LIMITS TO UNDERGROUND MINING AT DEPTH
(in the context of global demand for minerals)

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***Abstract*.**

Although global mineral resources are considered to be adequate to meet the needs of a rapidly growing world population, the United States is becoming increasingly dependent on imports. This could have implications for both the economy and national security. The US is a country with a strong tradition of leadership in science and technology. Impressive advances in autonomous underground mining systems reduce the adverse effects of heat and humidity in deep mines and focus renewed attention on ground control. Developments in computing power open opportunities to develop improved understanding of the important role of discontinuities (faults and fracture systems) and more effective design of deep excavations. Establishment of mining R&D Centers at leading US research universities, jointly funded by industry and US federal agencies is recommended as an effective step for the nation to remain an influential partner in world mining.

***Introduction*.**

> *"None of the arts is older than agriculture, but that of metals is no less ancient.. . for no mortal man ever tilled a field without implements.*
>
> *If we remove metals from the service of man, all methods of protecting and sustaining health and more carefully preserving the course of life are done away with."*
>
> ***Agricola (1558)*[i]**

Homo sapiens, generally acknowledged as the species from which modern Man has evolved, is considered to have originated in Swaziland some 100,000-200,000 years ago. Evidence of use of minerals in that region has been dated to earlier than 40,000 BC.[ii] Today, a large fraction of the elements of the Periodic Table are derived from minerals, and finding new applications in development of innovative technologies. Agricola's comments are as applicable today as ever.[iii]

Metals such as copper, tin, lead, iron and aluminum were mined and smelted several thousands of years BC. It was not until the Industrial Revolution, started in the latter half of the 17th Century in Northern England, where coal was available as an energy source, and iron as the basis for fabricating machinery, that dramatic change to society began to occur. Human toil was replaced by far more powerful machines. Rural communities migrated to work in factories in urban areas. Rapid transportation over long distances became possible, leading eventually to the world of today. The change spread to other parts of the world, bringing wealth and power.

Although now well established in some regions, the Revolution has still to arrive in many other parts of the world. This can be seen in Figure 2, which shows the relative wealth, or 'Standard of Living' as measured by the GDP/capita, of regions around the world. Regions such as North America, Europe, and Australasia [iv] are seen to have the highest standard. Thanks to today's global communications systems, regions with relatively low GDP/capita are well aware of 'how others live' – and eager to emulate them.

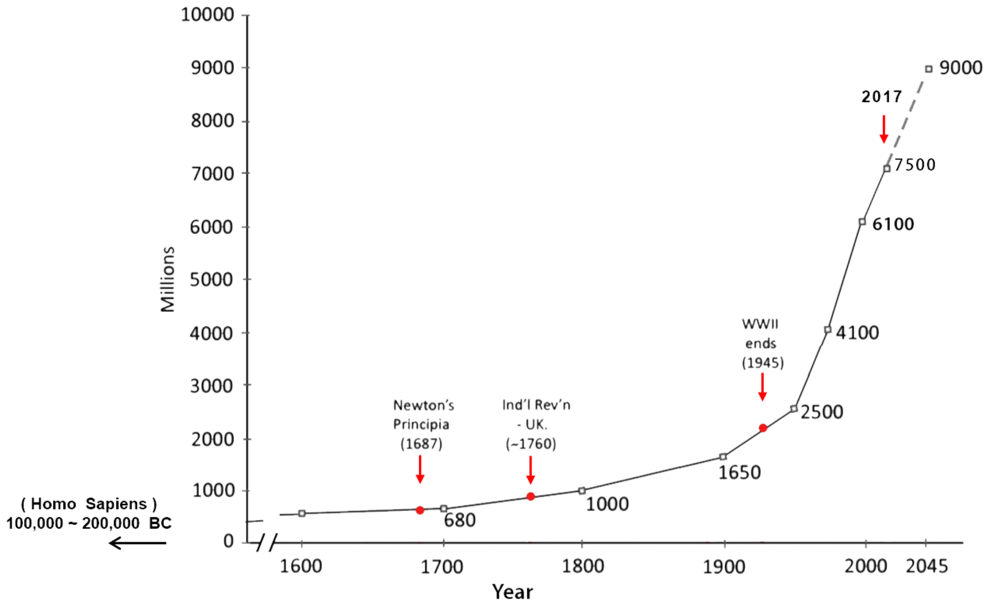


Figure 1. World Population 1AD to present - and projected to 2045.

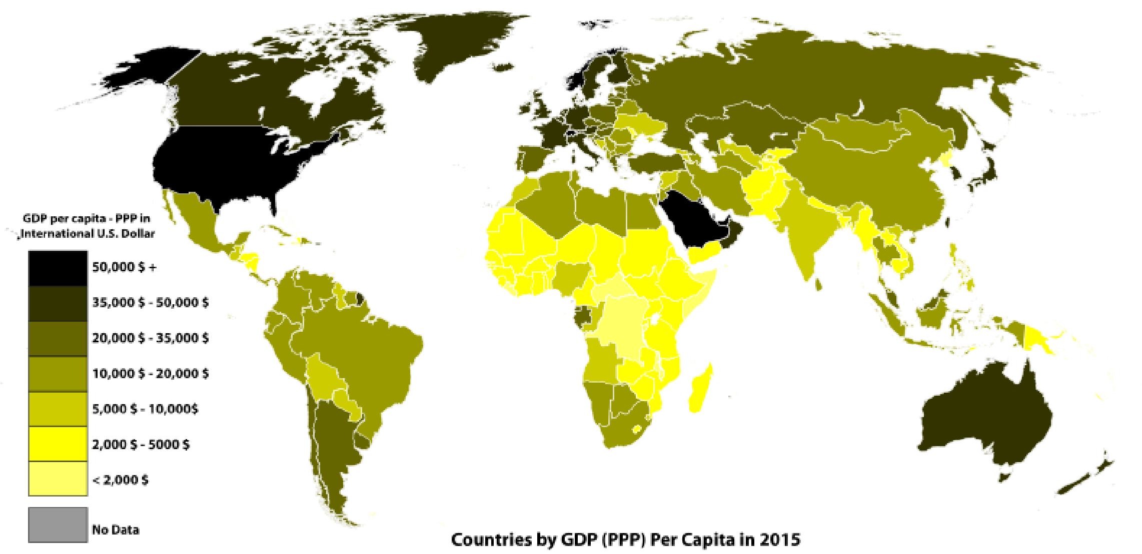


Figure 2 Countries by Gross Domestic Product (GDP) per Capita in 2015.
(original by Ali Zifan [v])

As seen in Figure 1, industrialization has been accompanied by an exponential growth in world population. Although there are several factors responsible for this rapid increase, much of the current population growth is occurring in some of the poorest regions – such as sub-Saharan Africa. Clearly, if these regions are to move forward, they will need to acquire or develop minerals.

The recent announcement of the New Silk Road or OBOR[vi] project, to develop the region between China and Eastern Europe – at an estimated cost of the order of four trillion dollars, is an example of what could occur in the next several decades.

What role will the United States play in these developments? More specifically, is there an opportunity for the US to take a leadership role in advancing mining engineering?

The United States is now considered by economists to be 'Post-Industrial societies', where white collar occupations predominate. As of 2006, 83% of all employed workers in the United States are engaged in production of services; 17% work in industries that produce tangible goods. [vii,viii.] Approximately 1% of all U.S. workers are engaged in the primary sector (agriculture, mining, forestry, fishing…). Today, mining accounts for ~ 0.1% of the US workforce. It is not surprising, therefore, that few in the general US population are aware of either the critical importance of minerals to the national economy and security or the possible risks in heavy reliance on imports.

Public attention in post-industrial societies such as the US tends to focus on the adverse consequences of the Industrial Revolution. Climate Change - attributed to the widespread global use of fossil fuels as the primary energy source – has led to major initiatives, nationally and globally, to replace these fuels with alternative 'green' energy sources. There are several realistic options.

The long-term adverse environmental legacy of past mining practice is also viewed negatively, but discussion of how to move forward[ix] has received very little objective national attention in the US.

Much of the US population is unaware of the fundamental importance of minerals to human well-being, while others are content to rely on imports. Emphasis has been placed on imposition of strict legislation to regulate mining and protect the physical environment. In 1995, Congress, presumably influenced by public opinion, eliminated federal support for research in mining.[x] To the writers' knowledge, no other mineral-producing country has taken such action.

Lack of Federal support for mining – related research at US universities - has contributed to a serious situation with respect to availability of mining engineers. A position paper [xi] published by the Society of Mining Engineers (SME) in March 2013 states,

"*As of 2012, in the United States, there are 12 degree programs in Mining Engineering. Over 50% of the faculty are likely to retire within the next five years. With low student enrolments and few Ph.D. faculty replacements available, several universities may decide to eliminate the degree program."*

Energy and minerals were the two primary components that facilitated the Industrial Revolution. They are similar in that an adequate supply of each is essential to the continued welfare of society. The crucial difference between the two is that there are no alternatives to minerals. Minerals are the source of most of the elements of the Periodic Table.

Substitution of iron by aluminum and, in some cases, renewable sources such as wood for metals and concrete in construction, is ongoing – but new technological developments increase demand for other elements. Recycling reduces demand and is used extensively for some elements, but is currently uneconomical for many others.

Renewal of the US infrastructure cannot happen without minerals.[xii] The manufacturing sector of the US is completely dependent on an assured supply of minerals. Any shortfall in domestic production must be replaced by imports.

"*In 2016, imports made up more than one-half of the U.S. apparent consumption of 50 nonfuel mineral commodities, and the United States was 100% import reliant for 20 of those. This is an increase from 47 and 19 nonfuel mineral commodities, respectively….. China, followed by Canada, supplied the largest number of nonfuel mineral commodities"* [xiii]

Heavy reliance on imports has significant implications for the well-being of the US, as noted in a 2016 Report to Congress by Dr John P. Holdren, Science Advisor to President Obama.

"A consistent approach for making assessments across a broad range of minerals and providing early warning of potential supply vulnerabilities is important to U.S. economic and national security. Critical minerals are essential to a wide range of leading technologies, ranging from aircraft and automotive components to electronics and telecommunications devices, and from displays to photovoltaics" [xiv]

This report to Congress contains a world map (Figure 6, p. 9) which depicts the 'Composite Government Index, intended to assess the perceived stability of governments around the world. The map indicates sizable regions of the world where a reliable supply of minerals may not be assured. This is the reality of today's world.

Also, substantial portions of the low governance (high risk) areas are regions of low 'standard of living', as shown in Figure 2, and high population growth – areas that will also have a significantly increased demand for minerals in the years ahead.

In summary, overall, the next several decades appear to be ones of considerable activity in mining globally.

Although the history of mining engineering in the US over the past several decades may suggest otherwise, we suggest that the current situation, as described above, presents opportunities for the US to develop international leadership in mining.

A 2014 report by the JASON group to the US Department of Energy (DOE) included the following comment

"We recommend that DOE take a leadership role in the science and engineering needed for developing engineered subsurface systems, addressing major energy and security challenges of the nation. Our overarching finding is that in addition to the engineered subsurface being important in several of DOE's mission areas, the science appears ripe for breakthroughs. Disparate research communities working in related areas can benefit from increased coordination (academia, industry, multiple government agencies), and DOE has specific capabilities that can effect these advances."[xv]

We try to illustrate this assertion by consideration of the Limits to Deep Mining – and specifically to mining with direct shaft access to the underground ore body.

We hope that this example will stimulate colleagues with expertise in other sectors of mining to describe similar opportunities.

Limits to Deep Mining.

Mining practice has evolved slowly over the past 40,000 or so years, starting with surface excavations and progressing slowly to a depth today of 4 km [Mponeng gold mine, on the Witwatersrand Reef, South Africa].

The primary determinants of a limiting depth of mining are value of the ore; working environment (heat and humidity); and *in situ* rock pressure at depth. For many years there has been a debate as to whether the environment or the rock pressure would decide the limit –assuming that gold ore values remained high. The virgin rock temperature at 4km is over 66°C (150°F), and special measures are taken to keep the temperature in the working areas below 30°C (86°F). It should be noted that the geothermal gradient in the Witwatersrand, at 9°C (16°F)/km, is relatively low, compared to the global average for lithosphere rocks of 25°C (45°F)/km. Mines in other regions of the world could not extend to such depths. In the 1960's, when the gold mines were about 2km depth, miners were subjected to a rigorous acclimatization routine, under medical supervision in specially designed surface facilities, to develop a tolerance for the extreme heat and humidity of the underground. (Wyndhan and Strydom, 1969).

Rockbursts, the sudden, violent release of energy due to slip on faults and similar discontinuities in the *rock or sudden collapse of the working face in the gold reef, were, and are a serious hazard. The Leon* Commission (1994)[xvi] reported that more than 69,000 miners had lost their lives and a further million injured from 1900-1994. The major cause of fatalities and injuries was 'rockfalls and rock bursts'.

With a gold ore value in the range of $400/ton, the maximum economic depth of mining is clearly higher than for ores of substantially lower value.

For many years the prevailing belief was that adverse environmental conditions would be the limiting factor on depth of mining. Recent and continuing, sustained research and development (R&D) on autonomous mining machinery, including excavation equipment, by equipment manufacturers, is now changing this view. Continuing developments in remote control remove miners from the most hostile and dangerous working environment, and focus attention on the issue of rock pressure and the design of safe excavations, for the protection of anyone underground – and of the equipment.[xvii]

The ability to excavate and maintain excavations at depth becomes critically dependent on a sound understanding of the mechanics of rock mass response to high stresses. The following discussion indicated the nature of this challenge, the opportunities presented by recent developments in numerical modeling of the mechanics of rock masses taking into account the influence of large-scale discontinuities in the rock mass.

Rock in situ.

Rock as it exists in place (*in situ)* is a much more complex material than the homogeneous solids used in many branches of engineering. Subject to tectonic processes of deposition, erosion, deformation, fracturing, and faulting over many millions -up to a few billions - of years, it contains discontinuities over a huge range of scales from grains to tectonic plate boundaries. Rocks of very different composition and mechanical properties may be adjacent to each other (e.g. sediments overlying crystalline formations). As a very rough guide, vertical rock pressure at depth is assumed to increase at a rate of 2.7 MPa/km (or 1psi/ft) [assuming a rock density of 2.7 gm/cc].The lateral pressure is usually taken to be one-third of the vertical pressure. Given the heterogeneous nature of rock, local deviations from these values can be considerable – values ten times or so larger than 'the average' have been observed in some cases. Given these complexities, it is not surprising that empirical rules, derived from a continuing process of 'trial and error' have provided much of mining practice with respect to 'ground control.'

As can be seen from Figure 1, for many thousands of years prior to engineers in general had essentially no alternative to empiricism, prior to Newton's introduction of his Laws of Motion in the late 17th Century. Indeed, it was not until almost two hundred years later that Newtonian mechanics had developed sufficiently to attract the attention of engineers.[xviii]

Despite all of the uncertainty and complexity of rock in situ, it was recognized that Newton's laws applied to rock just as to any other material. The problem, in essence, was to understand the constitutive behavior – the deformational response to loading of such complex material – and what practical insights could be gained from analyses of simpler systems. Some early applications of continuum elasticity theory to problems in mining rock mechanics are discussed by Fairhurst (2017).

Failure of the Malpasset Dam in Southern France, on December 2, 1959 – followed by the massive collapse of underground room and pillar workings in the Coalbrook coal mine, South Africa, January 21, 1960 – with over 400 deaths in each case – stimulated Professor Leopold Müller to establish the ISRM[xix] in Salzburg, Austria in May 1962. Malpasset, in particular, convinced him that discontinuities and the associated (three-dimensional) anisotropy in rock masses were major factors in the mechanical deformation and failure of rock masses, and must be given special emphasis in analysis and design of structures in rock.

This move led to international efforts to incorporate discontinuities into continuum analyses, study of physical models to simulate jointed rock, etc. Numerical modeling was in the early stages of development. Cundall, then a graduate student at Imperial College, London, decided to attempt to develop a computer model of a rock mass as an assembly of blocks, defined by the three-dimensional network of discrete fractures in the rock. The results of these studies are described in Cundall (1971)

His technique, now known as the Discrete (or Distinct) Element Technique (DEM) has evolved considerably over the past 45 years and is widely used to analyze the deformation and failure behavior of jointed rock masses.

Any change in force acting on a body propagates through the system at the speed of sound for that material. The DEM essentially 'samples' the forces and deformations of each block throughout the body- 'freezing' the motion at very short intervals (order of microseconds) as the wave motion develops. The DEM is thus computationally intensive –but it has the advantage that the deformation process can be followed in detail until the system reaches final equilibrium - which may not be reached until complete collapse of the system. The principle of the DEM calculation procedure for each element of the model is illustrated in Figure 3.

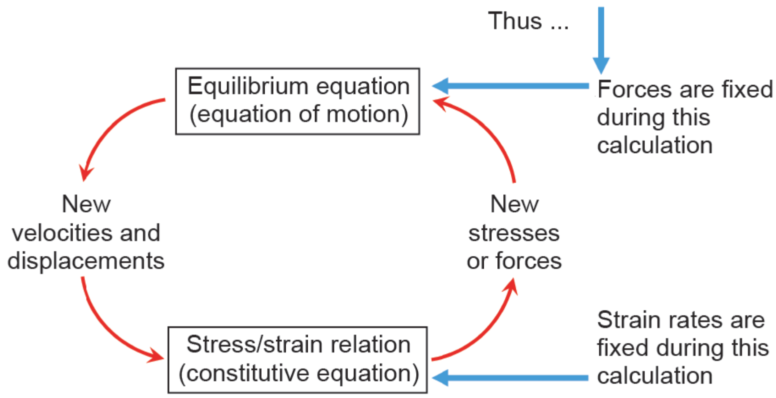


Figure 3. Calculation Cycle for the Discrete Element Method (DEM).

As shown, the DEM procedure involves simply the application of (i) Newton's second law of motion, $F = ma$, and (ii) an assumed constitutive response (force–displacement relationship) at the interfaces between elements of the system. The dynamic response is represented numerically in the DEM using a time-stepping algorithm in which it is assumed that the velocities and accelerations of each block are constant within each time step. To satisfy this assumption, as noted above, the time step must be very small; to follow the deformation process requires a large number of time steps.

By recording changes over very small time intervals, the DEM also models the dynamic response of the system (which can be compared with the dynamic response observed in field microseismic systems). Since the method records the deformation progressively at small time intervals, it is a relatively simple procedure to assemble a sequence of 'system deformations' and show these as a 'movie' reflecting how the system under study is predicted to deform as it progresses towards equilibrium.

Such movies are a powerful way to communicate the model predictions to colleagues who, although experienced, for example, in observation of rock mass deformation and collapse, may not be familiar with computational mechanics. The movies stimulate dialog and interaction between modelers, field engineers and geologists, and are an essential component in arriving at a mature understanding of the rock mass behavior.

Synthetic Rock Mass.

Development of the Synthetic Rock Mass (SRM) by Pierce et al.(2007) was a significant advance in practical application of the DEM to analysis of the deformation behavior of jointed anisotropic rock masses, as recommended by Müller, when he established the ISRM more than four decades earlier.

The rock mass is assumed to consist of two components

1. A large block of intact rock (with deformability and strength of intact specimens of the rock, as determined in standard laboratory tests – and able to fail at the rock grain boundaries. [The intact rock is represented by a Bonded Particle Model (BPM) (Potyondy, 2015) based on the same DEM principle]
2. A network of large-scale discontinuities as shown in the upper right block in Figure 4. These discontinuities, known as Discrete Fracture Networks (DFN's) are determined from field observations,

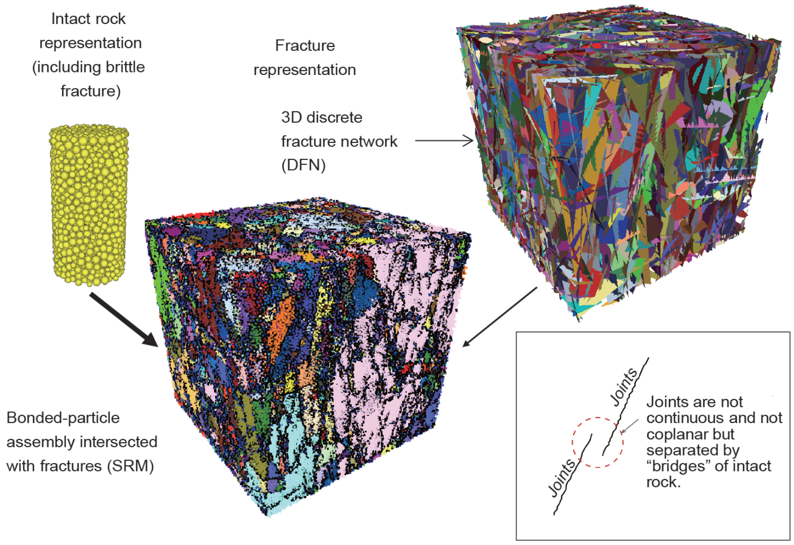


Figure 4. The Synthetic Rock Mass.

The Synthetic Rock Mass (SRM) is developed by superimposition of the DFN (upper right in Fig.4) the intact rock block – the center block in Fig. 4.

The current status of DFN determinations is described by La Pointe (2012).

Garza-Cruz et al., (2014) have used a version of the SRM with DEM analysis to study the design of support systems for excavations associated with block caving in deep mines. The following comment is an excerpt from their conclusions

"these models show that the unloading cycle does more damage than the loading cycle as a larger volume of rock is entering the inner shell (the zone of low confinement that is prone to extensional failure). As a consequence, the support will be more severely strained during unloading (relaxation) than during loading. ***This aspect of relaxation driven straining is not evident from conventional, continuum models and is seen as a critical support design element. Furthermore, relaxation related rock mass degradation and straining is not captured by any rock classification system****. Hence, support systems designed on the basis of rock classification may be suitable for tunnel construction, but are likely inappropriate for situations where mining induced straining due to fracturing and related geometric bulking is to be expected."*

Thus, DEM analyses taking into account anisotropic discontinuities (DFN's) lead to crucial differences in the predicted behavior of jointed rock masses than continuum analyses.

Current limitations to application of the DEM to ground support in Mining and related problems.

As noted earlier in this discussion, the principal limitation of the DEM is that it is computationally intensive. This is especially true of three-dimensional models – but it is known that two-dimensional models can give quite erroneous and misleading results. Hope that this limitation would become less significant as computer power advanced – as suggested by 'Moore's law' (i.e. processing speeds would continue to double approximately every 18 months) has diminished in recent years – and attention has turned to the notion of 'parallelization' – linking many computers together so that each can address parts of the modeling problem and achieve a solution much more rapidly than earlier. It appears that this is the path to follow for DEM analyses.

Considerable insight can be gained from running a model (e.g. the SRM) once or perhaps 'a few' times but, given the complexity and uncertainties involved in the rock mass, it would be valuable to be able to examine, statistically, the influence of these variables on the overall behavior of the rock. For example, the inset diagram on the lower right of Figure 4, is intended to illustrate that the region of overlap between two discontinuities is where the forces applied to the rock mass will be concentrated onto the small region of intact rock between the ends of the discrete fractures. It seems probable that this region will have a large influence on the rock mass strength. What factors (coefficient of friction along the discontinuities; whether the upper fracture overlaps above or below the lower fracture; how are stresses redistributed onto other overlap regions, as some overlaps begin to fail; etc).

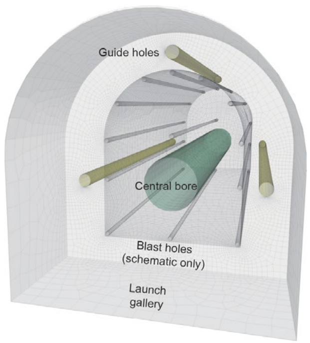
Engineers responsible for field operations frequently complain that colleagues involved in modeling of rock mass behavior cannot provide useful answers within the often very short time constraints of mining operations. Much of this stems from the fact that understanding of the mechanics of systems as complex as rock *in situ* requires dedicated teams of modelers working over many years in close association with engineers responsible for developing safe and cost-effective timely solutions. This can be accomplished only through the establishment, by mining companies, of R&D teams – similar to the R&D groups in mining equipment companies that are providing the valuable innovations in autonomous mining systems.

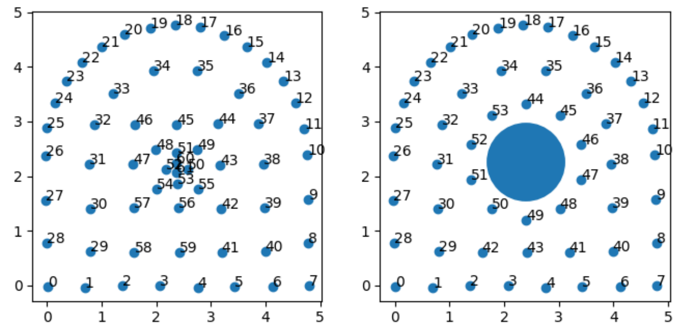
The following example, albeit in the very early stages, is presented as an example of the possibilities.

Modeling as a Mining R&D tool.

Rock Fragmentation and Rapid Excavation have been important concerns in mining for many years. (Dehkhoda and Fairhurst, 2017). Tunnel Boring Machines (TBM's) have reached a high stage of development, and advance rates are unlikely to increase significantly with current TBM designs.
This suggested that it may be timely to examine the possibilities for innovation in Drill and Blast (D&B) tunnel excavation. What are the opportunities to significantly increase advance rates? Given the major developments in directional drilling in the petroleum industry, is it possible to increase the advance per blast cycle sufficiently to make D&B a viable alternative to TBM excavation?

Excavation of a tunnel introduces stress concentrations in the immediate vicinity of the tunnel face, but these changes decrease rapidly with distance from the face – such that, at a distance of one tunnel 'diameter' ahead of the face, the stress state is almost unaffected by the existence of the tunnel. Blasting of rock at a depth (or 'burden') greater than one tunnel diameter is essentially 'blasting into the solid' For shorter burdens, the presence of the tunnel face allows the blasted rock to expand into the excavation. Experience, gained by empirical 'trial and error' over years has resulted in the rule that the tunnel burden should not exceed the mean dimension of the tunnel cross-section. The 'Burn Cut' blast procedure attempts to provide additional space into which the fragmented rock can expand by creation of a central cavity along the axis of the tunnel. The cavity is created by drilling and loading a series of parallel holes (to the full burden depth) in close proximity to each other, and blasting the holes simultaneously. This 'pulverizes' and ejects the rock – creating, in effect, a central cavity. As a variation on the Burn cut, a central hole is sometimes drilled ahead of the main blast, to serve as a cavity into which the rock fragmented by the subsequent sequential blasting to create the final excavation can expand. To what extent does the central cavity serves as a 'substitute' for the free face? How is this affected by the



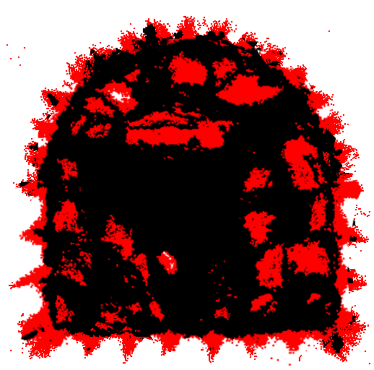


(a) Central hole; Parallel Drill holes. Launch gallery to allow parallel holes

b) Burn Cut

(c) 1.3m center hole

(4.8m x 4.8m tunnel; 60 holes, 50 mm diameter; Burden 7m



Burn Cut

Good fragmentation near the free face

Burn Cut Frozen 'Bootleg'

Inadequate Fragmentation. 7m from the face

Red – Rock intact, but damaged
White – Rock Intact, undamaged
Black – Rock Intensely fractured

<<< CLICK TO PLAY YOUTUBE VIDEO >>>

- ***Constraints***

Minimum diameter of explosive –charged holes is defined by the explosive manufacturer.
Hole lengths greater than 10m require multiple detonators along the hole.
Horizontal holes up to 100 m can be charged using a Swedish loader -air pressure pushes cartridge explosives along hose.

- ***Variables to be studied by numerical modeling***

Optimum combination of central hole diameter and blast pattern (hole diameter, spacing, detonation delay interval).
Effect of variation in rock type on blast effectiveness.
Design of 'smooth-blast' perimeter design; effectiveness in limiting vibration amplitude and energy transfer to rock beyond tunnel periphery; effect of rock type on blast effectiveness.

Figure 5. Example of Computer -based Drill and Blast Design- Preliminary Steps.

diameter of the central cavity? Could the central cavity approach allow burdens considerably longer than the tunnel cross-section to be introduced? What other 'issues' does this raise? Spacing and parallelism of the blast holes, etc. etc) Physical experiments *in situ* to attempt to address these and many other questions would be prohibitively expensive. A DEM-based 3D numerical model, 'Blo-Up', developed by Furtney, Cundall and Chitombo (2009) has been developed and tested successfully to simulate surface blasts –for open pit mining. The diagrams in Figure 5 illustrate some very preliminary results of Blo-Up modeling to examine the feasibility of long-hole D&B tunnel excavation.

Although the energy required to fragment rock to a given size is governed by fundamental rules, it is well known that explosive energy can be more effective than mechanical energy in rock fragmentation.

"Chemical energy is about 25 times more effective than mechanical energy for breaking rock, even though current explosives are still only 30% to 60% of their theoretical potential effectiveness for breaking and moving rock" [xx]

This suggested that it may be interesting to examine the possibility of innovation in the Drill and Blast system of Tunnel Excavation.

One obvious extension of the numerical modeling procedures described above is to the 'pre-conditioning' (in-situ fragmentation) of rock in mass mining e.g. block caving. Eventually, it will always be necessary to conduct a full scale test in the mine –but computer modeling can increase understanding and lead to a better informed, less costly development – and stimulate innovation.

Use of Computer and Mine as a Laboratory.

The important point to be made from the example of Figure 5 is that numerical modeling techniques are now becoming available that are capable of simulating, realistically, the mechanics governing rock mass behavior in practical situations in mining – including dynamic situations, such as blasting. Development of computer parallelization provides a realistic way to overcome the 'long simulation' constraint of DEM modeling.

Numerical modeling now offers mining engineering a major new tool – a computer-based laboratory in which 'experiments' can be run, inexpensively, to develop concepts, based on sound mechanics, to stimulate innovation. The validity of the models can be demonstrated by using them to examine past practice, including empirical rules. Awareness of the underlying mechanics of these rules can provide a sound basis for extending them beyond current experience. Eventually, the computer designs will need to be tested in practice – but the "concept evaluation/design-computer laboratory' approach will be far less costly – and less inhibiting- than the full-scale only, trial and error procedure followed to date.

The application of mechanics – based computer modeling to practical design in operating mines has broader implications. All branches of Earth Resources Engineering (Petroleum, Mining. Geological, Geothermal Engineering; ..and others) must confront rock in-situ, and need to understand mechanics and engineering in rock on the large scale. Mines provide a 'laboratory' that develops this understanding. Unlike most URLs (Underground Research Laboratories) around the world [including the DUSEL (Deep Underground Science and Engineering Laboratory) in South Dakota] the in-situ stress environment of a mine changes constantly, providing a richer test environment.

Eventually, as direct access mines reach their limit, the possibility of remote extraction techniques may need to be examined. Again, the understanding of the mechanics of rock in situ gained from mines can be valuable.

Development of the subsurface on other plants could also profit from the understanding of mechanics as described above. It is far easier – and certainly less costly – to study the effect of a change in gravitational attraction and other details in an analysis than it is to try to gain understanding by the classical empirical procedure – especially when there is no experience on which to build.

University Mining Research Centers.

The preceding discussion has emphasized the need and opportunity for R&D in mining engineering in the US. Much of the research is not specific to one mine or group of mines, and mines have not traditionally pursued R&D on a continuing basis. The sad state of US university programs on Mining Engineering has already been noted. It seems clear that the proposed R&D Centers should be located at or closely linked to, leading research universities in the US. Interdisciplinary collaboration in research is an international hallmark of these institutions, with emphasis placed on strong graduate programs.

Although frequently designated as a 'mature' branch of engineering, mining is definitely an emerging discipline with respect to research such as discussed in this paper.

As stressed earlier in this paper, continuing dialog with engineers experienced in the challenges of practical mining, is an essential component of such R&D Centers. One way to stimulate such interaction is to have the mines participate in funding of the Centers. Interdisciplinary R&D Centers typically require around $5/yr for a five year initial period (with an option to extend the funding for a further 5 years). Efforts should be made without delay to identify companies willing (together) to provide the industry component – and, at the same time, one or more US government agencies willing to match the industry contribution.

There is interest, currently, in US universities in stimulating qualified B.S. engineering graduates to pursue one year of additional study leading to a Professional Master's degree program. Establishment of Master of Mining Engineering programs as a component of the R&D Centers could help attract graduates from other disciplines into mining and help alleviate the current shortage of engineers in the industry

Conclusion.

A rapidly growing world population, coupled with a desire to improve their 'standard of living' suggests that global demand for minerals is likely to increase significantly over the next several decades. This has serious implications for the United States, which is increasingly dependent on imports**.**

As mines go deeper to extract ore economically, rock pressures and understanding how to mine safely become a primary challenge. Exciting developments in numerical modeling of the mechanics of rock mass deformation and failure behavior are described to illustrate one opportunity – probably of several – for the US to retain some international influence in mining.

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Endnotes

[i] *De re Metallica*, published in Latin by Georgius Agricola (born George Bauer, in Saxony) in 1556, was the primary text for mining engineers, especially in Europe, for approximately two centuries. The first English translation was published in 1912 by Herbert Hoover (President of the United States, 1929-33), a mining engineer, and his wife Lou Henry Hoover. (see https://en.wikipedia.org/wiki/De_re_metallica)

[ii] http://www.sntc.org.sz/cultural/ironmine.html

[iii] The minerals of importance in the 16th Century were primarily metals. All had to be mined

[iv] Saudi Arabia is an anomaly to this pattern in that national wealth is due in large measure to the enormous reserves of oil. The country is governed by a powerful monarchy, which controls most of the wealth of the nation.

[v] https://commons.wikimedia.org/wiki/User:Oganesson007

[vi] https://en.wikipedia.org/wiki/One_Belt_One_Road_Initiative

[vii] https://en.wikipedia.org/wiki/Post-industrial_society

[viii] http://www.ase.tufts.edu/gdae/pubs/te/mac/MAC_8_US_Economy_Aug_16_06.pdf See p. 8-4.

[ix] https://www.clareo.com/mine-of-the-future/

[x] "*In September 1995, Congress voted to close the Bureau of Mines and to transfer certain functions to other federal agencies. With USBM's closure, almost $100 million, or 66%, of its 1995 programs ceased, and approximately 1,000 of its employees were dismissed.*" https://en.wikipedia.org/wiki/United_States_Bureau_of_Mines
The US Geological Survey, with an annual budget of the order of $1 billion, conducts research in a wide variety of geological issues, including those relating to the occurrence and use of minerals –but has no mandate to conduct studies in mining engineering.

[xi] https://www.smenet.org/docs/public/USMiningSchools-SME.pdf

[xii] *Is Mining Important?* K.J.Reid (SME Video - 2min.07sec) https://www.youtube.com/watch?v=JXoQQB0_3SM

[xiii] Mineral Commodity Summaries, 2017.US Geol. Survey https://minerals.usgs.gov/minerals/pubs/mcs/2017/mcs2017.pdf [p.7]

[xiv] Report to Congress, *Assessment of Critical Minerals: Screening Methodology and Initial Applications.* March 2016 [Quote is last paragraph of the letter of transmittal] https://www.whitehouse.gov/sites/whitehouse.gov/files/images/CSMSC%20Assessment%20of%20Critical%20Minerals%20Report%202016-03-16%20FINAL.pdf

[xv] Subsurface Characterization -Letter Report https://www.energy.gov/sites/prod/files/2014/09/f18/2014%20SubTER%20JASON%20Report_1.pdf

[xvi] http://www.klasslooch.com/leon_commission_of_inquiry.htm

[xvii] The Kiruna underground mine in Northern Sweden, "*the world's largest, most modern underground iron ore mine."* makes extensive use of remote control to produce 100,000 tons of iron ore/day from a depth of 1.4km. http://www.mining-technology.com/projects/kiruna/ See also http://sverigesradio.se/sida/artikel.aspx?programid=2054&artikel=5312014

[xviii] Although Newton and Leibnitz had introduced calculus in the late 17th Century, continuum mechanics was not introduced until the early 19th Century; Cauchy (1821).The theory of elasticity developed and solutions to problems of interest to engineers began to appear in the second half of the 19th Century. The *Theory of Elasticity*, by S. Timoshenko, published by Mc Graw Hill in 1934, was the first textbook on this subject in English. WWII accelerated developments in many fields, including mechanics, computing, and numerical analysis. Applications of mechanics to rock and mining engineering increased considerably in the post WWII years.

[xix] International Society for Rock Mechanics –recently renamed 'International Society for Rock Mechanics and Rock Engineering' The official acronym ISRM remains unchanged.

[xx] *"Innovation—mining more for less", on the theme of innovation;* excerpts from Ian Smith's speech on 30 October 2013 [Internet]. 2013 Nov 18 [cited 2017 Jul 4]. Available from: https://ceecthefuture.org/comminution-2/innovation-mining-less/.