Ground Control for Underground Excavations -
Achievements and Challenges

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Abstract: An overview is given of the advances made over the past four decades, in
Australia and elsewhere, in ground control fundamentals, techniques and applications in
underground mining and construction in rock. Several varied examples are given of the
successful application of modern ground control methods. Finally, an analysis is given of
the challenges currently faced in transferring existing knowledge and technology into the
mining industry and in further advancing the state of the ground control art.

Key Words: geomechanics, ground control, rock reinforcement, underground
construction, underground mining.

Introduction

The themes of this conference are wide-ranging covering a full range of issues associated
with the applications of geomechanics and ground control in underground mining and in
underground construction. In this Keynote paper, an ambitious attempt will be made to
provide an overview of ground control methods for all types of underground excavations in
rock. The approach taken will be to examine the progress made over the past 40 years or
so and the current state-of-the-art as illustrated by a number of examples, and then to
consider the challenges faced in providing improved and more cost-effective ground control
systems in the future.

Some emphasis will be placed unashamedly on Australian experience and achievements.
Because the author’s experience has been largely in the fields of underground metalliferous
mining and underground civil construction, examples will be given mainly from these
fields although not to the total exclusion of underground coal mining.

Terminology

The terminology associated with geomechanics, ground control, support and reinforcement
is often confused, if not mistaken. For the purposes of this paper, the following
terminology will be adopted.

Geomechanics is the study of the mechanical responses of geological materials. It is
concerned with the physical and mechanical properties and responses of soils and rocks
and with their interactions with water. It encompasses the subject of rock mechanics,
which the Statutes of the International Society for Rock Mechanics defines in these terms:
"The field of rock mechanics is taken to include all studies relative to the physical and
mechanical behaviour of rocks and rock masses and the applications of this knowledge for
the better understanding of geological processes in the fields of engineering".

Mining geomechanics is that part of geomechanics (including rock mechanics) that is
concerned with the application of knowledge of the physical and mechanical behaviour of
geological materials (soil, rock and water) to the investigation, design, operation and
performance of mining structures including excavations. It is clear that geomechanics is a
basic mining science. It has different emphases in surface and underground and in
metalliferous and coal mining although the principles involved, including the principles of
engineering mechanics, remain the same.

Ground control is a term that is used more commonly in the mining industry, especially
the coal mining industry, than in the civil construction industry. It is taken to mean the
maintenance of the stability of the rock around an excavation and the more general control of displacements in the near-field of an excavation (Brady and Brown 1993).

**Strata control** is a term that was used widely in the mining industry before the development of the terms geomechanics, rock mechanics and mining geomechanics as defined above. It is still used in the coal mining industry to mean "the control and prediction of strata behaviour during development and extraction operations. This definition encompasses a wide range of tasks in underground coal mining, such as roadway design, pillar design, subsidence prediction, definition of caving characteristics and longwall face control" (Siddall and Gale 1992).

Support and reinforcement are important means of achieving ground control. The definitions adopted here will be those given by Windsor and Thompson (1993a) and Windsor (1997):

"The words support and reinforcement are often used interchangeably. However, it is useful to consider the two terms as being explicitly different due to the method by which they stabilise the rock adjacent to an excavation. Essentially, support is the application of a reactive force at the face of the excavation, and includes techniques and devices, eg fill, timber, steel or concrete sets, shotcrete, etc. Reinforcement is considered to be an improvement of the overall rock mass properties from within the rock mass and will therefore include all techniques, and devices that act within the rock mass, eg rock bolts, cable bolts and ground anchors.

**Pre-reinforcement** is the application of reinforcement prior to the creation of the excavation. **Post-reinforcement** is the application of reinforcement at an appropriate time after the creation of the excavation." (Windsor 1997)

**Beginnings**

It would be a futile, albeit fascinating, exercise to attempt to establish when identifiable mining and underground excavation geomechanics work was first undertaken in Australia. The following outline of the beginnings of the discipline in Australia is based on the author's earlier accounts of the development of geomechanics and of mining geomechanics in Australia (Brown 1991, 1992).

Australia's first miners and mining engineers came from England where they had gained experience mainly in the coal mines in the north and the tin and copper mines in Cornwall. One of the very first government mining officials was John Busby from Northumberland who took up the post of Mineral Surveyor and Civil Engineer to the colony of New South Wales in February 1824. His initial task was to develop the Newcastle coalfield but he is perhaps better remembered for the excavation of Busby's Bore, a 3.6 km long water supply tunnel for the growing city of Sydney in the period 1827-37 (Carroll 1988).

The South Australian silver-lead and copper mines which were opened in the 1840s used the mining and engineering methods imported with the Cornish miners and their managers or "Captains". However, it was the discovery of gold in mineable quantities, ostensibly by Edward Hargraves at Summer Hill Creek, NSW, in February 1851 and, more importantly, at Clunes and at Buninyong in the colony of Victoria in the same year, that led to the first development of a major indigenous mining industry (Blainey 1993). Mining in the Victorian goldfields was initially alluvial but soon evolved into the mining of the deep leads and then quartz veins at Ballarat and Bendigo. By 1895 George Lansell's 180 Mine in Bendigo had reached a depth of 970 metres; it was then said to be the deepest mine in the world.

The Australasian Institute of Mining Engineers was founded in 1893 and was transformed into the Australasian Institute of Mining and Metallurgy in 1921. The major mining geomechanics related issues referred to in the early volumes of the Institute's Transactions
were the provision of support by timbering (eg Godfrey 1901, Beaumont 1903) although, of course, these accounts are not presented in a modern geomechanics context.

Although the general topics of ground pressure (as it was called) and mining subsidence had been the subjects of systematic investigation in Europe and North America from about the 1870s (eg Fayol 1885, Young and Stoek 1916), Australian contributions to the development of mining geomechanics appear to have been minimal until the early 1960s.

A change began to take place in the early 1950s when rock bolting was introduced into underground coal (eg McKensey 1953, Horseman 1954) and metalliferous (eg Yates and Holly 1956, Cawdle 1957) mines in Australia. But it was the design and construction of the monumental Snowy Mountains Hydroelectric Scheme in the period 1949-69 which gave a major impetus to applied geomechanics research and practice in Australia. The most significant advances came in the then emerging discipline of rock mechanics, particularly in the areas of geological data collection and classification (Moye 1959), in situ stress measurement (Alexander 1960), underground excavation design (Lang 1957) and the theory and practice of rockbolting (Lang 1957, 1961, Pender et al 1963). The high standard of applied geomechanics work established on the Snowy Mountains scheme was emulated in the hydroelectric developments undertaken subsequently by the Hydroelectric Commission of Tasmania (eg Endersbee and Holto 1963, Maddox et al 1967).

The Australian mining industry soon took advantage of the development of rock mechanics expertise that took place in the 1950s and 60s. In the 1960s a number of mining companies used the expertise built up on the Snowy scheme to advise on specific problems (Barnes 1963, May 1980). In 1963, Mount Isa Mines established what soon became one of the strongest applied rock mechanics groups working on a particular mining operation anywhere in the world. Davies (1967) acknowledged the valuable influence on Mount Isa mining operations of the rock mechanics program described by Mathews and Edwards (1969).

**Progress - Fundamentals**

The purpose of this and subsequent sections is to provide an overview of the progress made in underground ground control in the past 40 years and to highlight some major achievements in the area. The developments referred to have been part of the general advances made in geomechanics, rock mechanics and rock engineering over the same period. Because of the data-limited nature and complexities of the problems involved (Brady and Brown 1993, Starfield and Cundall 1988), progress has been incremental and few, if any, final solutions have been developed. Nevertheless, progress has been impressive.

In the area of "fundamentals", taken to include basic mechanics, analysis, understanding, philosophy and process, the following have been among the more important developments in the author's view.

(i) The contributions made to site investigation methodology and the design and reinforcement of underground excavations in rock by the team led by T A Lang on the Snowy Mountains Hydro-Electric Scheme were highlighted above. Lang (1957, 1961) was the first to formulate an explanation of the way in which systematic rockbolting forms a largely self-supporting arch of reinforced rock in the roof of an excavation. On the basis of this understanding, Lang developed a set of design rules for rockbolting which still finds use today.

(ii) Although the elements of the approach had been understood earlier in Europe, it was not until the period under review that ground-support interaction concepts came to be widely understood and applied (Pacher 1964, Daemen 1977, Hoek and Brown 1980). This approach illustrates clearly the importance of the timing of installation, stiffness and yield characteristics of support and reinforcing elements.
(iii) The influence of discontinuities on the engineering responses of rock masses was recognised by the Austrian School of geomechanics from the 1920s. However, it was not until the 1960s that this recognition started to become widely reflected in underground excavation support and reinforcement design. Since that time, significant progress has been made in the measurement and analysis of discontinuities for rock engineering purposes (Priest 1993), the development of block theory and the key-block concept (Goodman and Shi 1985), reinforcement design packages based on assessment of the shapes and sizes of the blocks formed by the discontinuities in the rock mass (Windsor and Thompson 1992) and distinct element numerical methods (Cundall 1987).

(iv) In addition to the distinct element numerical methods referred to above, the development and adaptation of continuum based numerical methods (finite element, finite difference, boundary element) has provided the capability for carrying out a wide range of static and dynamic, linear and non-linear, two- and three-dimensional analyses of underground excavations and their ground control systems (eg Cowling et al 1991, Gale and Blackwood 1987, Nemčík et al 1998). Because of the difficulties of measuring or estimating the boundary conditions and rock mass properties required for these analyses, it is essential that a suitable modelling philosophy or methodology be adopted if these powerful tools are to be used to maximum effect (Salamon 1988, Starfield and Cundall 1988).

(v) The application of the observational method (Peck 1969) and the associated development and application of robust and sensitive monitoring systems (Dunnicliff 1988) has played an important role in developing an understanding of the mechanics and performance of underground excavations and their ground control measures and in ensuring their effectiveness (eg Siddall and Gale 1992, Windsor and Thompson 1993b). Formal back analysis methods developed in the 1980s (Gioda and Sakurai 1987, Akutugawa et al 1991) show promise of being able to provide back-calculated estimates of in situ stresses and rock mass moduli on the basis of monitoring measurements. However, to the best of the author’s knowledge, they have remained a specialist interest and have not been applied widely in practice.

(vi) Because of the prominence accorded the area in the papers submitted to this Conference, it is worth noting here the improved understanding of the geomechanics of underground coal mining that has developed over the past 40 years. Salamon and Munro’s (1967) classic study of pillar stability in South African coal mines involving considerations of probability, has provided the basis for a series of incremental developments in coal pillar design including some reported in this Conference (eg Galvin et al 1998). An important advance in this area has been the development of an improved understanding of the influence of weak roof and floor seams and contacts on coal pillar stability (Gale 1996, Hebblewhite et al 1998a).

Progress - Techniques

Just as our understanding of the nature and mechanical responses of rock masses and the analytical and numerical tools at our disposal have developed greatly over the past 40 years, so have the ground control techniques used in underground mining and construction.

Rock bolts and cable bolts

Rock bolts (generally up to 3m in length) began as simple mechanically anchored devices but have since been developed to include a range of friction bolts (eg Split Set, Swellex) and resin and cement encapsulated bolts. Early applications of rock bolting in Australia have been referred to above. The use of grouted rock bolts for permanent reinforcement was pioneered on the Snowy Mountains Hydro-Electric Scheme (Pender et al 1963).
Instructive diagrams and descriptions of several types of rock bolt are given by Hock et al (1995). Rock bolts are now widely used in underground coal and metalliferous mining and in underground construction to help create self-supporting arches and roof beams and as spot bolting to pin potentially unstable blocks of rock. They are the most commonly used support or reinforcing element. A range of new developments in rock bolt technology are reported in the proceedings of this Conference (eg Gray et al 1998, Rataj et al 1998).

**Cable bolts** (generally 3 to 15 m in length) are reported to have been first used in underground mining in Canada (Marshall 1963) and South Africa (Thorn and Muller 1964). Cable bolt and dowel (untensioned) reinforcement was introduced into underground metalliferous mines in Australia in the early 1970s (Clifford 1974). Although there was simultaneous interest in the technique in Canada and in Scandinavia, Australian research and practice in cable bolting led the world. The initial applications were to cut and fill mining (Fuller 1981) but subsequently, pre-placed cable bolt reinforcement was of fundamental importance to the introduction of large-scale open stoping methods of underground mining (Bywater and Fuller 1983, Thompson et al 1987). Australian engineers have also made significant contributions to the understanding of the mechanics involved and the development of appropriate design methods (eg Fuller and Cox 1978, Windsor 1997). As in the case of rock bolts, advances continue to be made in cable bolt technology (eg Hutchins et al 1990, Hyett et al 1992). In recent years, cable bolting has been introduced into underground coal mining with some effect (O'Grady et al 1994, Kent et al 1997).

**Shotcrete**

Shotcrete (sprayed concrete) was introduced into underground construction in Europe in the mid-1950s (Jaeger 1972). At the time of the construction of the Snowy Mountains Hydro-Electric Scheme, gunite (sprayed mortar) was used probably more effectively as a water- and weather-proofing agent than as support, as it had been since the early part of the century. By the 1960s in Europe, shotcrete had become an integral part of the so-called New Austrian Tunnelling Method (NATM) (Rabcewicz 1964), so much so that some believed it to be the NATM. This is not correct. The NATM is an approach to underground construction which applies most of the sound principles and practices of ground control used elsewhere (Brown 1981).

Shotcrete technology using mainly the wet-mix process and involving the use, where appropriate, of accelerators, plastifiers, fibre reinforcement and other additives, is now widely used internationally in underground construction in hard and soft ground and in underground mining. In metalliferous mining, shotcrete is used not only in infrastructure and accesses but also to provide support around stopes and other production openings (eg Lourence et al 1996).

**Mining with fill**

According to Dickbott (1973), back fill was first used to control surface displacements above a mining area in 1864. In the 1950s the dry fill formerly used was replaced with hydraulically placed fill in a number of Australian underground metalliferous mines (eg Cawdle 1957, Yates and Holly 1956). Mechanised cut and fill methods of mining were introduced for the Racecourse lead orebodies at Mount Isa in 1964 (Davies 1967) and adopted for the CSA Mine, Cobar in 1965 (Brady et al 1969). During the 1970s cut and fill was a primary underground metalliferous mining method at about 10 major Australian mines. The method was also being used in Canada and Scandinavia.

In 1969 an AMIRA sponsored research project on problems associated with cut and fill mining was commenced by the then CSIRO Division of Applied Geomechanics. Over the subsequent decade this project and its successors, coupled with the associated in-house research and development programs of the mining companies themselves, contributed to the productivity of the operations concerned. Particularly significant advances were made

Although cut and fill mining continued to be used in some locations, especially in the Eastern Goldfields of Western Australia (Swindells and Szwedzicki 1991), economic imperatives subsequently caused a large number of Australian underground metalliferous mines to adopt open stoping methods, usually with backfill. These developments relied heavily on the mining geomechanics knowledge and expertise that had been developed in the "cut and fill era". The contributions of geomechanics to these developments are well illustrated by the development of open stoping in the 1100 orebody at Mount Isa (Watson 1987) which required the use of a low cost cemented rock fill developed through a cooperative research program undertaken with the School of Mining Engineering, University of New South Wales (Williams 1977). More recent developments made in fill technology in other parts of the world include the use of fill to control convergence and improve safety in the deep level gold mines of South Africa (Jager et al. 1987, Gurtunca 1997) and the development of paste fill in Canada (Landriault and Lidkea 1993).

Yielding support and reinforcing elements for rockburst conditions

The understanding, prediction, control and amelioration of rockburst conditions in underground mining and construction remains one of the great challenges in mining geomechanics and ground control. Significant advances have been made since these problems have been studied systematically from a rock mechanics perspective in South Africa from the 1950s (Salamon 1983) and more recently in Canada (Kaiser et al. 1995). A particular ground control requirement in these conditions is to be able to absorb rapidly the large amounts of energy released from the rock mass and, as a consequence, to control the resulting displacements at the excavation boundaries. Two of the techniques developed for this purpose in South Africa will be outlined here.

Hydraulic props placed in lines as close as 1.0 m to the face have been used to control convergence and roof falls in the deep level South African gold mines for several decades. The need for rapid yielding hydraulic props to absorb the energy released by rockbursts was realised in the early 1960s. Under rockburst conditions, fractured rock can be accelerated to velocities in excess of 3 m/s (Jager 1992). Others have suggested that even higher velocities may be involved. After evolutionary development, a recently developed prop and headboard system can deform to a maximum displacement of 200 mm at a yield rate of 3 m/s and with a yield force of 400 - 500 kN (Jager 1992). Face support systems of this type are designed to absorb energies of 60 kJ/m². As Gurtunca (1997) notes, the use of these systems in South African mines has not met expectations, possibly because of the mass of each unit (32 kg). Gurtunca recommends that these units should be made from lighter materials and their mass reduced to 10-15 kg.

The reinforcing systems (rock bolts, cable bolts, mesh, straps and lacing) used in development openings (tunnels) in South African gold mines are required to control large displacements of yielding rock, often under rockburst conditions. A yielding rock bolt designed for this purpose, known as the cone bolt, is shown in Figure 1. The bolt is a

![Figure 1. The design of a cone bolt yielding tendon (Jager 1992)]
2.2 m long, 16 mm diameter, smooth high tensile steel bar having a conical flaring with a maximum width of 25 mm forged on one end. The bolt is debonded from the fully encapsulating cement grout by a coating of wax. The bolt is designed to yield at an axial force of 80 to 100 kN by the cone being pulled through the grout for up to 500 mm (Jager 1992). Gurtunca (1997) notes that a major impediment to the widespread industrial adoption of cone bolts is their cost. Steel cable cone bolts, 4.5 to 7 m in length, would appear to provide a valuable component of the reinforcement systems required to control rockburst damage in tunnels in deep level mines (Jager 1992).

Examples of Achievements - Civil Construction

It is now possible to construct larger excavations in what were previously considered to be unfavourable ground conditions, and often closer to the surface, than it was 40 years ago. We have seen the construction of long undersea railway tunnels, notably the 54 km long Siekan Tunnel in extremely difficult conditions in northern Japan (Matsuo 1986). The Channel Tunnel, despite its series of problems of other types, did not presene major ground control problems although the construction of the 21 m span and 160 m long UK undersea cross-over structure in chalk marl with a cover of 36 m to the sea bed was a major achievement (Fugemas et al 1992).

In Australia, a major achievement was the construction of the Bennelong Point Parking Station for the Sydney Opera House (Pells et al 1991, Pells 1993). The parking station is a double helix structure within a huge doughnut-shaped cavern having an excavated span of up to 19 m and an outer diameter of 75 m. The cavern is excavated in horizontally bedded, variably weathered Hawkesbury sandstone carrying high horizontal stresses. The flat roof spans of 17.5 to 19 m have a total cover of only 7 to 8 m, not all of which is rock, and underlie, in part, buildings of the Government House complex and some valuable trees which had to be preserved. This placed a major premium on the control of surface settlements which were generally less than 10 mm (Pells 1993).

Figure 2 shows the support and reinforcing systems used in the cavern roof. These systems consist of up to 7.5 m long tensioned Macalloy bar anchors, up to 4.5 m long galvanised dowels and a 150 mm thick skin of reinforced shotcrete and fibrecrete. Pells (1993) shows a comparison of the span to depth of cover ratios of several large near-surface rock caverns which suggests that, at the time, the Bennelong Point Parking Station had possibly the largest such ratio of any cavern in the world.

![Figure 2. Roof reinforcement for the Bennelong Point Parking Station, Sydney (Pells et al 1991)](image-url)
Probably the most impressive of all recent underground engineering achievements is the 62 m span Olympic Ice Hockey Cavern constructed at Gjovik, Norway, for the 1994 Winter Olympic Games. It is the world's largest underground excavation for public use. Its span of 62 m could not have been contemplated a few decades earlier. The structure is 90 m long and up to 25 m high and has a rock cover varying from as low as 25 m to about 50 m. Rock reinforcement in the main cavern consists of systematic untensioned, fully grouted alternating 6 m long rebar rock bolts (dowels) and 12 m long twin strand cables on square 2.5 and 5.0 m spacings, respectively, with a 100 mm layer of wet process steel fibre reinforced shotcrete. The engineering of this structure was a triumph for the Norwegian team who applied a full array of modern rock engineering techniques including detailed site and rock mass characterisation, distinct element numerical modelling, physical modelling and monitoring during and after construction (Barton et al 1994).

Examples of Achievements - Metalliferous Mining

A number of the advances made in ground control in underground metalliferous mining in Australia and elsewhere over the past 40 years have been referred to above. This section will outline briefly, the geomechanics issues associated with the development of a new, more economic mining method for the silver-lead-zinc orebodies at Mount Isa, and the application of some of the advances outlined to the design and operation of the Neves-Corvo mine in Portugal.

The silver-lead-zinc orebodies at Mount Isa have been mined by a variety of methods over the past 60 years, most notably by cut-and-fill methods from the 1960s. These orebodies are stratabound, well-bedded, banded sulphides contained within the Urquart shales and having a fairly uniform 65° westerly dip. The orebodies are 4 - 35 m wide and their separations range from 4 to 80 m. Since early 1991, all cut-and-fill operations in the Lead mine (as it is known locally) have been replaced by a more economical bench stoping method described by Wylie and Jarc (1992), Villaeascusa et al (1994) and Villaescusa (1996).

The Mount Isa bench stoping method is illustrated in Figure 3. Typically, bench stopes are of full orebody width, have an average length along strike of 100 m, and have inclined hangingwalls ranging from 12 to 45 m down dip. The successful introduction of the bench stoping method relied upon advances in the understanding of hangingwall behaviour, improved ground control techniques especially cable bolting, backfilling technology, improved drilling and blasting practices, and the application of remote mucking technology (Villaescusa 1996).

![Figure 3. Bench stoping geometry at Mount Isa.](image)

(a) Longitudinal section looking west; (b) cross-section looking north (Villaescusa 1996)
Hangingwall stability was found to be a function of the extraction sequence, blasting practices, the size and shape of the unsupported span and rock mass quality as determined by bedding plane breaks and cross jointing. An empirical stability chart method of bench stope design was developed using an in-house rock mass classification scheme developed specially for the purpose.

In addition to the backfill, the ground control techniques used include permanent pillars, rock bolts (Split Sets) and cable bolts. Major advances in the efficacy of cable bolting have been made by paying particular attention to cable bolt load-deformation characteristics and installation practices including grout design (Villaescusa et al 1994). Resulting annual savings of $2 million in Lead mine support costs were highlighted in the MIM Holdings Limited's 1993 Annual Report as an important contribution to its productivity.

The design, development and operation of the **Neves-Corvo copper-tin mine** in the Iberian Pyrite Belt near the town of Almadovar in southern Portugal is a modern success story which owes much to the application of geomechanics knowledge and modern ground control philosophy and techniques. With annual production of around 2 million tonnes of copper and tin ores it is one of the world's largest underground copper mines.

The discovery, project development and early mining of the Neves-Corvo ore bodies are described by Bailey and Hodson (1991). Caupers et al (1993) provide an account of a trial stope experiment and early stope design and ground control measures. As Bailey and Hodson (1991) note, the choice of a stoping method was governed by a number of key factors:

(i) very high *in situ* copper grades which made maximum extraction and low dilution a priority;
(ii) the generally good geomechanical quality of the major orebodies and a strong hangingwall;
(iii) flat orebody dips, averaging about 30° (see Figure 4);
(iv) a generally weak and sheared shale footwall and footwall contact;
(v) the presence of several major faults which displace the ore; and
(vi) the wide and rapid variation in ore thickness (see Figure 4).

![Figure 4. Geological transverse section through Corvo and Graça orebodies, Neves-Corvo mine, Portugal (Bailey and Hodson 1991)](image-url)
Some initial mining studies reached pessimistic conclusions about stable opening spans, permissible overall mining spans and the possibility of achieving 100% extraction. Ultimately, a longitudinal drift-and-fill mining method was chosen and implemented with great success. This method has several advantages (Bailey and Hodson 1991):

(i) the ability to develop initial drifts following the hangingwall contact minimised dilution and afforded mine geologists easy access to the orebody to define fault structures and contacts;
(ii) the ability to allow considerable flexibility in stope layout and direction to take account of local variations in orebody characteristics;
(iii) the continuous and full extraction concept avoids the creation of potentially troublesome highly stressed pillars;
(iv) in wider parts of the orebody the technique could be modified as necessary to use transverse drift-and-fill from a central longitudinal drift; and
(v) the relatively large number of working faces would permit appropriate blending of the variable ore.

The quality of the cemented hydraulic fill and the achievement of tight placement against stope backs is of central importance to the success of the drift-and-fill mining method. Paste fill has been introduced recently. Rockbolting (Swellex and resin grouted bolts), cable bolting and some shotcreting are used to ensure stability of access and drift backs. Tensioned and grouted cable bolting is used to help ensure the overall stability of the mine structure. Horizontal spans of mined-out areas reach up to 100 m. In recent years, the sill pillars left between stoping blocks have been mined successfully using adaptations of the drift-and-fill method, allowing effectively 100% extraction of the Graca and Corvo orebodies (Figure 4). Wet mix mesh and fibre reinforced shotcrete, rock bolting, cable bolting and lacing of the type used in the deep level South African gold mines are used to reinforce infrastructure which can be subjected to high stress conditions.

Since 1996 mining of the Neves North orebody has been by a “mini” bench stoping method similar to that used at Mount Isa. In 1997, production by this method also commenced from the Neves South orebody. The more favourable ground conditions in these deeper orebodies and improved geomechanical understanding and ground control systems have permitted this mining method to be introduced most effectively.

Examples of Achievements - Coal Mining

Coal was first discovered in New South Wales in 1791 and mining commenced in 1799 (Lama 1993). Underground mining was always the major source of black coal production in New South Wales but from the 1970s an increasing proportion of coal came from open cut mines in the Hunter Valley. Following the initial unsuccessful attempts to introduce mechanised longwall mining in the 1960s, longwall production has risen steadily and is now the most productive mining method used in New South Wales coal mines (Lama 1993).

In Queensland, the mining of coal began on the banks of the Brisbane River at Goodna in 1843 (Sleeman 1993). Coal was mined by underground methods until the 1960s when the major open pit mining developments in Central Queensland began and soon became dominant. In 1983, development of the first modern longwall mine in Queensland began at Capricorn Coal Pty Ltd’s Central Colliery. Following the successful introduction of longwall retreat mining into the Bowen Basin in the late 80s and early 90s, Sleeman (1993) suggested that “the decade commencing in 1990 will probably mark the transition from open cut mining back into underground mining if demand for coal holds good”.

The successful introduction of mechanised longwall mining into Australia’s two dominant coal mining areas has been a significant engineering achievement. A range of difficulties have been encountered and overcome. The initial disastrous attempts in New South Wales failed essentially because of inadequate face support capacity (Lama 1993).
Significant problems have also been experienced with gateroad instability, the effects of high horizontal stresses, faulting causing displacement of the seams in Central Queensland, massive sandstone roofs causing problems with caving and gas emissions. Australian efforts at resolving the ground control problems involved through field instrumentation, computer modelling and the development of rock and cable bolt support systems, have been so successful that they have been “exported” to the United Kingdom and elsewhere (Gale 1996, Kent et al 1997, Siddall and Gale 1992).

It has also been found that the classical view of longwall caving mechanics and the distribution of vertical stresses around longwall faces developed for UK conditions (Whittaker 1974) does not generally apply in Australia (Kelly et al 1996, 1998). This has necessitated the establishment of a continuing program of field based research to develop new understandings.

For some time a high percentage of the coal mined in Australia has been produced from surface mines. However, mining dipping coal seams (other than brown coal) by open cut or strip mining methods can reach economic limits and the limits of dragline operation at depths of typically 50 - 60 m. There is a region between this limit and the minimum depth limit for underground mining in which hundreds of millions of tons of potential coal production are sterilised.

Initially in central Queensland (Seib 1989), and more recently in New South Wales (Ferguson 1998), an approach known as highwall mining has been introduced to address this problem. This method involves the remotely controlled mechanical excavation by continuous miners of a series of parallel or sub-parallel unsupported roadways driven under the highwall for distances of up to 300 m. The selection of the roof spans (usually not less than 3.5 m because of equipment requirements) and the sizes of the pillars left between the drives are crucial to the success of this method (Duncan Fama et al 1995). Methods of pillar design developed and implemented successfully use two- and threedimensional finite element and finite difference (FLAC) elasto-plastic stress analysis, a purpose-developed modified Hoek-Brown yield criterion (Medhurst and Brown 1996) and suitably adapted empirical pillar strength criteria (Trueman et al 1994, Duncan Fama et al 1995). It is highly unlikely that this method of mining could have been implemented successfully without this geomechanical input.

Challenges

It is clear from the outline and examples given above that since the time of the construction of the Snowy Mountains Scheme, great advances have been made in our understanding of ground control fundamentals, in the development of ground control techniques and in their application to underground mining and construction. This has been part of the evolutionary development of geomechanics in general, and of rock mechanics in particular, over the past 40 years. As Watson (1987) has said, the application of geomechanics in the Australian mining industry has been part of the technological innovation that has sustained its growth and international competitiveness in increasingly difficult economic circumstances.

But this apparently rosy picture does not tell the full story, particularly in the mining industry. In both underground coal and metalliferous mining, the Australian and international mining industries face serious challenges. The continual need to reduce costs in order to remain competitive and, in some mining provinces at least, the need to improve safety underground, including the need to reduce fall-of-ground-related accidents and fatalities, remain areas of concern. In some cases of fall-of-ground accidents of which the author has some knowledge, the causes appear to have been associated more with a failure to apply modern knowledge, techniques and best practice rather than with “acts of God”.

Concerns about costs and productivity on the one hand, and ground control and safety on the other, can appear to act in contrary directions, although this should not be the case. Pressures to reduce costs and produce short-term profits can cause corners to be cut in the
interests of financial expediency. Associated with this tendency there has been, in the Australian metalliferous mining industry at least, an apparent reduction in the continuing availability of specialist engineering skills on minesites. The net result has been that the available ground-control knowledge and technology is not always used to maximum advantage. In Australia, a number of experienced consultants are able to make up some of the shortfall. The overall position appears to be much more favourable in the underground construction industry than in the mining industry, in Australia at least.

So, in the author’s opinion, the greatest challenge that we face is not in making further incremental advances in knowledge, or even in solving the great unsolved problems, but in successfully applying existing knowledge and technology in practice. This is an issue of education (in its broader sense) and of training.

Of course, there exist a number of challenges of a technical nature requiring further research and development. High on the author’s list of such items would be

- further improving site and rock mass characterisation techniques including the ability to know or predict ground conditions ahead of excavation;
- adding to the value of the numerical analyses that are now widely used in practice, especially by consultants, by improving the realism of the constitutive models, boundary conditions and material properties used. Salamon (1988) addressed these issues eloquently when he wrote
  “The bewildering array of constitutive laws and models of behaviour proposed in the last two decades or so contain many physical parameters that are often ill defined and have not been investigated experimentally. Also, it appears that the growth in the number and breadth of field investigations to collect hard observations for comparison with modelled data has not paralleled the rate of proliferation in computation. Both of these neglects may lead to a situation where the computed values do not reflect the real world. If this development is allowed to progress unchecked, the value of the magnificent new computing technology will be undermined”;
- developing a better understanding of the mechanics of rockbursts and, ultimately, the ability to predict their occurrence. Similarly, the development and implementation of methods of controlling and alleviating the rockburst hazard remains a major need in underground mining in many parts of the world;
- further improving and reducing the costs of the materials and installation of several of the support and reinforcement techniques referred to in this paper; and
- developing new and improved understandings of several aspects of longwall caving processes, especially under the mining conditions found in Australia. Several papers to this Conference address this issue (eg Kelly et al 1998) while others address the related issues of rib and roadway behaviour and support (Hebblewhite et al 1998b, Tarrant and Gale 1998).

Gurtunca (1997) recently reviewed rock engineering strategies and challenges for deep level gold mining in South Africa. With suitable modification to reflect the industry sectors and local issues of concern elsewhere, his conclusions are considered to provide an excellent overview of the ground control challenges faced more generally in underground mining and construction:

“(i) Analysis of the rockburst and rockfall accident figures indicate that there has not been any reduction in rockburst and rockfall accident rates in recent years.
(ii) There are a number of rock engineering strategies to reduce rockburst and rockfall hazards, but the implementation of these strategies has not been achieved satisfactorily.
(iii) It is believed that if the rock engineering strategies are to be implemented on gold mines, rockburst and rockfall casualties could be reduced by 30 - 40 per cent.
(iv) There are still significant rock engineering challenges and problems which require intensive research work.
(v) However, training of mine personnel should be given the highest priority so that they can implement rock engineering strategies successfully."

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