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Rock Engineering Issues in
Underground Urban Infrastructure Construction
Workshop on Research Needs

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The American Rock Mechanics Association
Foundation
INTRODUCTION


The workshop was organized to develop an agenda of topics that required further research in order to more efficiently construct underground in rock in densely populated cities. To that end, interested participants of the NARMS were invited to hear a series of international experts describe their experience in underground rock construction. These experts hailed from Finland, USSR, and Canada, as well as Boulder Colorado; Chicago; Minneapolis; New York City; and Seattle in the U.S. The audience then broke into two working groups to identify specific areas of need.

This is a report from the workshop and is divided into three sections: Background, Presentations of Practice, and Recommended Action. The Background consists of a description of the differences between soil and rock excavation, and considerations of the general construction environment. The Practice section focuses on accomplishments in the area of rock construction from around the world. Finally, Recommended Actions of the workshop are given.

Several of the practice reports, power point presentations, or photograph collections are excellent and can be seen at ARMA’s Web site, [www.armarocks.org](http://www.armarocks.org). They are presented in their entirety on the website in order to include all of the detail, much of which is photographic in nature.

ARMA

Bernard Amadei, University of Colorado, Boulder, President of ARMA

General results of two recent workshops developed by the American Rock Mechanics Association have broad implications for rock mechanics needs for urban rock construction. The first, held in 1998, focused on future research needs. Its four objectives were the identification of 1) a strategic vision for the future of rock mechanics, 2) critical issues facing rock mechanics, 3) the role of research in identifying these issues, and 4) critical areas of research. The second, held in 1999, focused upon partnering between academia, industry, and government. Four key questions were raised 1) what role does rock mechanics play in the mining, civil, and petroleum industries? 2) what are the needs in education and research? 3) how should rock mechanics be taught in a university
system that is becoming more and more focused upon basic research? 4) what new trends are emerging in the field of rock mechanics? Prior to the workshop, industry representatives were mailed a questionnaire that asked 1) what has rock mechanics contributed to advances in the past? 2) what has it not done? 3) what would you like to see in the future? 4) what are your suggestions for partnerships? Both of these reports are available from ARMA in downloadable format at ARMA’s Web site: www.armarocks.org

An examination of both of these reports reveals several conclusions regarding rock mechanics and the disciplines that support an industrial economy (as opposed to an information or biological economy). First, the economy has changed, or at least perceptions have. The percentage of the GNP spent on infrastructure has declined significantly in the last 30 years. Thus, interest in disciplines that support the infrastructure also declined. The bill for this “delayed maintenance” may have come due this year in the form of clogged airports, parking lot-like freeways, and California’s power crisis. It is becoming clear that information in the information age must be supported by a sound industrial infrastructure.

Second, rock mechanics has been successfully employed to model and predict the behavior of jointed rock masses. There exist well-developed computational tools. While they provide workable solutions, they are in need of modest improvement over time, especially in the areas of pre- and post-processing of complex three-dimensional geometry.

Third, participants at both workshops agreed that in addition to the decline in investment in infrastructure, two other political-economic changes have occurred. Most importantly, entire governmental institutions that nurtured the development of the nation’s infrastructure have been eliminated or severely reduced in size. The closing of the U.S. Bureau of Mines has left major scars in the mining engineering industry. This group provided oversight for applied rock mechanics research. The Bureau of Reclamation has shrunk from 1,200 employees in 1990 to 600 in 2000. Very little of the slack has been assumed by industry. Industrial investment in R&D on infrastructure matters has declined as the long-term horizon has shrunk from years to several quarterly reports.

The need for partnerships is acute. Problems are increasingly becoming global and interdisciplinary. Thus partnerships between academia, industry and government not only provide a new paradigm for funding, but also provide a mechanism for interdisciplinary interaction.

There are four principal benefits to partnerships. They provide 1) mechanisms of integrating research and teaching with real-world considerations of design and construction, 2) opportunities for researchers to become aware of industry’s true problems, 3) opportunities of for industrial and governmental access to university labs, libraries, and computational infrastructure, and 4) a supply of experienced graduates for the job market. ARMA can facilitate the formation of these partnerships.
BACKGROUND

The Nature of Rock Construction

Most construction of underground structures in the urban environment is relatively shallow and involves soil. Thus, most intuitive understanding of underground activity is based upon the expected reaction of soil. In order to capture that experience of most readers, the general behavior of rock is described relative to that of soil.

Rock excavation and required support differs from that of soil in several major aspects. Most importantly, rock can be orders of magnitude stronger than soil. However, to complicate matters, rock properties are heavily influenced by discontinuities: whereas soil properties are more a function of a continuum. Finally, conservative design of the support systems incorrectly leads to fewer expectations for excavation difficulty for rock than for soil. Often these differences between rock and soil excavation will be overshadowed by the uncertainty of underground conditions in general. This discussion will steer clear of problems caused by this uncertainty of the subsurface, as it has been the topic of many other workshops.

Rock’s High Strength Requires Unusual Excavation Techniques

Consider the importance of strength. The strongest of typical soils have compressive strengths of 55 psi (0.4 MPa), whereas the strongest of rocks have strengths 500 times greater or 200 MPa. This huge difference results in the necessity of completely different excavation techniques for rock. Whereas soft soil can be excavated by hand, soft rock requires mechanical assistance. Furthermore, strong soil can be excavated by relatively simple mechanical assistance; however, strong rock requires sophisticated mechanical assistance such as tunnel boring machines (TBM) or explosive fragmentation (a technology not employed for soil). In soil, TBM’s are employed for unusually soft conditions, whereas in rock they are employed in typical conditions. In soil, explosives are almost never employed for excavation.

Rock TBM’s have become very sophisticated, large and expensive in order to simultaneously overcome the two major obstacles to rock extraction: high strength and the high abrasion resistance. New TBM developments now require a diverse team of mechanical, electrical, and hydraulic engineers who are experts in machine-rock interaction and a highly capitalized fabrication organization. The large capitalization requirement and relatively small market, has led to a consolidation of the industry. Fortunately, evolutionary advances in TBM technology continue to be promoted, advertised, disseminated, and otherwise commercialized through the Rapid Excavation Technology Conference (RETC) that is held every other year. Revolutionary advances have slowed in recent years in the U.S. as a result of the decline in public investment in the infrastructure and the de-emphasis of a nuclear defense deterrent.

Explosive technology or blasting remains less intensively mechanized than that for TBM’s in the U.S. and the world in general. This relative unsophistication represents both a challenge and an opportunity. The challenge is to raise the level of blasting practice in the U.S. to that in leadership countries, mainly Scandinavia, where high-
quality rock dominates the construction landscape. The opportunity is to raise the level of practice even higher, as is discussed by Hood et al (1998) and summarized separately. These challenges and opportunities in the blasting area have been magnified in the recent past by the closure of the U.S. Bureau of Mines (USBM). In the U.S., most fragmentation research was conducted by the USBM, and its demise has left a huge void in the development of explosive technology. In the U.S., explosive technology is presently developed by manufacturers of explosives, and dissemination is accomplished through the International Society of Explosive Engineers and ARMA. Basic research in the area is vetted through the Fragblast Journal and, every other year, through the international FRAGBLAST Symposium. None of these venues can replace the focus, resources, and oversight of the USBM.

Discontinuities Control the Behavior of Rock Masses

Richard Goodman has developed two acronyms of great value--CHILE and DIANE. These are helpful to describe another important distinction between soil and rock at shallow infrastructure depths: the dramatic effect of discontinuities. Relative to rock, soil is CHILE: Continuous, Homogeneous, Isotropic, and Linearly Elastic. Whereas relative to soil, a rock mass’s joints, shear zones, and foliation make it DIANE: Discontinuous, Inhomogeneous, Anisotropic, and Nonlinearly Elastic.

To gain an appreciation of the importance of weaknesses in rock, consider the rock beneath Central Park in New York City. At a depth of hundreds of meters, blocks of hard, abrasive metamorphic rock are bounded by persistent foliation shear zones that are clay-like in their strength. Thus while explosives are required to fragment the rock between the foliations, the support required must account for the clay’s weakness.

While the clay seam example of rock weakness is extreme, all rock at shallow depths, where most infrastructure is constructed, is fractured and jointed. These fractures and joints form planes of dramatically weaker, more deformable and more permeable properties. In fact, these weaknesses can so overwhelm the strength of the intervening intact rock, it can be said, “What is important in rock is what isn’t rock!”

Unexpected Conditions Can be More Negative for Rock

Conditions within a rock mass are often more difficult to predict than for soil with exploration efforts typical in soil. This difference is brought about by the high cost of rock drilling, the importance of small discontinuities, the often-deeper depths and longer linear extent of tunnels in rock. These systemic differences are exacerbated by the difficulty of separating considerations of support from those of excavation in both rock and soil.

While it is difficult to separate support from excavation for underground facilities in either rock or soil, the construction consequences for unusually difficult excavation in rock tend to be more surprising and more negative for rock than soil. These more negative consequences in rock are due in a large measure to the importance of discontinuities described above in controlling rock behavior. While the rock mass can be
weakened by discontinuities on a scale of the span of the structure, the intervening intact rock can still be strong, abrasive and difficult to excavate.

Consider the consequences of estimating during design either a rock or soil material to be weaker than it is found during construction as is normally done in the name of conservatism. A stronger soil than predicted will be an asset. All soil (except the very weakest) can be excavated relatively easily by some form of scraping or shoveling. Thus excavation differences will not be great, and support will be less challenging. On the other hand a stronger intact rock normally requires significantly greater excavation energy, even though the support will also be less challenging. The support effort is usually only marginally less challenging because of the importance of the discontinuities.

A Variable Soil – Rock Interface Increases Difficulty of Both Excavation and Support

Often urban rock construction involves the interface between rock and soil because of the typically shallow nature of urban infrastructure. Accurate knowledge of the location is important to the construction process. Unfortunately, this interface is often highly variable in its vertical location. This variability of elevation is a function of the parent rock type in the case of residual soils and erosion patterns in the case of deposited soils. The large excavation energy required for rock places a great premium for excavation in soil. This discussion will not treat construction in the interface, as it is dealt with elsewhere.

Public Infrastructure Investment

In the late 1980s, an economist at the Federal Reserve Bank in Chicago, David Aschauer, began to investigate the correlations of various economic indices with public investment in the infrastructure. His conclusions regarding the link between general economic productivity and infrastructure investment are of interest, as underground construction is a result of public investment in the infrastructure. Greater public investment in the infrastructure will result in more heavy construction and more underground construction.

While Aschauer’s study is now over ten years old and does not include investments in the information infrastructure, the identified trends of investment in the infrastructure are important in this discussion of the research needs of rock mechanics. In a sense, they explain why simultaneously our highways are clogged, our airports delayed on a regular basis, and now California has insufficient power. It is clear that funds will have to be allocated to catch up with the “delayed maintenance” of the infrastructure.
First consider the history of infrastructure investment shown in Figure 1. The investment in the infrastructure, the smooth curve in the figure, has been declining since 1970. At that time it was 2.3% of the GNP. It bottomed out at 0.4% in the middle 1980’s.

This peak of investment in 1970 correlates with the frenzy of infrastructure construction in the early 1970’s. The Interstate highway system had not yet been completed. For instance, the Straight Creek Tunnel under the Continental Divide was under construction. Sewage treatment plants were being built with a passion. Nuclear power plants were under construction. The four units at North Anna that now power Washington, D.C. without producing carbon dioxide were under construction. The airline hubs in Atlanta, Chicago, and Dallas were yet to be built.

How does infrastructure investment in the U.S. compare with the other nations in the G7? Aschauer’s data in Figure 2 show that the US lagged behind all but Great Britain in investment as a percentage of the gross domestic product.

Given the need to catch up in infrastructure investment, the demand for urban construction and thus urban rock construction will increase. Thus it is important that the ability to construct underground in rock not be lost. It is also important that more efficient means of rock construction be discovered, as the increased construction will take place in an environment already crowded with existing infrastructure.

PRACTICE FROM AROUND THE WORLD

United States

Boston, Washington, and Minneapolis

Susan Nelson, American Underground Construction Association, Minneapolis

Extensive underground construction in rock in the U.S. is principally found only in densely populated cities that are located in rock with shallow soil overburden. This rock urban “underground-scape” is dominated by New York City. Additional rock facilities are found in the Twin Cities in Minnesota and Kansas City for storage, and Chicago and...
Milwaukee with their deep tunnel (TARP) projects. Construction of the infrastructure for mass transit has brushed with rock in isolated sections in Washington, DC, Atlanta, and Philadelphia. However, as the easily developable soil sites in densely populated metropolitan areas disappear, the necessity to construct in rock increases. For instance, residential construction on rock requires blasting for the installation of utilities.

This lack of geological imperative leads to focus more on soils for the work of the American Underground Construction Association. Of the four cases described, only one involved principally rock. They all involved construction in tight urban conditions where functionality of immediately adjacent facilities had to be maintained.

The most ambitious present project is the undergrounding of the Central Artery in Boston. This project involves construction of 161 lane miles of highway with much of it placed in tunnels. Some have described this project to be similar to performing open-heart surgery on a tennis player, while playing. Successful completion of this project will reduce carbon monoxide emissions by 12 percent, produce 25 acres of parkland along the waterfront in downtown Boston, double the access to the airport, and eliminate the dead end of the Mass Turnpike in downtown Boston.
Before and after photograph and model in Figure 3 demonstrates the environmental enhancement produced by the undergrounding of the Central Artery. These advantages accrue to the undergrounding surface facilities in general.

While the Central Artery involves rock only as a foundation element for the depressed artery, it clearly demonstrates the need for intense coordination with the affected neighbors and travelers. This intense community involvement can be seen at the project’s Web site, [http://www.bigdig.com](http://www.bigdig.com). Intense public involvement and extensive expenditure of funds for the mitigation of environmental degradation during construction will become increasingly important for future urban projects.

The second and third projects involved the undergrounding of a parking structure in Boston and the undergrounding of the addition of the Smithsonian Museum in Washington, DC. The parking structure was built with private funds and replaced an above-ground structure with one below ground. The museum addition had to be constructed to avoid disturbing the foundation of the adjacent Smithsonian Castle.

The final example is the undergrounding of the Civil Engineering Building at the University of Minnesota as shown in Figure 4. The structure is 95 percent underground and scores well on all of the sustainability measures described by Riekkola below. It extends to a depth of 34 m (110 ft.) in St. Peter Sandstone. The deeper levels are employed for laboratories and clean rooms. This project was so successful that several other below-ground structures have been constructed, the most recent of which is a storage facility for the University Library.
New York City

Reuben Samuels, Parsons Brinckerhoff Quade & Douglas, New York City

“It’s going to take a long time to build a subway system in New York City.”
William Barkley Parsons, founder of Parsons Brinckerhoff Quade & Douglas

Parsons then proceeded to build 21 miles of subway – from design to operation – in two years to open in 1904. By comparison with the 40-year history of Seattle’s Link project, this accomplishment is a rare and almost miraculous event. It could not be repeated today. From that auspicious beginning, rock construction in New York has served as a leading example of what can be accomplished.

It is fitting that this presentation of urban rock construction in New York City focuses on examples of past accomplishments rather than future needs. History reveals what has been done well and poorly and thus provides a framework for envisioning the future. New York City rests on shallow rock and thus its construction history is steeped with urban rock lore of almost heroic proportions. It is also fitting that this presentation be made by a contractor who helped to create some of the legends. (Editor’s note: The presentation was largely photographic, and cannot be reproduced in full. Thus selected
specific projects will be highlighted as examples of what can be accomplished in rock in the tight confines of one of the world’s most densely populated cities. The complete set of photographs is available on ARMA’s Web site.)

History repeats itself. Consider the proposed construction of a new railroad terminal for the Pennsylvania Railroad from Long Island adjacent to Penn Central Station. The terminal will consist of large caverns with spans of 20 some m (60 to 70 ft.), 21 m (70 ft.) high, 300m (1000 ft.) long at a depth of 21 m (70 ft.) below the top of rock. It will be located beneath 50-story buildings that exert column loads of 3000 to 4000 tons. The solution was to put it where the buildings weren’t, under the 43 m (140 ft.) wide Park Avenue. Thus, only the front column lines of the Park Avenue buildings will be undermined. This is a challenging project.

Figure 5: Rock Excavation Between Operating Tracks during the Expansion of Grand Central Station in New York City in 1930. Could we do this again?

Excavation was conducted beneath an operating station before in 1930 at Grand Central Station to create a loop in which to turn trains around. Figure 5 shows the construction of the lower loop (cut out between tracks) without disrupting operation of the trains above. Rock was blasted only when trains were not present overhead. Obviously, the proposed project can be built from a rock mechanics point of view. The question remains, can it be executed from a project management point of view?
White of Spencer, White and Prentice, once said that “good ground makes good contractors” and Figure 6 shows how unjointed, unfoliated rock can be explosively carved like soap. This blasting up to the adjacent building is regularly conducted today in New York City by slashing a deep slot at the building line by drilling a line of contiguous empty holes.
How about excavating rock beneath an operating subway line? This was not a problem at Bowling Green as shown in Figure 7. That’s a train in the upper right, just above the ladder.

Figure 7: Worried about Excavating Rock Beneath an Operating Subway? That's a Subway Train to the Right above the Muck Pile.
Seattle

Harvey Parker, Geotechnical Consultant, Seattle

The history of the current underground mass transit project in Seattle gives perspective on how long major infrastructure projects take. This project, called Link, is the construction of a light rail line from the airport, SeaTac, far south of downtown to the University of Washington, north of downtown. It began in the mid 1960s as part of a $1.15 billion heavy rail system called Forward Thrust. In 1968, the required bond issue failed. The project grew to $1.32 billion and was put to a vote and lost again in 1970. In 1980, interest in regional transit flared up again and a bus tunnel was built downtown. A Regional Transportation Authority was established in 1991 that developed another mass transit plan that again failed at the ballot box in 1995. Finally in 1996, a $3.9 billion plan, of which Link is a part, passed and bids are to be opened in late 2000. Completion is scheduled in for 2007.

This project history demonstrates several key considerations for urban heavy construction involving rock. They take longer than it is apparent to the general public. The 40+year span between concept and reality is typical for large projects such as dams, subways, etc. They are almost always controversial. They change over time. They are exceedingly expensive. So the next time “fast tracking” is applied to a large infrastructure project, remember to think in terms of decades, not years.

Link will be built as a design-build contract. Thus, outside of general overall initial performance criteria, specific locations and appearance, both design and construction will be performed by the same overall consortium. This type of contracting, long popular in Europe, is becoming more prevalent in the U.S. as it eliminates a seam between two contractual bodies, the designer and the contractor. This decision was driven by the long lead times for tunnel boring machines and a desire to decrease the number of overlapping contracts.

The importance of this design-build trend for the field of rock mechanics is the increasing need for rock mechanics experts on the staffs of general and specialty contractors. These experts will need to be expert in both design and construction, much like present-day mining engineers.

Finland

Reijo Riekkola, Saanioi & Riekkola, Helsinki

The Finns believe that to develop more efficient design and construction techniques, it is most important to educate the planners and decision makers about the usefulness of underground facilities. To that end, they have produced a series of books that photographically demonstrate the potential attractiveness of the underground. The latest of these is The Fourth Wave of Rock Construction, which is available through the Finnish Tunneling Association. This book concentrates on environmental issues both above and below ground mitigated through underground facilities. It describes the history of
underground rock construction in Finland and photographically demonstrates the pleasing environment that can be produced underground such as this swimming pool in Figure 8.

![Figure 8: Architectural Finish, Paint and Lighting Eliminate Cave Environment for Underground Swimming Pool in a 30m (100 ft.) Wide Cavern beneath Helsinki](image)

Geopolitics even plays a major role in Finland’s (and Sweden’s and Norway’s) expertise in underground construction. During the Cold War, they put underground critical infrastructure components as a military defensive measure. In addition, Finland, in particular, built civilian underground facilities to serve as civil defense shelters as well. In fact, there remain today economic incentives to underground facilities that are not present in other countries. The world can now benefit from this added investment in the technologies and supporting planning processes necessary to support underground rock construction.

Scandinavia, and Finland, in particular, are world leaders in rock underground construction for a wide variety of reasons, the most important of which is the general lack of soil overburden. The last glacial advance scoured away most of the soil and weathered rock. The remaining rock is close to the surface and is, for the most part, relatively strong crystalline igneous and metamorphic rock that is relatively unjointed. Relative to most of the rest of the earth’s surface, it is strong and continuous. Thus, in order to build at all, rock must be excavated, and building economically requires expertise in rock construction. The combination of excellent geology, necessity, and technical skill has resulted in a host of unique underground facilities such as this underground water treatment plant in Figure 9.
Underground space use can be divided into five different categories: 1) general public facilities, such as the swimming pool above and connectors between subways, 2) transportation systems, such as mass transit, roadways and parking, 3) technical maintenance, such as water and sewerage treatment (such as that shown above), power generation, and corridors for the utility pipelines and cabling, 4) industrial and production facilities, such as mass temperature controlled storage, noisy and dusty processing, and 5) special use, such as defense facilities, and telecommunication facilities.

The attractiveness of rock “utilidors,” tunnels housing infrastructure utility services, such as the example shown in Figure 10, is often overlooked because utilidors transport materials (communications, petroleum products, steam, water and waste water, etc.) rather than people. Since they do not transport people, there is no access depth limitation as there is with subways. Thus, they can be located deeply in strong rock strata where they will last “forever” on a human time scale. The most extensive examples in the United States are the third New York City water tunnel at a depth of 200 m (700 ft.) and Chicago and Milwaukee’s Tunnel and Tunnel and Reservoir Plan (TARP) projects. Chicago’s TARP consists of more than 110 km (70 mi.) of 10 m (30 ft.) diameter tunnel at depth of 60 to 90 m (200 to 300 ft.) that both stores and transports storm and waste water for treatment for the entire Chicago Metropolitan Area.
The Finns have discovered that there are six major advantages to underground rock construction based upon the principles of sustainable development: 1) minimize environmental hazards, 2) save energy and conserve natural resources, 3) increase the functional diversity of the urban structure, 4) reduce the need for surface transportation and increase transportation accessibility, 5) extend the and protect the urban landscape and culture, and 6) underground rock structures last forever on a human time scale. This last attribute is unique to rock. All the others are possible in soil as well. A detailed listing of the advantages of underground rock structures is given in Table 1.

The experiences in Helsinki demonstrate that sub-surface spaces can be made economically to develop a city, even in a relatively small (one million inhabitants) city. This has been assisted by:

- Good Precambrian bedrock, which is generally only 0-20 metres from the surface of the ground;
- A good geotechnical database serving the entire area of the city;
- Highly-developed Nordic hard-rock excavating technology;
- Continuous monitoring measurements of sub-surface spaces, to prevent damage;
- Taking underground construction into account in city planning;
- Participation of architects in the design of sub-surface spaces; and
- Good co-operation between the client, the designer the contractor, and building inspectors.
Table 1. Underground space in the urban structure: pros and cons

Advantages

Economic
+ allows for more compact urban structure
+ saves building land from secondary uses (traffic, parking) for recreation, work, housing
+ the bedrock can be utilised both for heating and cooling

Technical
+ constructing in rock is cost-effective because of the hard bedrock in Finland

Functional
+ new streets do not cut across areas
+ safety in the urban community

Social
+ taking streets down into tunnels improves the quality of life in city centers

Environmental
+ tunnel construction helps to protect the natural landscape and saves urban areas
+ underground construction does not affect the superficial shape of rocks or the natural conditions of the area
+ environmental stress factors (e.g., noise pollution) can be reduced by underground construction
+ underground construction helps to protect environmental and cultural values (e.g., townscape)

Disadvantages

Surface connections (portals and shafts) may significantly increase the costs of underground construction if the quality of the soil is poor.

Surface connections are technically demanding projects in poor-quality soil.

Connections with the traffic network above ground may be difficult to arrange.

Lack of external control is one reason for prejudice against underground traffic solutions (tunnels, underground car parks) orientation difficult.

Underground construction may lower groundwater table.

Job satisfaction in facilities with no windows is generally lower than in facilities above ground.

Location of ramps and other surface connections is difficult.

(Editor’s note: The full text of Riekkola’s paper along with a color Power Point presentation can be found on ARMA Web site. These papers provide additional photographs and cost data of facilities constructed in rock underground in Finland. A more comprehensive presentation can be found in The Fourth Wave in Rock Construction published by the Finnish Tunneling Association.)
Canada

Jacques Besner, Secretary (Given by Susan Nelson)
Associated Research Centers for the Urban Underground Space (ACUUS), Montreal

Like the U.S., Canada’s major centers of underground activity are in its two largest cities, Montreal and Toronto. For the most part, underground activity involves predominately soil. Thus, this presentation by ACUUS focused on shallow excavation that would of necessity involve soil materials.

More importantly the presentation focused upon inducing urban inhabitants to efficiently utilize underground passageways between offices and stores that connected them to subways. Attracting pedestrians to these underground connections is integrally linked to the usefulness of the space. The connectors are underground because they are linked to mass transit that is of necessity undergrounded to avoid competition with existing surface transport. In addition they serve as weather protected passageways much as Minneapolis’s above-the-street store connections. Mass transit is typically constrained to relatively shallow depths in order to provide rapid ingress/egress via escalators and thus in only unusual situations needs to penetrate rock.

![Figure 11: The Hidden Underground City Beneath Montreal Produced by Creatively Connecting Subway and Nearby Buildings.](image)

Montreal’s walkways are some 30 km long and link the light toned structures shown in Figure 11. Linkage to this system has become a driver in the value of commercial property. In fact, developers have always paid for the connections and are responsible for maintenance, surveillance, and liability insurance. These linkages serve as public space and as shown in Figure 12 can be attractively designed.
The Toronto underground passageway system, PATH, consists of more than 3 km of underground walkways. Until a uniform system of signage was developed, this maze connecting stores and subways seemed more like a grouping of underground shopping malls, with no sense of connection. The signage system was developed and paid for by both government and private funds, but took over five years to implement. The lesson learned was the necessity to include the signage during initial construction of the connectors, when there is greater interest.

There are four critical factors for the success of underground connector cities. They must connect an equivalent population of some 350,000 to 500,000 office workers and inhabitants as in the case of Toronto and Montreal. This threshold size is necessary to support the stores connected to the walkways. Secondly, this underground city must be fully integrated with an existing underground mass transit system. Third, as was discovered in the Toronto signage system, an integrated partnership is necessary between city government and developers. Finally, design of the underground should be seen as an integral part of the surface. “These two spaces would have to be seen as a whole, living in harmony and being in support of the city.”
Russia

Sergey Yufin, Center for Underground Engineering, Moscow

This presentation focused entirely upon Moscow and the problems that face that city. Many of these problems stem from the absence of automobile transport during the Soviet era. With the institution of a more free enterprise system, the number of automobiles has increased by multiples of 2 and 3 each year since 1992. The ring-structured city has no provision for cross traffic, or for parking downtown. The discussion presented a number of potential projects to address the issues of access, commuting and parking. Since Moscow is located on a river, rock is not close to the surface. Thus most of the discussion revolved about cut and cover construction and soil tunnel construction.

The hub, spoke, and ring structure of Moscow is rather typical of European centers that grew from fortresses. These fortress cities grew by infilling until only narrow streets remained and then a larger diameter ring would be constructed. This combination of narrow streets and circular roads, is of great historic and tourist value: however it presents almost impossible transport challenges without a well-developed underground mass transit system and a continually improving controlled access highway system. Most western European cities have been addressing this issue by building subway and light rail systems over time.

Australia

Michael Hood, CRC for Mining Technology & Equipment, Brisbane

This complimentary view of the needs in underground rock construction is summarized from an article coauthored by Michael Hood, a developer of water jet-assisted roller cutters. Since excavation technology is one of the principal factors that differentiates urban underground construction in rock from that in soil, this view is particularly useful. The article, entitled “Mining in 2015- New Technology in Open Cut and Underground Mining,” was presented at the 1998 symposium, “Technology – Australia’s Future: New Technology for Traditional Industries.” The title captures the challenge of all infrastructure development: it is considered “traditional,” and its offshore source underscores the impact of the loss of the Bureau of Mines in the U.S.

First, the trend is identified that all rock excavation is the movement from use of separately controlled drills--shovels, load-haul-dump (LHDs, e.g., trucks)--toward continuous, intelligent, automated mining systems. The authors then investigate a number of developmental areas wherein the goal (prize) is identified. The impediments (problem), the path to solution (technological needs) and current state of practice (status) are also identified. The following paragraphs will summarize prizes, problems, and technological needs in areas relevant to urban underground construction in rock.
**Develop Geological Vision**

Increases in the ability to “see” through a rock mass to find rock structure and strength will yield large dividends both in increasing excavation efficiency as well as improving design. Currently, exploration drilling—sometimes supplemented with some geophysical exploration--forms the basis of defining the subsurface. In mining (and to a large extent this view is still a traditional attitude) there is nothing like “holding a piece of rock or core to understand the nature of the rock mass.” The flaw in this intuitive approach is that important features between holes are missed. What are needed are improved geophysical methods to interpolate between exploration holes. There are a number of impediments to increased use of geophysical methods. These include development of robust, inexpensive sensors, methods of deploying these sensors as a regular part of the exploration and excavation process, and methods of for interpreting the results in a user-friendly manner.

**Integrate Numerical Modeling of Blast Fragmentation with Excavation**

Rock blasting will be the principal method of breaking strong rock in the foreseeable future. However, it is an imprecise tool. Blasting makes it difficult to control the fragment size. It produces collateral damage to adjacent rock. It creates environmental problems (fumes, dust, noise, and vibration) and it can be hazardous. Some of these problems might be reduced through more accurate computer modeling before the actual blasting. Existing models are currently limited because necessary information on rock and joint properties is much less well known than the charge behavior and sequential timing of initiation. This limitation can be overcome during excavation by instrumenting drills to automatically detect changes in rock mass properties during drilling for immediate input into a numerical blasting model.

**Improve Non-explosive Methods of Rock Breakage**

Almost all current rock excavation, except some tunneling, is conducted with the batch process of drill-blast-support-muck. Non-explosive rock breakage can transform this process from batch to continuous. Long wall coal mining, TBM’s and trenching machines are examples of this paradigm shift. The difficulty in duplicating this approach in hard rock is that cutting tools wear out or fail prematurely in hard abrasive rock. Several approaches to overcome premature failure include water jet assistance and vibratory or oscillating disk cutters. Work in this area needs to be accelerated.

**Automate the Excavation Process**

In addition to the obvious necessity of automation to allow continuous excavation, automation will also reduce worker exposure to hazards and prevent overloading of machine components. Since excavation geometry is not fixed and is laden with
unexpected impediments, it is far more similar to NASA’s Mars Pathfinder vehicle than factory robots. Thus, automation will require robust sensors, development of software to generate a model of the local operating environment from sensor data. Currently tele-remote operation of LHD vehicles is operational, and the next quantum step will be to let the trucks drive themselves.

Improve Equipment Reliability

Miniaturation of computers, increased sensor data and increased numerical model sophistication will facilitate real-time computer-based performance assessment. This performance assessment should allow early detection of potential failure of components. These data will also allow quicker improvement in equipment design.

RECOMMENDATIONS FOR FURTHER STUDY

Those in attendance at the workshop split into two groups, 1) exploration and design, and 2) excavation and support. The exploration and design group identified a need for greater technological sophistication in exploration and the challenges posed by intense public interaction on environmental considerations of urban design. The excavation and support group focused more on excavation. These foci may have been a result of the mix of individuals in attendance. On the other hand, they may reflect the areas in greatest need of development. The exploration/design group’s discussion will be summarized first.

Exploration

Challenges to exploration in the urban environment focused upon the limitation of placement possibilities. Most often access is limited to that which is available from the streets. Even then special care must be exercised because of the high density of utilities beneath the streets.

One of the most counter-intuitive challenges is the lack of adequate geological data from past construction. These data are often fragmented, kept by differing agencies (if kept at all), and often relatively unsophisticated due to their age.

Solutions to these challenges are thought to lie in the direction of more sophisticated technology such as geophysics as described below, greater requirements for archiving as-built information, construction diaries, exploration data, and the like, and development of directional drilling as an exploration tool.

Develop more and better geophysical methods

Indirect or geophysical methods of exploration were thought to have the greatest promise because they allow interpretation between bore holes. This interpolative ability is important in rock because of the relatively high cost of exploratory drilling. Geophysical
methods may also allow interpretation of near-hole phenomena. Considerations to be taken into account in development of new approaches are the cost per unit of useful information, time required for acquisition, and the degree of technical sophistication.

**Design**

*Increase the resolution of the knowledge of existing structures*

Many of the early design challenges revolve around the necessity to employ the rather poor resolution of the exploration data. The most obvious is the necessity to construct around existing structures and supply infrastructure that were poorly documented. Chief among related concerns is the deformation, vibration, or movement of the foundations of the existing structures.

*Develop better means of locating exit and entries to the below-ground excavation*

This challenge is another problem that is exacerbated in an urban setting. These interfaces with the above-ground world must be located with great care to cause the least disruption to the existing urban activity while maximizing the ease and economy of construction. It is at these locations of greatest public and contractor interaction that third-party safety and mitigation of environmental effects become critical.

*Earlier and more significant involvement of neighbors*

Given the integrated nature of construction in an urban environment, too little effort at the outset is spent working with neighbors. Earlier involvement might reduce the difficulty of the project closeout and releases of liability. Of course, one of the most important neighbors is the governmental agency or agencies with jurisdiction over the project. Their codes—which may not necessarily be compatible—must all be followed or amended by detailed testing. Elimination of overlapping jurisdictions and codes would be an important step.

**Excavation**

*Expand efforts to predict field penetration rates from exploration data*

This recommendation falls at the boundary between design and excavation. The suggested direction was for the development of a small scale TBM (1 m in diameter) to employ in controlled cutting exercises in a wide variety of rock masses. Results of these exercises could then be employed to extrapolate borehole rock properties to field scale performance. This machine should be equipped with both water jets and special, exchangeable cutter heads and be directionally controllable. The rock masses would have
to be well defined both for intact rock and rock mass (jointed) properties. This special machine might be thought of as a compliment to a National Geotechnical Experimental Site for Rock. In addition, a similar small-scale field machine is needed to support research on boring excavation in mixed ground at the rock-soil interface.

**Continue to develop innovative means of rock cutting**

Several novel means of rock cutting require further investigation. These include vibratory disks as well as the integration of water jets with disk cutters. Finally, boring of non-circular holes would be of great help in excavating utilidores (utility corridors).

**Accelerate development of directional drilling techniques**

Utilidores can be excavated by micro-tunneling if properly developed. To that end greater efforts should be made to cross-fertilize technology from the petroleum industry to decrease the radii of curvature and to accelerate the development of coiled casing. Another advantage to increased directional drilling technology is that it can be linked to TBM excavation. A small diameter side probe could precede the TBM slightly to physically probe ahead and serve as a rock radar antenna or receiver. These maneuvers would help identify the unobserved discontinuities that control rock mass properties.

**Increase scientific application of controlled blasting techniques through greater field robustness of data acquisition devices**

The key to increasing the use of advanced technology in blasting is the development of information-intensive feedback loops. For instance, there is a potential feedback loop during blast hole drilling. Penetration rates can be employed to estimate rock mass strength and the location-specific charge density. Another loop occurs with vibration monitoring. Vibration measurements can be employed to design the next blast for more efficient fragmentation – and thus lower vibration levels. These loops require greater field robustness of data acquisition devices.

**Develop methods to decrease specific energy consumed to explosively fragment rock**

Currently, shock pulses are thought to dominate fracture and fragmentation of rock. Developing explosives that produce controlled gas pressurization to extend fractures may allow fracture extension with lower specific energy. Approaches to carving with explosives rather than fragmentation may yield further reduction of specific energy. Development of these approaches will require the development of a pressure gauge that can withstand the high explosive shock to be able to measure the lower, but longer lasting, gas pressurization pulse.
**Develop more efficient methods to isolate buildings from explosive vibrations**

Heavily populated urban centers imply more human receptors for vibration. Developing methods of isolating structures from adjacent blasting would greatly reduce the accusations of annoyance from blasting.

**Support**

**Develop additional methods of emplacing support closer to the excavation face**

Since early emplacement of support reduces loss of the internal strength of a rock mass, the sooner it is placed, the stronger the rock mass. There are several techniques that require further investigation: new forms of reinforced shotcrete, alternates to shotcrete, foams, etc. New materials for rock bolts would allow them to be automatically placed closer to the face.

**Develop mechanical means of excavating through poor rock**

The most challenging issue for the use of TBM’s is to increase their flexibility. They are excellent at excavating through uniform rock, but can become very expensive tunnel liners when attempting to penetrate intermittent zones of very weak or soil-like rock in otherwise strong rock. Typically, smaller tunnels are excavated in a stacked or circular geometry through the weak zone to provide an opening for the TBM. Development of small, micro-tunnel machines for this purpose could eliminate much of the batch process or hand mining of these smaller tunnels.

**Develop geophysical means characterizing the rock mass at the TBM face**

Early warning of changing excavation conditions can allow appropriate response. The rotating face of TBM’s provides a platform for mounting robust geophysical tools.

**REFERENCES**


ENR (1988) Study Links Productivity Sag to Neglect of Infrastructure, 1 September


THE AMERICAN ROCK MECHANICS ASSOCIATION FOUNDATION
The ARMA Foundation

WORKSHOP ON
UNDERGROUND SPACE IN THE CITY: ROCK ENGINEERING ISSUES IN THE
DEVELOPMENT OF URBAN UNDERGROUND ENVIRONMENT

Sunday, July 30, 2000
University of Washington

Agenda

8:00 am Welcome, Introductions
Peter Smeallie, Executive Director: American Rock Mechanics Association
Mark Liebman AGRA Consultants (Moderator)

8:15 NSF's Geomechanical Research Program
Rick Fragaszy, National Science Foundation

UNDERGROUND SPACE IN THE CITY. A WORLDWIDE LOOK

8:30 Urban Underground: Canada
Jacques Besner, ACUUS: Secretary
Associated research Centers for the Urban Underground Space, Montreal
Given by Susan Nelson

9:15 Urban Underground: Russia
Sergey Yufin, Center for Underground Engineering, Moscow

10:15 Urban Underground: Finland
Reijo Riekkola, Saanioi & Riekkola, Helsinki

11:00 Urban Underground: U.S.
Susan Nelson, American Underground Construction Association, Minneapolis

11:20 Urban Underground: Seattle
Harvey Parker, Geotechnical Consultant, Seattle

11:45 Building Underground in New York City
Reuben Samuels, Parsons Brinckerhoff, Quade & Douglas, New York City

12:30 Lunch
ROCK ENGINEERING ISSUES IN THE DEVELOPMENT OF URBAN UNDERGROUND ENVIRONMENT

Bernard Amadei, University of Colorado, Boulder
Past President of ARMA

1:30 What is the role of rock mechanics/rock engineering in the development of urban underground space in rock and the rock-soil interface
Charles Dowding, Northwestern University, Evanston
ARMA Board Member

2:00 Research Needs in Urban Underground Rock Mechanics and Rock Engineering (working groups)
Robin Amadei (Moderator)

- Exploration and Design
  Geophysical Engineering
  Rock/soil interface
  Seismic considerations
- Construction, Excavation and Support
  Near-surface underground excavations
  Deformation of existing aboveground structures during excavation
  Blasting in developed urban underground space
  Mechanical excavation
  Advanced drilling and excavation technologies (e.g., non-mechanical, non-blasting)
  Grouting
  Comminution/storage/disposal/reuse of rock
- Use
  Operation & Maintenance
  Rehabilitation
  Instrumentation
  Micro-vibration sensitivity
- Miscellaneous
  Social costs of urban excavation
  Environmental issues

3:00 Plenary--Working group reports.

4:00 Adjourn
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