WORLD TUNNEL CONGRESS, IGUASSÚ FALLS, BRAZIL, MAY 14, 2014

QUO VADIS TUNNEL ENGINEERING? PREDICTING THE UNPREDICTABLE

MEMORIAL CLOSING LECTURE by **PROFESSOR Z T RICHARD BIENIAWSKI**

*"The **Illiterate** of the 21st century will NOT be those who cannot read and write, but those who cannot **learn, unlearn** and **relearn**."*

Alvin Toffler, *Futurist*

It is my distinct pleasure to visit Brazil for the second time and I thank President Hugo Rocha and Chairman Celestino for their kind invitation to deliver this Closing Lecture – an honor, which I highly appreciate.

My first visit to Brazil took place a long time ago, in 1974 during the 2nd International Congress on Engineering Geology in Sao Paulo but I remember it vividly because my friend, the late Victor de Mello, a brilliant professor and engineer showed me around the site of your world-famous ITAIPU dam (8 km long!) and powerhouse (a record 14,000 MW) and I learned much from that visit. What also helped to keep it in my memory was that next I attended a football match in Rio de Janeiro at the equally famous Maracaná Stadium – the largest in the world for over 170,000 spectators! As a former football player and an aficionado, I was simply overwhelmed!

Today I am privileged to view Brazil from another angle: that of the Theme to which this Congress is dedicated: "***Tunnels for a Better Life***", and my function is to assess whether the mission of all of us here, organizers, authors, participants and exhibitors, was achieved in terms of this Theme, and also to identify what significant directions of development might we expect in the future.

In this task, I am assisted by the thoughtful Alan Muir Wood Lecture and the Keynote Addresses delivered during the Opening Session.

I had the honor to know personally Sir Alan Muir Wood and we have met on many occasions going back to his time in South Africa working on the 80-km water-carrying Orange-Fish Tunnel, and also during his term of office as the first President and Founder of the International Tunnelling Association. We became friends, although he was my senior by some 15 years, and we kept in contact while I was vice-chairman of the newly formed SANCOT (South African National Committee on Tunnelling). During a number of social hours Sir Alan shared with me his views on what one should expect from attending a World Tunnel Congress! Well, have YOU thought about it? He, an accomplished engineer and leader but also – being of a Scottish heritage with a great sense of humor – he said to me: ***"With so many congresses and colloquia and symposia taking place every year, I demand of the people that I send to attend: 'bring me back just one and only one good idea which I can use and I will pay all of your travelling expenses plus throw in a bottle of wine'!"***

I liked it so much that – today – I have selected three areas of tunnel engineering for you to choose, and will scrutinize what ideas have emerged from each, and how they relate to the Congress theme. For this reason, I encompassed the three options under my bold title: "***Quo Vadis Tunnel Engineering? Predicting the Unpredictable***".

By the way, the phrase "**Quo Vadis**" is a famous Latin expression meaning "Where Are You Going?" used to indicate a future destiny. It is based on a book by the Polish Nobel Prize author, ***Henryk Sienkiewicz*** (1895).

For us here, to answer our QUO VADIS, I re-state this prediction:

*"The **Illiterate** of the 21st century will NOT be those who cannot read and write, but those who cannot **learn, unlearn** and **relearn**."* ***Alvin Toffler,*** *Futurist*

This message will be an umbrella for my Closing Lecture.

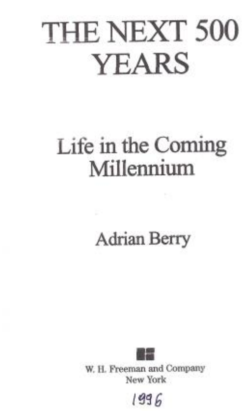
The topics I selected for your consideration are:

(1) Tunnel Design Methodologies,

(2) Education for new cadres of tunnel engineers and planners, and

(3) Site investigation expenditures needed for effective tunnel design and construction.

Immediately you might ask: "Why predicting the unpredictable? Is this reasonable and possible to do at all – within our life span?


THE NEXT 500 YEARS

Life in the Coming Millennium

Adrian Berry

W. H. Freeman and Company
New York
1996

The answer is: Certainly! And it has been done before on an even grander scale!

Please consider this Figure showing the title of a book published not so long ago: "The next 500 Years (!) – Life in the Coming Millennium" by Adrian Barry. The author maintains that there is a rule about predicting the future, namely, that events only seem extraordinary at the time when they are predicted, never after they have happened. Thus the present seems "ordinary" to us and the future appears "fantastic." But the present was once someone else's future, and the future will be someone else's present. Thus when Brazil was discovered, people were filled with wonder, but today they see it as an exciting and interesting place where millions of people live.

If you are a little confused, consider the next Figure, which is much closer to our profession: "***The next 50 years** of the ISRM and anticipated future progress in Rock Mechanics*" by John Hudson, president (2007-2011) of the International Society for Rock Mechanics. He pointed out that Hippocrates, the Greek physician (460-377 BC), used a method for predicting the future which is summarized as:

"***Consider the past, diagnose the present, foretell the future***".

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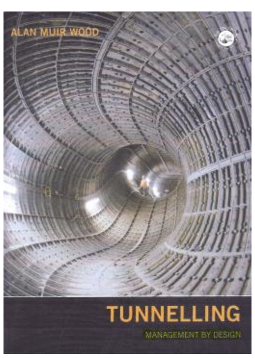
The next 50 years of the ISRM and anticipated future progress in rock mechanics

J.A. Hudson
Department of Earth Sciences and Engineering, Imperial College of Science, Technology and Medicine, London, UK
President International Society for Rock Mechanics (2007–2011)

Accordingly, based on what has been achieved in the past, and knowing what the state of the art is today, let us identify the major problems in the three areas I mentioned above, the problems, which need to be solved in the future. Hudson believes that predicting the future is not only possible but also interesting, "because it encompasses relevant questions relating to the nature of the rock engineering community, storage and disseminating knowledge and the impact of the increase in computing power." To this, I would add the impact on the society and the environment of the positive influence of the use of tunnels - the theme of our Congress.

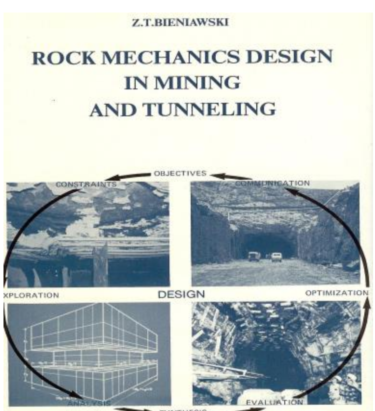
Emerging Methodologies and Principles of Tunnel Design

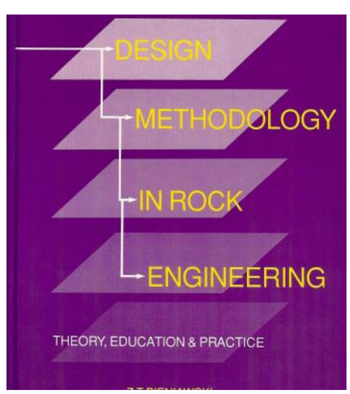


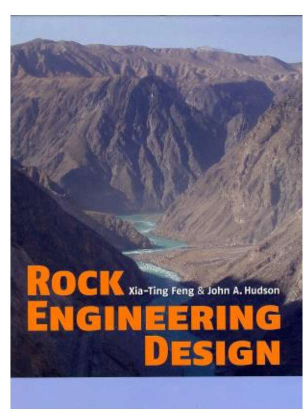
"*It is not the things we don't know that cause us problems, but the things we think we know for sure.*"

General Dwight Eisenhower

Yes, this quotation is to remind us that we are all quite sure how we design tunnels, but we should always keep an open mind for new ideas. In this respect, our ITA Founder Alan Muir Wood insisted on the importance of applying scientific principles to engineering design. This was emphasized in his book "***Tunnelling: Management by Design***",







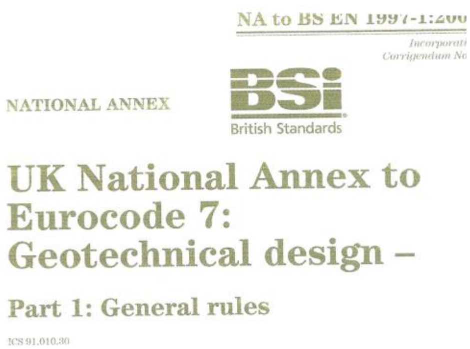
published in 2002. This Congress had an abundance of good presentations dealing with the subject of TUNNEL DESIGN and it seems every tunnel engineer has their own approach to design. In fact, the ITA had a Working Group devoted to this subject and the ISRM did likewise.

Tunnel design has been treated extensively in various textbooks over the years by a number of authors: "***Rock Mechanics Design in Mining and Tunneling***" (1984) and "***Design Methodology in Rock Engineering***" (1992). Recently, Xia-Ting Feng and John A. Hudson published their book "***Rock Engineering Design***" (2011).

This latest books points out that the subject of design methodology "*is now experiencing and will continue to experience major developments in the future because of new capabilities provided by the use of computer programs that can model the rock behavior in new and more insightful ways.*"

In this spirit, the ***Systems Design Methodology for Rock Engineering*** was proposed two decades ago (Bieniawski 1992) and is depicted on the next page. It was used subsequently by Feng and Hudson as a basis for a modified approach.

At the same time, at this Congress and at the last 2013 Rapid Excavation and Tunnelling Conference, a considerable number of papers describing important tunneling projects did not describe specifically any tunnel design methodology used, or only provided a superficial mention. One of the reasons for it is that there is no requirement by the Owners/Planners nor by government agencies to disclose a standard design procedure because it does not exist, except the European Union ***Eurocode 7 for Geotechnical Design***, which allows a number of exceptions.



NA to BS EN 1997-1:200

NATIONAL ANNEX

BSI British Standards

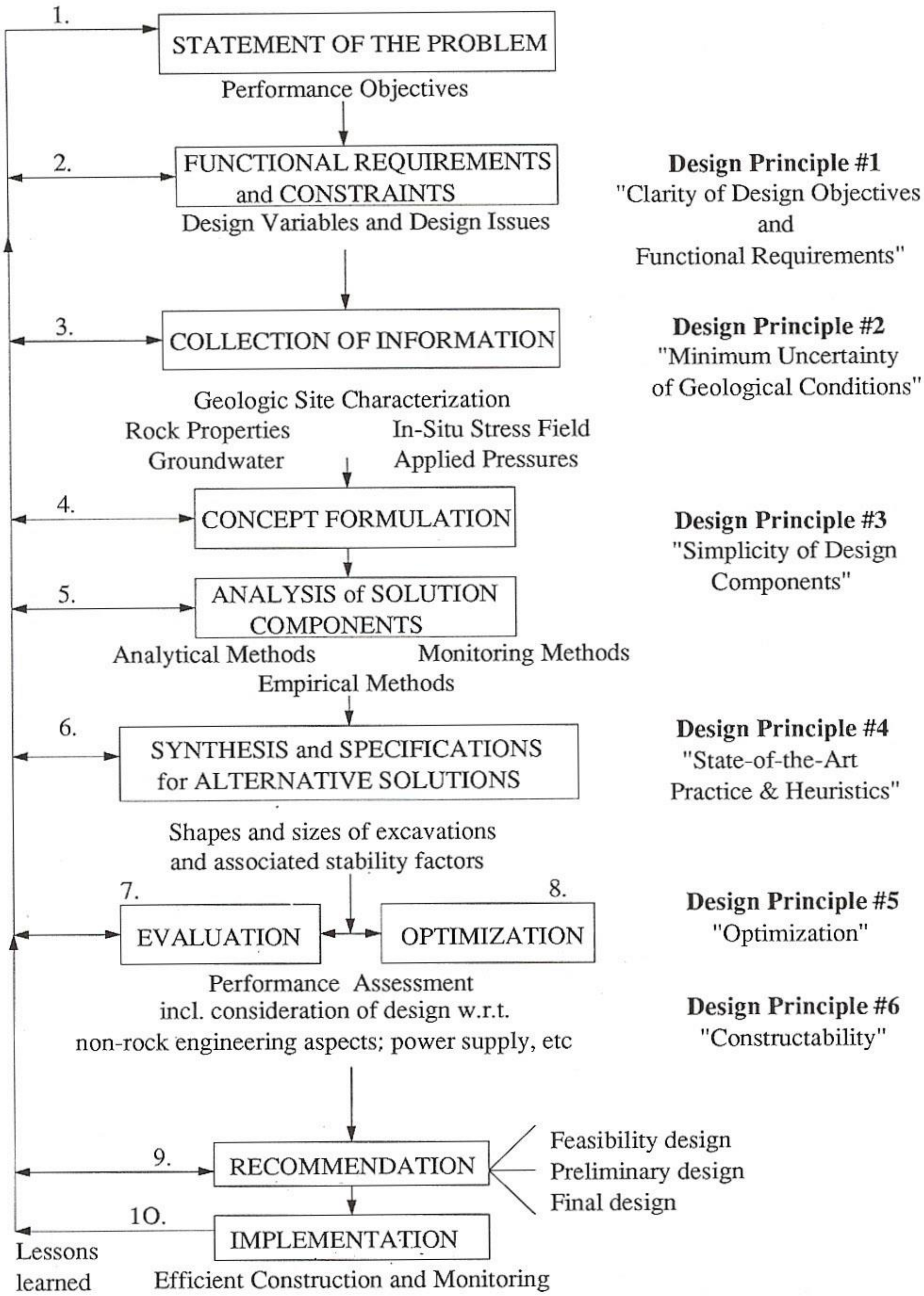
UK National Annex to Eurocode 7: Geotechnical design –

Part 1: General rules

The intent of the Eurocodes is to ***unify the design methodology.*** They replace the 27 existing national building codes in Europe with one building code covering the entire European Union. In total, there are 58 parts and 5500 pages. ***Eurocode 7 defines the design* of *'geostructures'.*** The design principles and methods are unified, but nationally varying conditions (such as rock mass strength and predominant stress field) can be taken into account via National Annex Documents (NADs). Many countries lack a NAD suitable for rock engineering, but the United Kingdom has produced one.

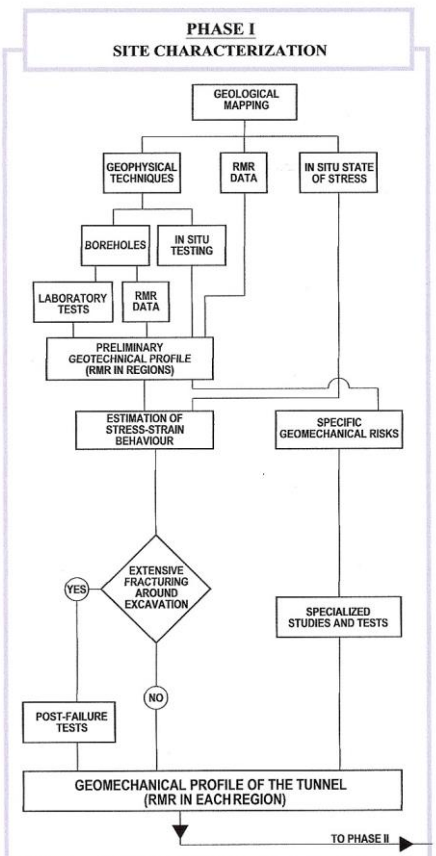
The Eurocodes do not explicitly state how to design rock excavations, but they define the ***minimum requirements*** for design.

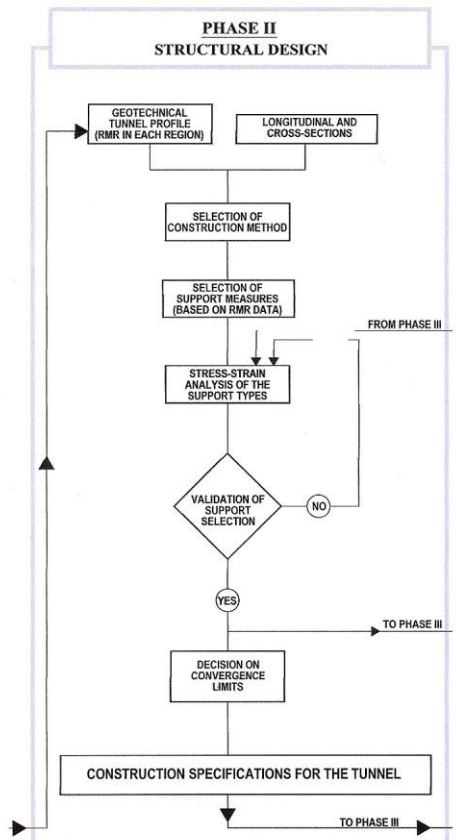
I believe the need for unified design methodologies will become more pronounced as the subject of underground nuclear waste disposal, a sensitive political issue, will come to the fore calling for verifiable tunnel design principles and methodologies, as it did temporarily in the USA during the site selection program at the Yucca Mountain Nuclear Storage Site.



Systems Design Methodology for rock engineering, including the use of design principles

In the meantime a workable compromise has emerged with the approach reported from Spain by Dr Celada and his team introducing the DEA (*Diseño Estructural Activo*) concept, translated as "Interactive Tunnel Design Methodology". This is depicted in the next three Figures, dealing with the three phases of DEA: Site Characterization, Design Procedure, and Tunnel Construction. The details and advantages are discussed elsewhere (Celada 2011).

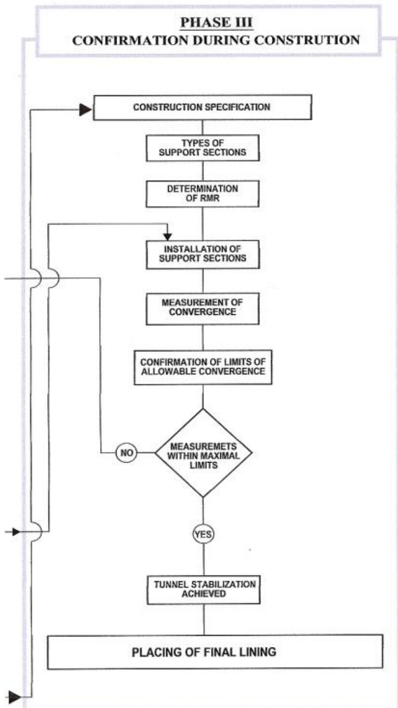




The advantages of the Interactive Structural Design (DEA) concept as a design methodology for tunnels are:

(i) ***Increased safety during construction*** due to tunnel deformations being confirmed by stress-strain analyses assessing each support type;

(ii) ***Opportunity to compare analytical calculations with the actual measured deformations*** thus providing reliable values of the convergence, which reflects the behavior of rock masses; &



(iii) ***Minimization of instrumentation in the tunnel*** because the control of rock mass behavior is based on *only* measurements of the convergence.

In considering different design methodologies, we can benefit much by exchanging ideas derived from mining - civil engineering interaction. This is important because I have observed that it is not often that civil engineers relate closely to mining technology and vice versa. In fact, I was fortunate to be equally involved in both these disciplines and learned that here are many practical considerations, which are different when designing tunnels in mining and in civil engineering. Our founder Alan Muir Wood (1979) believed that these differences in practice arise from different traditions, different acceptable standards and different regulations as well. However, in my opinion there are some essential differences in the design of mining and civil engineering tunnels:

(1) most civil engineering tunnels are virtually permanent (e.g. underground railways, water tunnels, etc.) while mining tunnels are temporary, although, of course, some mining tunnels can have a service life of several decades;

(2) civil engineering tunnels serve mainly the general public whereas mining tunnels are used only by trained miners;

(3) the total length of tunnels in mines exceeds many-fold the length of tunnels excavated for civil engineering purposes and it is not surprising, therefore, that more exacting standards are employed in civil engineering than are in mining engineering (for example in site exploration, in excavation, in support, etc.);

(4) ground conditions in mining are better known because of the mining activities over a number of years while civil engineering structures are usually placed in ground needing detailed site exploration;

(5) civil engineering structures are generally at shallow depths (less than 500 m below surface) with the influence of the field stress being frequently neglected and the absence of a well-developed compressive stress field giving rise to the dominant effect that geological factors have in civil engineering - in mining the stress field is of paramount importance;

(6) since mining is a dynamic process, mining excavations are subjected to changing stress conditions and this necessitates different rock reinforcement than for static stress situations – civil engineering tunnels, in general, do not experience changing stress conditions;

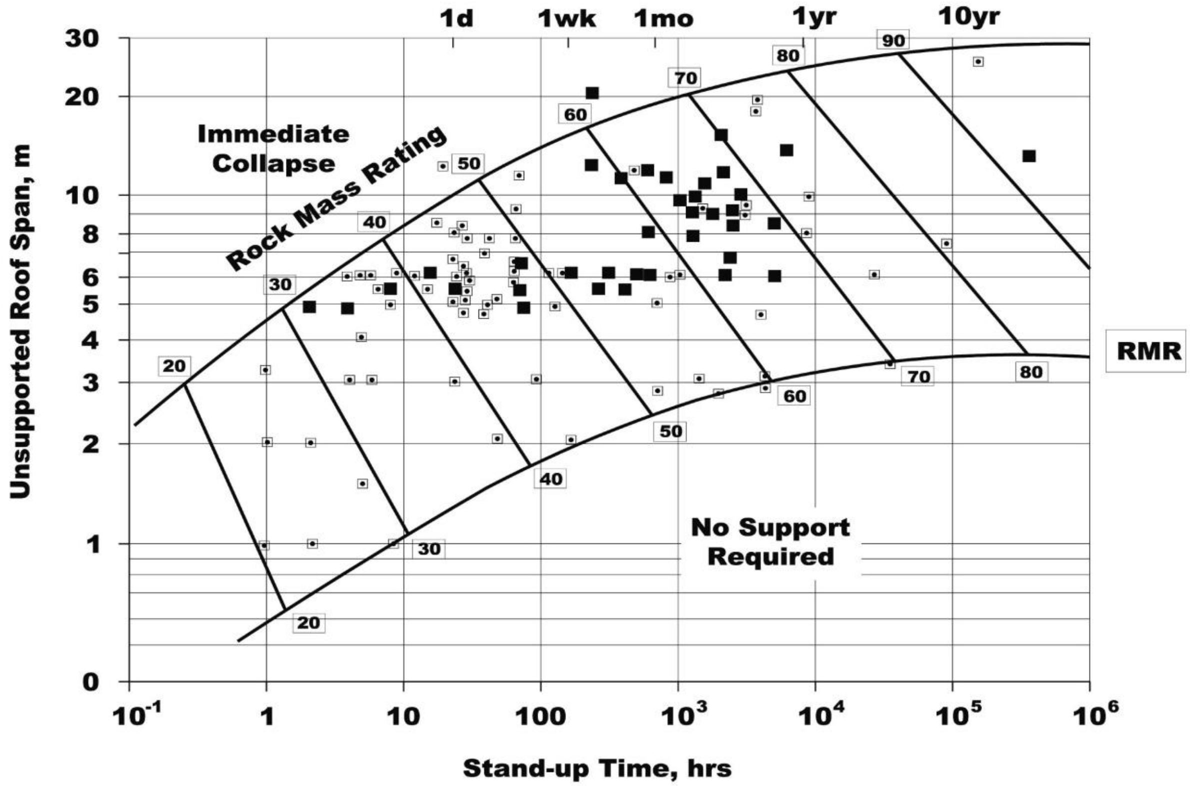
(7) mining aims at increasing profits and funds are less available for design investigations than in civil engineering; and

(8) civil engineering sites can often be selected for their superior rock conditions, whereas in mining the ore location dictates the site.

The special area where mining has made most significant progress concerns the maximum extraction of ore or coal compatible with acceptable criteria for stability.

I would like to suggest that, in the spirit of Alan Muir Wood's recommendation of taking home "one thought provoking idea", we should make a resolution such as this: "***Be specific when describing the chosen tunnel design methodology and use it as a check-list (similar to what a pilot does prior to take off) to ensure that all aspects of the undertaking are incorporated.***" Thus mining case histories in the Figure below were most essential when compiling data of the stand up time for unsupported underground excavations.

Figure . The stand up time of tunnels constructed by drilling and blasting as a function of RMR (Bieniawski 1989). Black squares represent mining cases.



Training Tunnel Engineers and Educating Planners/Owners

"Each modern profession worthy of its name requires three elements: ***Theory, Education and Practice****. The reason: they are needed to guarantee its capacity for renewal and development."*

Philosopher Herbert Simon (1969)

With reference to the above quotation, the profession of ***tunnel engineering***, supported by the science of ***rock mechanics***, certainly may pride itself on having theory as one of its elements and the presence of magnificent tunnels and other underground works provides plenty of proof for well-established practice in our field, going back to the times of *King Hezekiah (700 BC)* whose tunnel is mentioned in the Bible (2 Kings 20:20).

But what about the element of education, that is, of training new cadres of tunnel engineers and engineering geologists, and educating non-technical planners and owners who control the purses of our projects?

The Brazilian organizers of this Congress have presented all of us with a challenge as well as an objective for this gathering here at the lovely Iguassu Falls. In setting the theme "Tunnels for Better Life", they state in the introduction to the Program: "***The WTC 2014 comes at an important moment of development in South American countries…tunnels can provide a better life for the population…Brazil and Latin America have the opportunity to prove that this is possible…the technical community must show authorities the applications tunnels can have and how they can improve the population's quality of life …and to spread tunneling culture***."

Have we made a start at this Congress to achieve these aims and what should we do next?

Yes, there are a number of note-worthy papers (see Bibliography) indicating the importance of tunnels in our lives, while preserving the precious surface for the population to enjoy leisure, work and quality living.

But two challenges remain: (i) training new tunnel engineers and engineering geologists through dedicated degree programs and continuing education which are currently lacking at most technical universities, not only in South America but also in the developed countries of Europe and North America. I can speak from first-hand experience having taught in the USA and in Spain, Great Britain and in Poland; the fact is that, with some exceptions, there are few dedicated professional programs for tunnel engineering as universities struggle and compete for subject allocations. What there is are broad degree programs in civil engineering or mining engineering but not for specialists in tunnel engineering.

To be more specific, a recent study (2010) on "*Education in Underground Science and Engineering*" by the Rock Mechanics Foundation, stated its findings as follows:

"***The current status is that graduate education in rock engineering does not have a broad base of support among institutions of higher learning. For example, among the approximately 200 civil engineering departments studied, less than 10% have substantial graduate programs in rock mechanics; those with geotechnical programs are mainly focused on soil mechanics. Most universities with mining departments do have rock mechanics, those are few in number and departments tend to be small.***"

In essence, rock engineering education has not been well-recognized or established in the universities, and the numbers of both students and instructors may be shrinking. What might come is enhanced need for education due to growing needs in mining and petroleum industries, which in turn may lead to a renewed interest in rock engineering.

Nevertheless, at this Congress, an excellent initiative took place during the pre-Congress ITA Training Session about tunnels for energy. Its 16 hours of classes, delivered by renowned professionals and experts, certainly enhanced the education and training of graduate students and young professionals.

Another recent significant initiative was that of the new ITA president, Dr Soren Degn Eskesen, who called on member nations to form their own YOUNG members groups. Interest in this has already been reported – by an editorial in the journal "Tunnels and Tunnelling" – in the following ten countries: Australia, Austria, Canada, Czech Republic, Denmark, Greece, Hungary, Italy, Norway and the USA.

In addition, other initiatives are also on record, namely: a Master of Tunneling degree at Warwick University in England, a Master in NATM-Engineer at jointly Graz University and University of Leoben, Austria, one year programs in tunneling at Texas A&M University and at the University of Turin, in Italy, and degree courses at the AGH University of Science and Technology in Kraków, Poland, in the College (Wydzial) of GeoEngineering. If I missed other developments, please let me know and I will announce them on my website.

All of the above are very worthy initiatives but they are still only exceptions to the current stagnation status in rock tunneling training and education.

The second challenge is to educate non-technical persons involved in planning tunneling projects or being owners or government officials administering underground projects. These people long to be better informed about the finer aspects of tunneling, applications and use, as well as cost control – but where should they seek such education? I believe that the tunneling community should provide such opportunities.

So, once again, in the spirit of Alan Muir Wood's vision, please make a note of this "thought-provoking idea #2": ***explore further possibilities for improving training of young tunnel engineers – men and, yes, women – as well; if you are a professor or a teacher, take the initiative at your institution of higher learning, if you are in the tunneling business, help secure funds for a new industrial course; if you are neither: write articles to the press and the media suggesting action for the benefit of the society.*** Finally, for all of us at this Congress: let us support the concept of "continuing education" for tunnel engineers and engineering geologists, and "short courses" for non-technical tunnel planners, administrators and government officials to become better acquainted with our field and its practitioners.

When is "Enough" sufficiently Enough for Tunnel Site Investigations?

"*Not all experience is necessarily good.*
We must learn only the best practices -
those used most widely in the most
successfully competitive firms"
John Dixon (1991)

We often plan the scope of site investigations based on our experience with similar projects. The quotation above warns us to be careful, as not all experience is necessary good.

When I look back on my 50 years of involvement in rock engineering (since 1963) I notice a peculiar trend, which concerns me - site investigations for tunnels. In the first two decades of my tunneling activities, I saw tremendous developments of new site investigation techniques and the increasing scope of site investigation programs based on the understanding that spending sufficient time and money in the early phases of a tunneling project will ultimately save on design and construction, will provide increased safety and will avoid costly disputes or corrections of wrong guesses. Oddly enough, in the past two decades I noticed precisely the opposite trends: as the owners/planners tried to trim their budgets and tunnel designers competed for projects, the first thing cut to reduce costs and completion times, was the scope of site investigations. Increasing more emphasis was placed on computer modeling both to impress the owners with colorful graphics and to demonstrate having "cutting edge" technologies.

In fact, a stage was reached where the sophistication of analytical modeling far exceeded the level of reliability of the input data on rock mass properties from limited site investigations. All of this leads to a question, which has been asked before but which is more pressing today because of the emergence of mega-tunneling projects: "***When is enough ENOUGH***" for tunnel site investigations? Let us look at some examples. In the 1980's I carefully compiled the relevant data from a number of projects during an era of major growth of the tunneling industry.

An example of detailed costs of a tunneling project

The case of the Elandsberg project in South Africa serves as an example of a successful design methodology featuring an efficient cost-benefit approach (Bieniawski 1992,p.123-127). In view of the fact that the rock engineering investigations were so extensive in scope and so ambitious in effort, it may indeed be asked what were the direct benefits of the exploratory tunnels and enlargements and what were the costs involved in this design case. As said earlier, because the author realized the uniqueness of the project from the start, he kept a design diary recording the technical events, personal observations, design decisions, and costs. Some of this information has been published (Bieniawski, 1976; 1984) and the permission of the owner has been acknowledged.

The justification for the in situ trials lies in the fact that there was no other reliable way than a full scale test enlargement to predict the maximum rock spans for the powerhouse. In addition, in view of the unusual depth of weathering, i.e. 60-100 m below surface, through which the outlet (tailrace) tunnels had to pass, a tailrace test enlargement was necessary for the most economic tunnel design. Moreover, only a large in-situ test such as a radial press test could determine reliably whether a concrete lining, instead of steel, was acceptable for the penstocks. This alone saved the owner about $260,000 (in 1977 dollars).

Apart from these justifications of the exploratory excavations, there were direct benefits, namely the tunnels could be utilized when actual construction started. For example, the access tunnel to the exploratory works would be enlarged to construct the eventual main access tunnel. Most of all, the rock conditions would be so well known that the element of risk of 'unforeseen conditions' would be removed from the contractor's bid thus resulting in a substantially lower overall contract price. As far as the costs of the design investigations are concerned, the total costs including the site characterization program and exploratory tunnels were ***2.8% o***f the civil construction costs of the project, as listed below. The cost of the rock engineering investigations alone (design and data analyses, equipment, and drilling of test boreholes in adits) was $670,600 or only 0.6% of the civil construction costs.

The full cost details are listed below (in 1980 dollars):

Mechanical and electrical installations	$133,000,000 (41.6%)
Surface facilities	63,800,000 (19.9%)
Civil construction	119,700,000 (37.4%)
Design costs	3,353,000 (1.05%) (**2.8% of civil construction**)
Overall costs	$319,853,000 (100%)

Details of the design costs totaling $3,353,000:

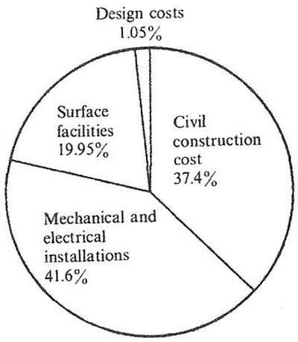
Pilot tunnels and test adits:	1,995,000 (59.5%)
Drilling for geologic site characterization:	687,400 (20.5%)
Design and data analyses (3 years):	368,600 (11.0%)
Rock mechanics equipment:	168,000 (5.0%)
Test boreholes in adits:	134,000 (4.0%)

It is concluded from this project that well planned, well executed design investigations were performed over 40 years ago (!) using a range of tests and methodologies that would be hard to match even today. In fact, the author's involvement on this project provided him with such a wealth of design experience that it could be used on any modern project without fear of being out-of-date. On the contrary, some recent design investigations on major projects do not even come close to those conducted at Elandsberg so long ago. For example, no plate bearing tests of this scope have been performed in the United States in the past decade!

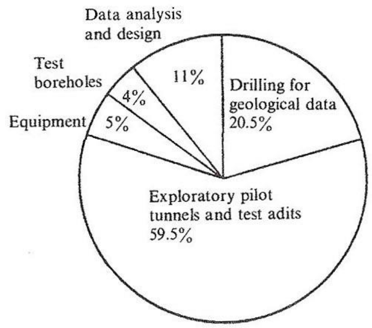
At the same time, the US National Committee on Tunneling Technology (USNC/TT) published a major study in 1984 entitled "*Geotechnical Site Investigations for Underground Projects*"*: Review of Practice and Recommendations*" and concluded with these guidelines: "Expenditures for geotechnical site exploration should average ***3%*** of the estimated project cost." Today typical levels are less than 1%, which is totally incompatible with the over 10% average of project costs being doled out in payment of legal claims, usually for unexpected subsurface conditions.

However, this recommendation requires considerable planning and justification, stated as follows by the USNC/TT: "*The geotechnical site investigations cannot predict every problem that may be encountered, and attempts to do so generally result in programs that are disproportionately expensive for the value received. For every underground project, cost-benefit is a key element. Increasing the level of effort and funds for exploration is demonstrably beneficial and cost-effective.*"

Below is further cost information on a range of other tunneling projects.



Distribution of costs on Project 1



Details of design costs on Project 1

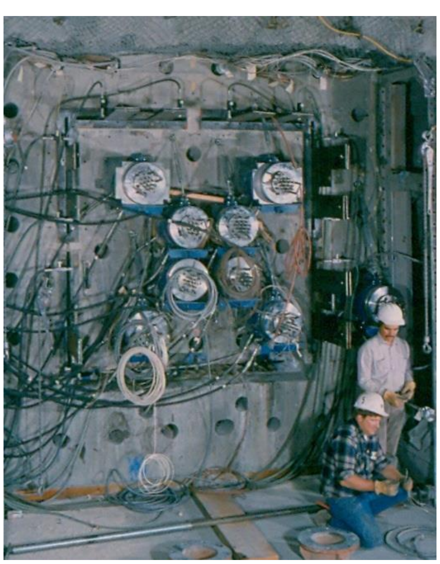
Costs in thousand $	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
Construction cost*	119,700	63,840	31,425	1,500,000	200,000	885
Design cost (incl. site characterization)	3,353	1,968	2,515	12,000	2,940	11
Total cost	$123,053	65,808	33,940	1,512,000	202,940	896
Design cost as % of total cost	2.72%	2.99%	7.41%	0.80%	1.45%	1.23%
Remarks	22 m span machine hall for power station	24 m span machine hall for power station	7.5 m dia 3 km long undercity tunnel	Very large tunneling project	Long water conveyance tunnel	Mining hoist chamber in good rock

*Construction cost does not include mechanical and electrical installations such as incurred on civil engineering underground hydro-electric projects. For example, for Project 1, the mechanical and electrical costs were $133 million plus the cost of one dam and access roads of $63.8 million. The overall cost of the project was thus: $319.85 million. The cost of design investigations as a percentage of this overall cost was thus 1.05%.

Figure . Costs of design investigations for underground excavations in rock, in 1980 U.S. dollars.

Could somebody in the audience share with me the relevant comparisons of expenditures on site investigations from projects in South America, particularly from Brazil, please?

Let us consider another example. First of all, we have major deficiencies with the lack of



measurements of in situ stresses in the overburden and of the rock mass strength and deformability. Seldom do we hear of a tunneling project where the complete state of stress was measured, say, by a CSIR triaxial cell or a 'doorstopper' cell. Ironically, when disputes rage today among energy experts about the issues of "fracking", how many ***hydraulic fracturing*** measurements are actually made for tunnel stress determinations? Moreover, rock mass strength is never measured, only estimated, using empirical strength criteria.

Rock mass deformability, or the in situ modulus, is another example of current deficiencies. Can you point out a recent large-scale test such as the plate bearing test or a large block test conducted in your country?

In fact, they are not commonly in use. Instead, we are using correlations (figures below) based on rock mass quality which, however, are only as good as can be confirmed by actual in situ measurements performed on the given project.

So, once again, in the spirit of Alan Muir Wood's vision, please make a note of this "thought-provoking Idea #3: ***"Let us ensure that sophistication of analytical modeling matches the reliability of the input data on rock mass properties – best determined from dependable field tests!"***

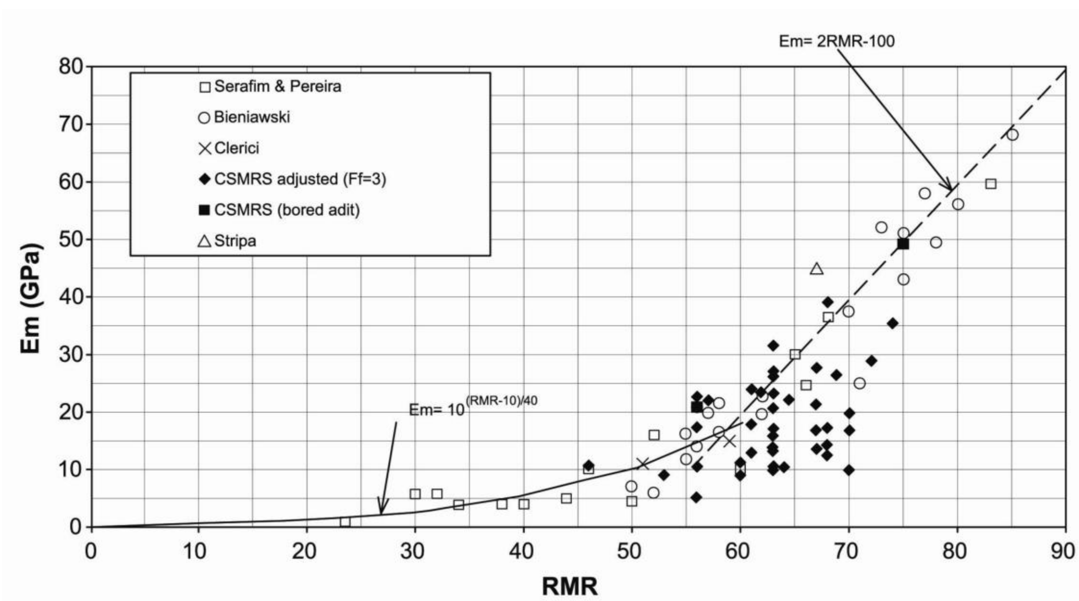


Figure . Correlation between **RMR** and the modulus of deformation of rock masses **E$_M$**
(Palmström & Singh 2001)

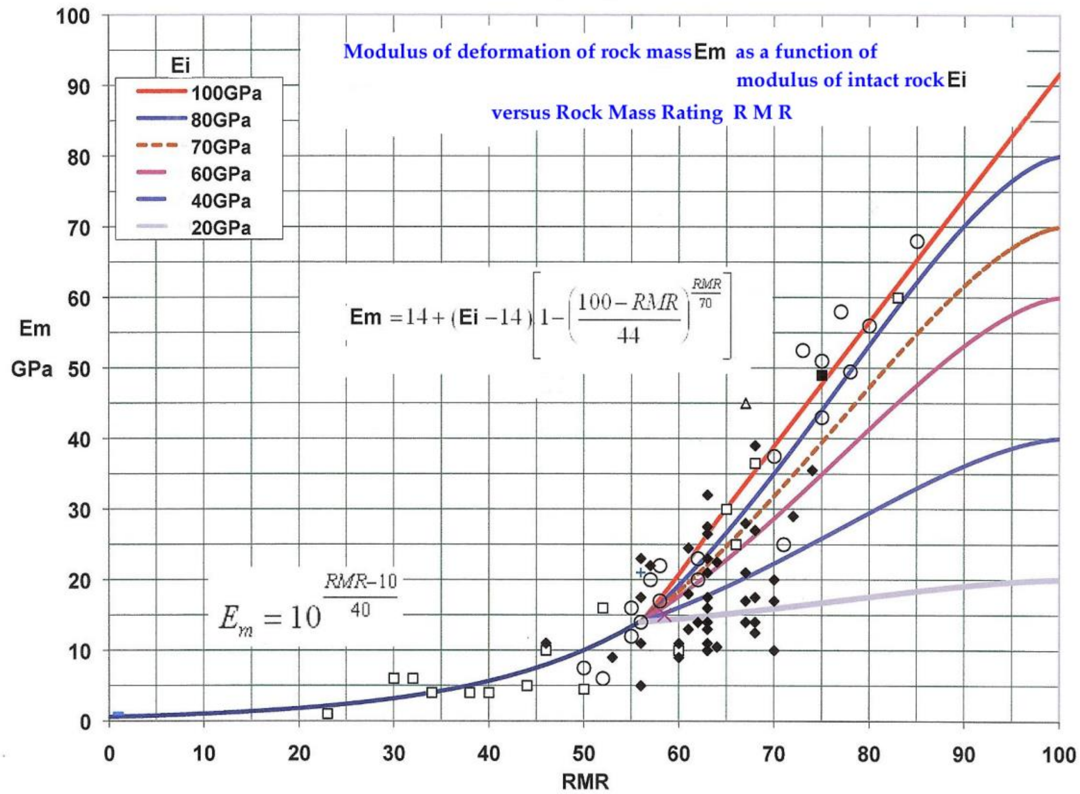


Figure . Improved correlation for determining the modulus of deformation of rock masses **E$_M$** as a function of **RMR** and intact rock modulus **E$_i$** (Lowson 2013).

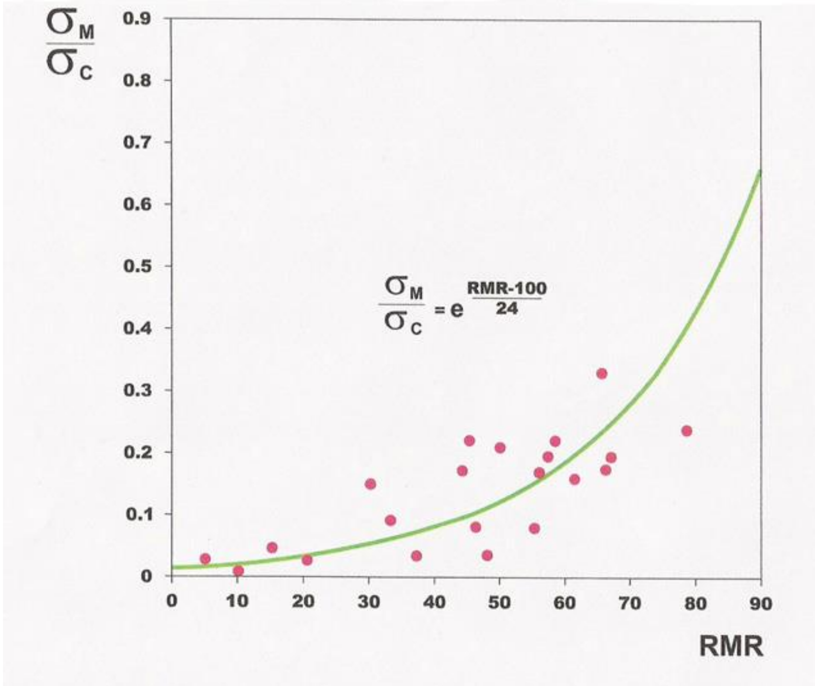


Figure . A strength criterion for rock masses as a function of RMR and uniaxial compressive strength of rock material (Kalamaras and Bieniawski 1995). Experimental data are from *in situ* shear strength tests in Japan reported by Aydan and Dalgic (1998).

Quo Vadis Tunnel Engineering

Having identified three aspects worthy for identifying as "thought-provoking ideas", the question arises how they meet the objectives of the Theme of the Congress and how they were addressed by the individual papers on the program. Moreover can we predict, as promised in my title, what the future holds for developments in the areas of tunnel design methodologies, education of tunnel engineers and owners and in site characterization programs?

In essence, how will we help the Congress Organizers in achieving the mission stated in the main Theme?

Well, first the good news is that the Congress Organizers selected an excellent theme: "***Tunnels for a Better Life***" because this has just received special attention elsewhere under the cover "***The World in 2014***". I direct you to this SLIDE-18, the cover of the leading international news magazine *THE ECONOMIST,* presenting the most significant and expected developments for this year.

THE WORLD IN 2014 Business 123

Great bores of tomorrow

Peter Collins

Record lengths of tunnels will be dug in 2014

More than half the world now lives in towns; by 2030 the urban population will be close to 5 billion. Cities are running out of space. Many are building upwards, with ever-taller skyscrapers. But they are also digging downwards, encouraged by the increasing sophistication of tunnel-boring machines.

In 2014 record lengths of tunnel will be bored—perhaps around 1,000km (620 miles) in all. Boring machines will burrow beneath traffic-choked cities in China, India, the Middle East and Latin America, to bring new or expanded subway systems. Add the massive water, sewerage and other projects under way and the amount of tunnelling in 2014 will be perhaps double that of five years earlier, reckons Lok Home, the boss of Robbins, an American maker of bores.

Beyond boring

Tunnelling will be completed on two large projects

On page 123, is the article: "Great Bores of Tomorrow: Record length of tunnels will be dug in 2014." It predicts a length of over 1000km of tunnel to be constructed this year, and emphasizes – guess what? – yes, the benefits of tunneling and underground space development! It concentrates on the use of boring machines, which we know as TBMs, and singles out their potential in Latin America, as an answer, among others, to dealing with "traffic-choked cities." It encourages governments to be "more adventurous" with tunnel projects and concludes with the prediction: "*An exciting future beckons for tunnel boring*."

In terms of coverage by the papers presented at this Congress, dealing with the three areas I discussed, the topic of DESGN received most attention with 38 papers actually emphasizing this term in their titles.

At the same time, NO PAPERS dealt with education and training of tunnel engineers and non-technical personnel. Perhaps, ***at the next Congress, WTC 2015 in Dubrovnik***, a special session might be devoted to this topic? I challenge our organizing friends from Croatia to consider this, please!

Finally, site investigations for tunneling were addressed in many papers, presenting varied scopes of tests and studies, but I could not find guidance to answering the question: "When is enough, enough?" to compare with an earlier statement by Feng and Hudson (2011): ***"Currently there is no international procedure for checking suitability of rock engineering design, but it is likely to be implemented in the future. Site information auditing as a component of the overall technical auditing will be a key element for validation of rock engineering design methodology."***

PREDICTIONS:

Something Expected and Something New

Let us now consider what might lie ahead in terms of our future challenges, particularly in South America. And let us remember the quotation I presented at the beginning, from the futurist Alvin Toffler:

*"The **Illiterate** of the 21st century will NOT be those who cannot read and write, but those who cannot **learn, unlearn** and **relearn**."*

Something Expected: Consistent with the current trend, we can expect and predict that the use of TBMs and further mechanization of tunneling operations will grow considerably in the future. I recommend, as one priority, the development of techniques able to assess rock mass conditions ahead of TBMs as construction proceeds in real-time.

As underground excavations will become **larger, longer, deeper and more complex**, they will also become more difficult to execute and will be more expensive. [I remember the times when a TBM cost a few million dollars; last year the Seattle machine cost $80 million] Hence tunnel design will be more challenging and will dictate more extensive site investigations, including large-scale field tests, and exploratory pilot tunnels. In essence, reliable input data from field tests to determine rock mass properties will be fully justified to match the sophistication of computer modeling techniques.

[Note latest tunneling news from Seattle: the largest TBM in the world ($80 million machine of 17.52m diameter) by HITACHI is shut down since December 6 for repairs]

Something New: In South America, where the lore of the Andes was enshrined in poems and songs, such as he Peruvian "*El Cóndor Pasa*" by composer Daniel Alomía Robler and sang by Simon & Garfunkel, tunnels can be expected to be built for accessing the great reserves of copper, silver, gold and the strategic minerals needed for new technologies. These tunnels will be placed at greater depths than currently, in conditions where rock-bursts and high water pressures will hinder them. I read that rockbursts were observed during the construction of the ***Olmos Trans-Andean Tunnel*** in Perú.

I remember flying over the Andes from Chile to Argentina, and back by another route, and seeing the vast expanse of these mountains - some 500 km in width. Increasing mining in the Andes will necessitate better access. New and better railroads and highways will be essential, which in turn, will call for more tunnels to avoid steep gradients and sharp curvatures of roads and rail tracks. *The Pascua Lama gold mine* comes to mind.

In addition, certain geotechnical practices will have to be revised; not only by more extensive site investigations as mentioned earlier to provide reliable input data for design purposes, but also by developing improved modeling to include the effects of ***plastification*** under great stresses, and to incorporate post-failure mechanisms, as well as - in special cases - deal with ***coupled problems*** of a mechanical-hydro-thermal-chemical nature.

For tunnel boring machines (TBMs), the use of which will be more extensive, the challenges will be to bore tunnels under high rock pressures and high water pressures, both in hard rock and in soft ground conditions; these challenges are simply extraordinary. Thus we need to acquire improved understanding of, and the ability to predict the effects, of ground stresses and their changes, and of the phenomenon of rock-bursts and the measures for their amelioration.

The planned *Aconcagua Bi-Oceanic corridor* – a rail link – between Argentina and Chile is an example of a project in planning faced with these issues.

In all this, the potential of geophysical techniques should not be overlooked. They will become more extensive due to their rapid development as technologies improve.

Finally, monitoring and convergence measurements during construction will become indispensible under more difficult conditions.

CONCLUSIONS

In concluding this presentation, I wish to congratulate the Congress Organizers for making this occasion such a significant event for the tunneling community and for increasing the awareness of society at large to the benefits and achievements of our profession.

We have shown that in the future we need to pay better attention to tunnel design methodologies, to better education of new tunnel engineers as well as non-technical planners and administrators, and to better cost-benefit driven site investigations.

Today, the time has come for me "to ride into the sunset" which means that after a long career, I need to "hang up my *hard* hat" and this is my last venue to leave you with a farewell message. As I happily conclude my professional activities in the theory and practice of tunnel As I happily conclude my professional activities in the theory and practice of tunnel design and construction, I say "happily" because I have discovered a personal ***secret*** to achieving full satisfaction in my chosen profession and I want to share it with you. The secret is simply to ***involve your spouses or life partners in your work***; my wife of 50 years of marriage has always been at my side editing my books, papers and often finding ways to improve them, as well as listening to my presentations at many conferences. In fact, she is here with me at this time not just as an accompanying person but also as a partner in technical matters. Believe me, a happy spouse is a fine investment for a successful and enjoyable tunneling career!

This photograph was taken **last year on our *50th Wedding Anniversary***, so my wife tolerated my tunneling "addiction" for all these years!

And on this note, as we are about to adjourn for the Gala Banquet, may I suggest that you contemplate, in the spirit of *Alan Muir Wood*, just what is ***that ONE best idea that you have acquired at this Congress***, and please share it with your companions at the Gala. It will inspire others to share and discuss their best ideas with you! And who knows? When you get back to your office, and share your best idea with your boss, you might even win a bottle of fine wine!

The future of tunneling seems secure to me and I wish to leave you in high spirits with this quotation:

> ***"Enthusiasm is the greatest asset in the world; it beats money, and power and influence."*** Henri Chester

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