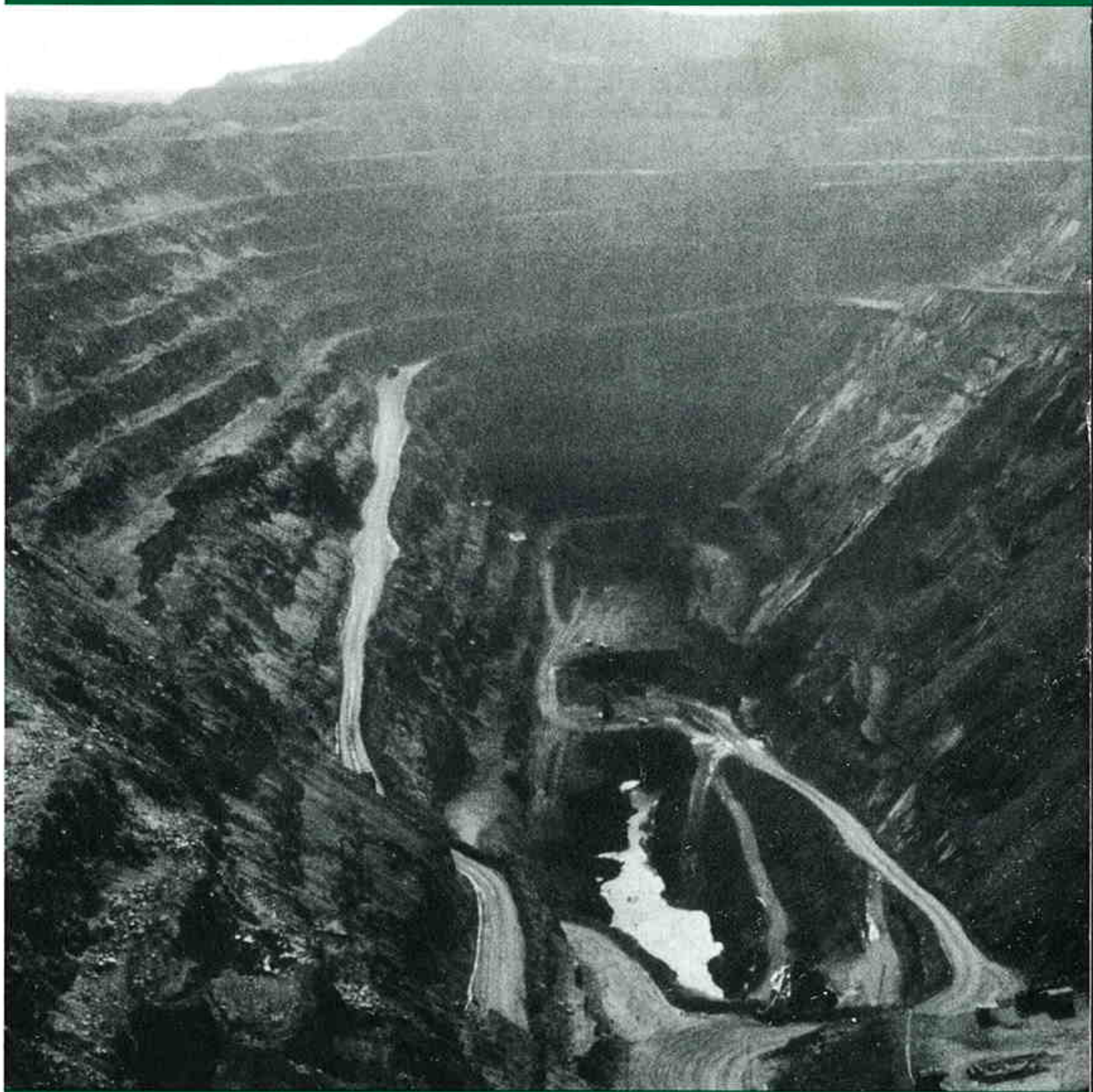
Photographic technique for detection and monitoring of ground movements associated with mining and quarrying
P. Grainger and P. G. Kalaugher A48

Layered mine waste co-mingling for mitigation of acid rock drainage
R. Poulin, J. Hadjigeorgiou and R. W. Lawrence A55

Prediction of mine tailings delta profiles
P. H. Morris and D. J. Williams A63

Approach to the quantification of hanging-wall behaviour
D. M. Milne, R. C. Pakalnis and P. J. Lunder A69

Technical note
Empirical approach to prediction of damage in bench blasting
Navid Mojtabai and Susan G. Beattie A75



Mineral resources and the environment

Modelling slope behaviour for open-pits

S. R. Hencher, Q.-H. Liao and B. G. Monaghan

Synopsis

The options for designing slopes in complex geological conditions are reviewed. It is demonstrated that modelling—especially numerical modelling—allows a degree of analysis that cannot otherwise be achieved. Examples are given of how numerical modelling can be used to investigate fundamental aspects of rock mass behaviour; it is demonstrated that an important consequence of change in scale is that the mechanisms of failure also change. The complex failure of the footwall slope in a large open-pit mine in southern Spain is discussed. Numerical modelling with UDEC (universal distinct-element code) has allowed displacements measured in the field to be simulated realistically. The calibration of the model gives confidence that it can be used to predict the effect of future mining and to assess the effectiveness of possible remedial measures.

Open-pits need to be designed so that the mineral can be extracted economically while reserves are optimized. Slopes are generally cut as steeply as possible; minor rockfalls and bench failures are considered inevitable and are even taken as an indication that the geometrical configuration is not too conservative. Little attempt is made to stabilize temporary slopes. Care is taken, however, to avoid major failures that might disrupt operations, although solutions requiring active reinforcement, such as anchoring, are not adopted unless absolutely necessary, partly because such measures are often ineffective.[1] With such a management philosophy there is considerable onus on the geotechnical engineer to design safe slopes primarily on the basis of the relationships between the geometry of discontinuities and that of the slopes.

At many sites the general geological structure will dictate overall slope design, and the principles that must be observed to avoid sliding on or toppling due to major discontinuity sets, such as bedding, schistosity or cleavage, are well established.[2,3] Most relatively small-scale (and many large-scale) failures are geometrically quite simple and, therefore, amenable to direct mathematical analysis provided that the shear resistance of the sliding surface can be accurately determined. Piteau[4] provided a good review of those geological features which may control slope stability in open-pit mining. More complex sites are less readily dealt with and, particularly in the case of very large slopes, there may be general concern over stability even though no clearcut mechanism has been identified from investigation.

At recent conferences devoted to mining and the design of open-pits[5,6] the vast majority of contributors have discussed slope stability with reference to the relatively simple methods of analysis that were developed more than 20 years ago for well-defined, discrete failures controlled by individual discontinuities (e.g. Ashby[7]). Only a few (e.g. Rapiman[8]) have referred to the use of currently available, sophisticated geotechnical software for the modelling of slope behaviour. Stacey[9] suggested that further research is necessary in recognition of the fact that simple gravity-block analysis is not always appropriate for slope design in open-pits. It is clear that modelling, and especially numerical modelling, will play an increasingly important role in this research effort.

Dealing with complex masses

Although failures through rock are often controlled by single discontinuities or sets that are well defined geometrically, in many other situations the potential mode of failure is far more complex, with many different discontinuities contributing greatly to the deformation mechanism yet not uniquely controlling it. This is particularly true where stresses are high relative to the strength of the rock material, when the failure of intact rock bridges becomes a possibility. Such conditions are most likely in relatively weak rock—for example, where hydrothermal alteration is present at depth. The more geologically and geometrically complex the situation, the more difficult it is to derive representative engineering parameters to use in general analysis and the less justified it is to use a simple limit-equilibrium approach.

Among the difficulties are: the impossibility of testing at a sufficiently large scale to derive representative rock mass parameters; poor theoretical or empirical understanding of the influence of scale on mass behaviour; the inherent difficulties in dealing with complex systems from first principles in a theoretical way; and the difficulties in using a back-analysis approach without oversimplifying the problem.

Three possible approaches are: to treat the rock mass as an isotropic continuum; to design by precedent; or to use modelling.

Isotropic continuum approach

When dealing with fractured rock in which clear, kinematic modes of failure controlled by well-defined discontinuity sets have not been identified a strength envelope can be derived for the mass by use of the Hoek–Brown criterion.[10] The general criterion, as discussed most recently by Hoek[11] and Hoek and co-workers,[12] takes the form

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_b \frac{\sigma_3'}{\sigma_c} + s \right)^a$$

where σ_1' is major principal effective stress at failure, σ_3' is minor principal stress at failure and σ_c is uniaxial compressive strength of intact rock. m_b is a constant for the rock mass and corresponds approximately to the friction angle, ϕ, in the linear Mohr–Coulomb criterion. It varies both with rock type (m_i component) and with an index known as the geological strength index (GSI), which, in turn, is directly related to the rock mass classification ratings of Barton and co-workers[13] and Bieniawski.[14] s and a are constants that depend on the characteristics of the rock mass; s is approximately analogous to cohesive strength in the Mohr–Coulomb

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Fig. 1 Complex slope failure in weak rock mass, Tsing Yi Island, Hong Kong

criterion and tends to zero for a very poor-quality rock mass, reflecting the low tensile strength of such a weak mass. For a given rock type (e.g. sandstone or granite) the parameters m_b, s and a vary with structure (classes range from widely jointed and blocky to crushed) and with the surface condition of discontinuities (conditions vary from very rough and unweathered to slickensided or clay-infilled). Generally, the parameters s and m_b reduce markedly with increasing number of discontinuity sets, increasing fracture frequency and lower shear strength of discontinuity surfaces. Within the various ratings, however, no allowance is made for the *degree of adversity* of jointing; it is taken as a basic assumption for the Hoek–Brown criterion that joint orientations are 'very favourable', as defined by Bieniawski.[14]

It is of note that whereas the Hoek–Brown criterion predicts a reducing shear strength with increasing fracture frequency for an isotropic rock mass, regularly jointed models tested by Bandis and co-workers[15] indicated the reverse to be true, the models that comprised the smallest block size showing the highest strengths. This apparent paradox appears to relate to the fact that sliding along discontinuities is, by definition, not the dominant mechanism for a Hoek–Brown mass, whereas frictional sliding was the main mode of failure in the physical models tested by Bandis and co-workers.[15] These authors suggested that where sliding does dominate, the reduced stiffness of the more closely jointed mass and the greater ability of small blocks to rotate may increase the effective roughness component of shear strength.[15]

Clearly, not only are the predicted effects of scale different for these two scenarios but the cases also represent opposite extremes of a complete spectrum of possibilities for rock mass conditions. In many situations, although the fracture network does not permit failure to be dominated by sliding along a single set of discontinuities, impersistent and adversely orientated sets of discontinuities may be present within the rock mass and sliding along these will contribute to the process of deformation and, probably, to reduced rock mass strength.[16,17] An example of a slope failure involving partial sliding along non-daylighting discontinuities as well as failure through intact rock is given in Fig. 1.

It must be emphasized, therefore, that the Hoek–Brown approach is only appropriate where the rock mass can be regarded as truly isotropic with 'very favourable' joint orientations.[11] Also, care should be taken in adopting the shear strength data from this approach for slopes as the strengths are more likely to reflect the confined rock mass conditions typical of underground situations. However, provided that the conditions are favourable, strength parameters calculated from the Hoek–Brown equations may be used in a search for potential failure surfaces using a generalized method, such as that of Sarma[18] or of Janbu.[19] Probabilistic analyses can then be carried out for a variety of potential failure surfaces through the rock mass to allow for the scatter in input data and to define the level of risk.[20] There are many commercially available geotechnical software packages (e.g. SLOPE, XSTABL) that can analyse such situations, albeit with some difficulty where the strength parameters vary non-linearly with confining stress.

An alternative approach—provided that the rock mass can be considered essentially as a continuum—is to back-analyse measured displacements to obtain rock mass parameters, as outlined by Sakurai.[21] Basically, displacements measured in the field are used in stress–strain relationships, expressed perhaps within a finite-element model, to derive representative elasticity and strength parameters. For slopes Sakurai[21] argued that a mechanical model should not be assumed prior to back-analysis but that the measured strains should instead be used to derive a unique model comprising a series of parallel layers with differing properties. Adopting such an apparently simple approach, Ono and co-workers[22] described how they were able to predict behaviour in a large slope using parameters derived by back-analysis of displacements that developed during the early stages of excavation. Sakurai and co-workers[23] used the same approach to determine geomechanical parameters for a large slope in sandstone and slate. Those parameters were then used in further analysis to calculate a factor of safety against failure. Such an approach seems particularly attractive for large open-pit slopes where faces are excavated bench by bench and where displacements are routinely measured. The increasing development and capability of geotechnical software, such as UDEC (discussed later), should allow sophisticated back-analysis of more complex geological situations than has hitherto been possible.

Design by precedent

Again, provided that the mass might be regarded as isotropic, an alternative approach for dealing with complex or very large rock masses is to design by precedent, stability being expressed empirically (by observation) with respect to simple relationships, such as slope height versus slope angle.[2,24] One of the problems with this approach, however, is that the situation may be overgeneralized and the conclusions may be questionable owing to a lack of sufficient data or only valid within very severe constraints (the discussion by Leroueil and Tavernas[25] on the difficulties in interpreting individual cases is relevant). This conclusion is supported by the results of a major study of the stability of weathered slopes in Hong Kong (CHASE) that was conducted in the early 1980s using empirical methods.[26] The aim of the exercise was to identify key factors associated with slope failure that could then be used as inputs to the design process or at least for checking. The study stemmed partly from perceived difficulties in determining the shear strength of severely weathered rock at either the small, intact rock scale or the mass scale and the anomalous survival of some slopes despite calculated factors of safety of less than unity. More than 200 failed and stable slopes were described in great detail, involving teams of geologists, geotechnical engineers, site investigation contractors and surveyors in fieldwork for more than six months. More than 400 items of information were collected for each slope and multivariate statistical analysis was used in the attempt to discriminate between failed and stable slopes. The results of the research showed that, despite great care and effort, no simple rules could be determined that would allow instability to be predicted with any confidence.[27] One conclusion following the experience of the CHASE study, which was later confirmed by detailed studies of several major landslides, is that failures are commonly the result of site-specific geological features that cannot be dealt with realistically using an empirical approach.[28]

Modelling

Where the geology is complex such that potential slope instability may involve several mechanisms, such as sliding on some discontinuities, toppling and, perhaps, failure of intact rock, all acting within the same failure, analysis by traditional methods is particularly difficult and it is in this type of situation that modelling may play a key role. Modelling is also particularly useful for investigating the development of failure mechanisms with time (progressive failure), an aspect that normal kinematic analysis of the factor of safety cannot hope to address. Over recent years numerical modelling, in particular, has become a cheap and viable option for site-specific problems. In the present contribution modelling approaches will be discussed that can provide insight into potential modes of failure. Examples will be given of how measured deformations can be explained through modelling with some degree of confidence that the envisaged mechanisms are correct.

Principles of modelling

Models can be useful both for assessing conditions at particular sites and as research tools to investigate some of the fundamental unknowns.

Starfield and Cundall[29] reviewed the use of models for geotechnical studies and offered several important comments and guidelines, some of which can be summarized as follows: models are simplifications; models should be designed to answer specific questions; a few simple models may be better than one complex model; and the approach should be that of a detective rather than a mathematician.

Despite this good advice to keep things simple, models are being increasingly used—and with remarkable success—to simulate some very complex situations. For example, Barton *et al.*[30] reported almost perfect agreement between measured displacements and those predicted by numerical modelling of a cavern with a span of 62 m in rock of only fair quality.

Physical modelling

Physical models have been used for many years in structural geology and rock mechanics to simulate rock mass behaviour. Construction can be from a range of materials, from the carefully scaled sand, oil and water glass used by Griggs[31] to the brick models of Fumagalli.[32] Physical models can also be used to simulate particular aspects of a problem, such as the shear behaviour of rock discontinuities.[15,33] Many authors have considered the problems of scaling from the field situation (prototype) to the laboratory, and several have attempted to provide a fully dimensionless scaling of the rock mass.[34,35,36] It seems, however, that it is not possible to scale all aspects of a model consistently with the prototype at the same time and it is therefore necessary to concentrate on scaling particular relevant parameters according to some 'similar performance criterion' that is selected on the basis of the nature of the problem that is being modelled.[37,38] Most

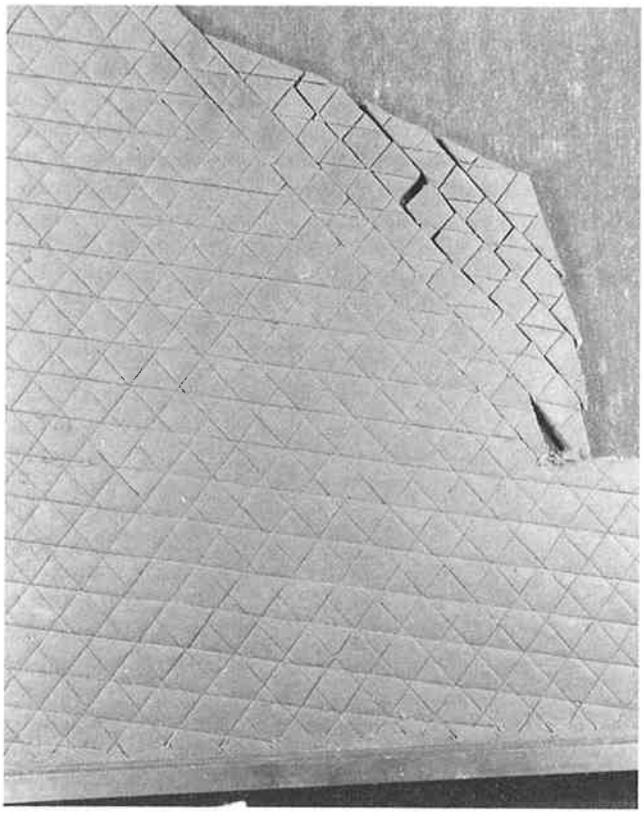
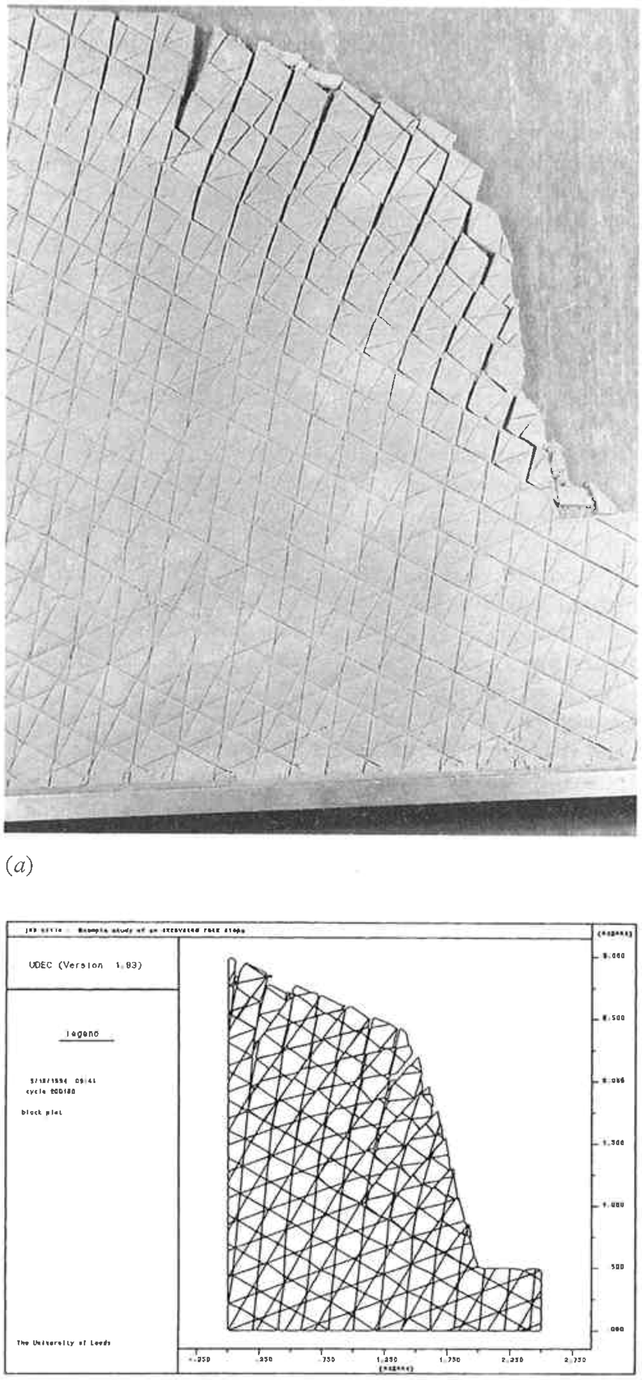


Fig. 2 Base-friction model of slope failing by sliding on daylighting discontinuities

modellers try to scale tensile or compressive strength while assuming that frictional characteristics are the same for both rock and model. This assumption may limit the quantitative nature of any conclusions.

One of the most useful physical modelling methods for the relatively low-stress conditions of the majority of slopes is the base-friction system, in which a model is constructed from a weak material, perhaps bound with plaster, on a flat bed that is coated with frictional material, such as sandpaper. When the base is moved relative to the model the frictional drag simulates the effects of gravity in a fairly realistic way. The theory of base-friction modelling was discussed in detail by Bray and Goodman[39] and the development of the technique has been reviewed by Al-Harthi and Hencher.[38] Model materials can be recyclable, which means that the method is easy, rapid and cheap and allows the influence of the various inevitable uncertainties at a site to be systematically explored without major difficulty. An example of a base-friction model of a slope is presented in Fig. 2. Comparative tests of base-friction and numerical models can show good correlation[38,40]—at least in a qualitative sense—as will be illustrated in the following section.



(*a*)

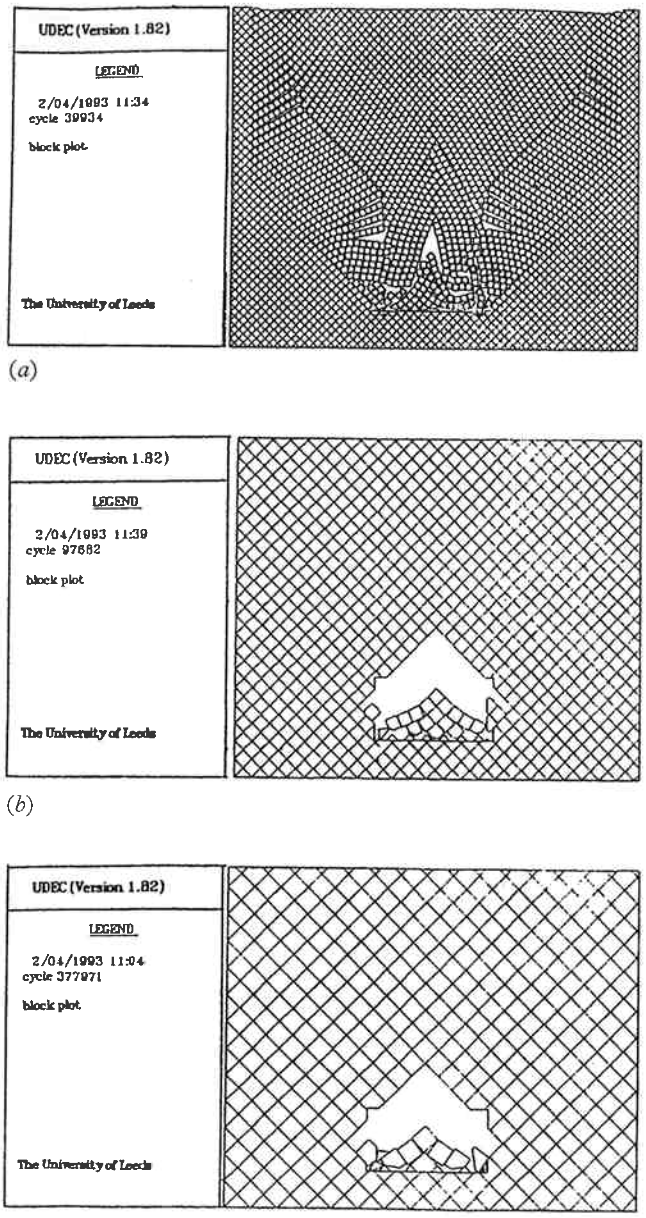
(*b*)

Fig. 3 (*a*) Base-friction and (*b*) UDEC models of slope with four sets of discontinuities

Numerical modelling

Numerical methods are increasingly being used to model rock masses and have been reviewed in the context of underground excavation by Hoek and co-workers.[41] Models are used in a general way to explore site-specific behaviour or may be applied to investigate fundamental aspects of behaviour. Continuum methods, such as finite-element, finite-difference and boundary-element, may have a role in open-pit slope design but are not designed specifically for anisotropic, blocky rock masses although they have been used in this way.[42] Over the last decade methods that allow the modelling of masses consisting of discrete blocks have reached an advanced stage of development. For example, the discontinuous deformation analysis (DDA) method of Shi[43,44] has attracted much recent attention and is the subject of continued development (e.g. by Amadei and co-workers[45]).

The universal distinct-element code (UDEC), originally described by Cundall,[46] has now been developed into a very powerful code that is capable of dealing with intensely fractured and complex masses in two or three dimensions and is widely used for modelling the behaviour of both underground excavations and slopes.[47] The code solves numerical procedures that involve the equations of motion of particles or blocks rather than the continuum. Discontinuities are generated in the model either individually through reference to a grid-point system or as sets defined by such



(*a*)

(*b*)

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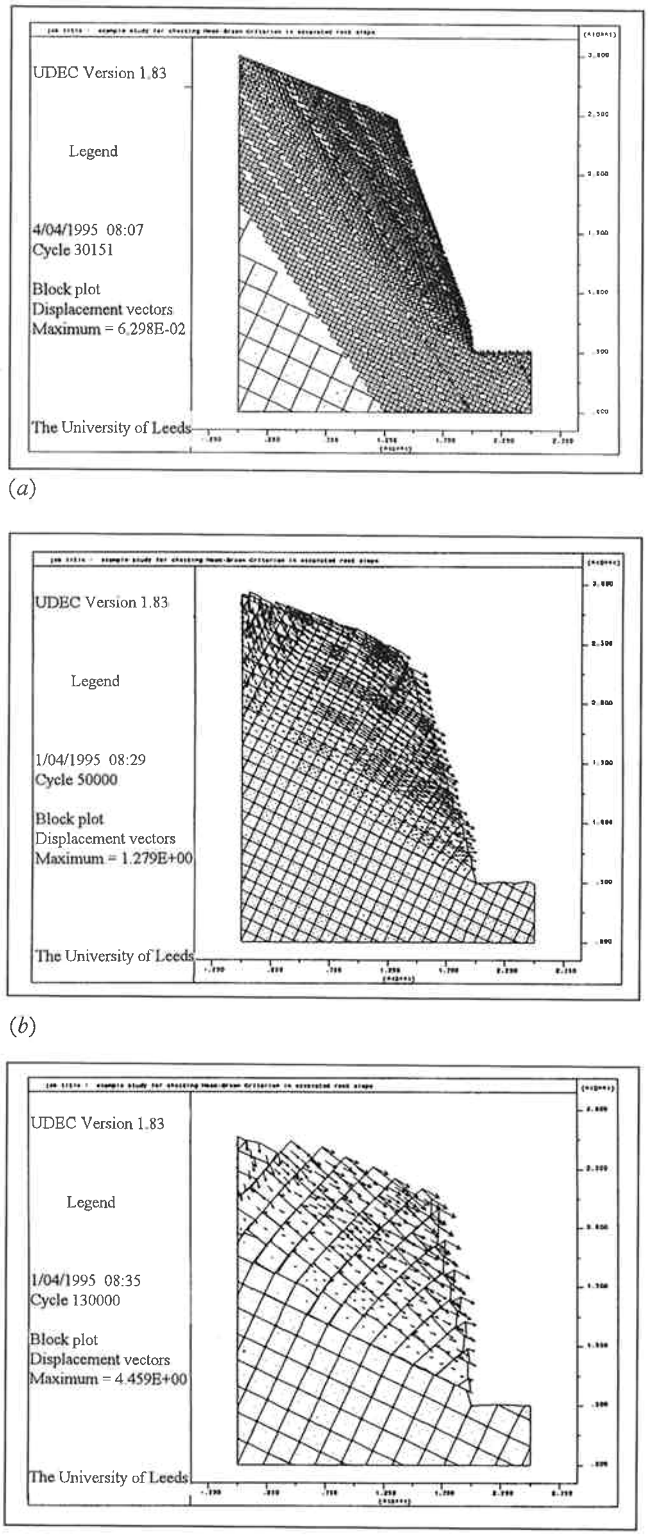
Fig. 4 Effect of changing block size on failure mechanism in regularly jointed rocks for an underground excavation. (*a*) Block width ≈ *h*/10, (*b*) block width ≈ *h*/5 and (*c*) block width ≈ *h*/3, where *h* is height of opening. (After Al-Harthi and Hencher[40])

parameters as dip angle, trace length and spacing. Although UDEC requires that fractures cannot terminate within intact rock, this restriction can be overcome by generating 'fictitious' joint segments with parameters chosen so that they behave as intact rock.[48] Constitutive laws are used to define the engineering behaviour of both the intact rock blocks and the discontinuities between rocks, with several options available according to the perceived nature of the rock. For example, blocks may be taken as either rigid or deformable through the use of finite-strain elements within the blocks. Rock joints are represented as contact surfaces between the edges of blocks and the shear behaviour may be defined by various models, including that of Barton and Bandis (Bandis and co-workers[49]). Fluid pressures within the discontinuities can be included. Although highly developed, such methods are not always straightforward to use. In particular, the decision on which parameters to employ in the model is not trivial and difficulties are often encountered owing to numerical problems (contact overlap of blocks) and such aspects as trying to simulate the various stages of excavation realistically. Such difficulties can be frustrating, particularly as each run may require considerable computing time.



(*a*)

(*b*)

(*c*)

Fig. 5 Effect of changing block size on failure mechanism in rock slope. (*a*) Block width ≈ *h*/50, (*b*) block width ≈ *h*/20 and (*c*) block width ≈ *h*/10, where *h* is height of steepest section of slope

UDEC, like its sister continuum code FLAC (fast Lagrangian analysis of continua), is a time-stepping program. The gradual development of failure mechanisms can there-