STIFTELSEN BERGTEKNISK FORSKNING
ROCK ENGINEERING RESEARCH FOUNDATION

2021–2025 Research, Development and Innovation Programme for the Swedish Rock Engineering Research Foundation, BeFo

2021–2025 Research, Development and Innovation Programme for the Rock Engineering Research Foundation, BeFo

Release date: 2020-10-15
Last updated: 2023-01-01

www.befoonline.org

Postal address: Box 5501, SE-114 85 Stockholm
Visiting address: Storgatan 19, Stockholm

INTRODUCTION

Today, rock engineering that involves major civil engineering projects in rock and in the mining industry is more extensive than ever, with new projects about to start or already under development. The existing stock of facilities and mines that require management is considerable. These facilities include tunnels, underground caverns, shafts and tunnels for transport, energy and mining operations. The existing stock also consists of facilities that are being rebuilt to use for purposes other than those originally planned, requiring new investment and redirected efforts for operation and maintenance. Coping with this new construction, redevelopment and maintenance of existing facilities and meeting the requirements for social, environmental and economic sustainability require more specialised skills and expertise.

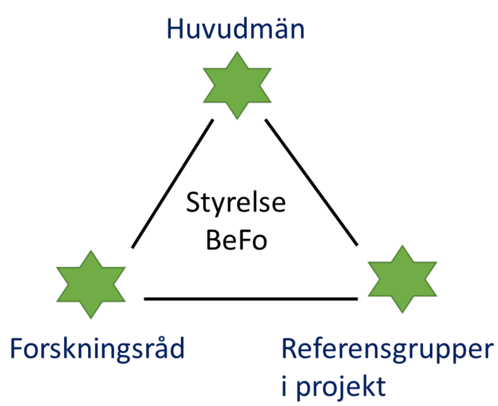
BeFo's activities and its wider research programme aim to promote safe, sustainable and the most economically viable rock engineering solutions that bolster our principal funding bodies, industry and society at large. Achieving this purpose requires a holistic view and cross-cutting research in disciplines other than solely rock engineering as such. We are starting to see that researchers from different areas of expertise are collaborating more and more, thus both broadening and boosting research to new levels. This can involve collaboration broadly between researchers in rock engineering but also others in fields like soil mechanics, material degradation (concrete and steel), artificial intelligence and sustainability.

The foundation's approach aims to facilitate uptake of research results by the market. Projects that are awarded funding are needs-driven, so the research programme is developed in dialogue with BeFo's principal funding bodies including technical universities and other higher education institutions. The research projects are conducted in close collaboration among the parties, providing a stable foundation for disseminating the results.

1. Organisation

Since its founding in the 1970s, BeFo has served as a stable long-term organisation that brings together stakeholders in the rock engineering industry and pursues a well-functioning national research and innovation environment in the industry.

BeFo's principal funding bodies consist of a wide array of private companies and public organisations that share a common interest in advancing rock engineering. They represent government agencies, universities, research institutes, facility owners, planners, contractors, mining companies and suppliers engaged in planning and implementing various underground facilities and who manage and operate these facilities. BeFo's principal research funders, led by the Swedish Transport Administration and Swedish Nuclear Fuel & Waste Management Company SKB, along with 28 other principals (2022), earmark funds to conduct collaborative research projects on behalf of



the foundation across all areas of BeFo's research programme, bringing long-term value to each organisation.

BeFo has three funding period calls each year (January-April, May-August and September-December) when idea proposals and applications for research funding are submitted. The purpose of the idea proposals is for the researcher to obtain an assessment from BeFo's Research Council stating the relevance, feasibility and need for the research idea, which can then be developed into a potential funding application. Applications for research funding are evaluated and assessed by BeFo's Research Council, which makes a recommendation to the Board before deciding on which projects should be awarded funding. Within the framework of the research programme, the principal funding bodies sometimes announce targeted applications in high-priority research initiatives for each organisation.

The budget at BeFo's disposal for existing and new research projects is close to SEK 20 million annually. This means that BeFo can have 30-45 ongoing research projects, of which just over half are PhD projects. The research projects vary in duration, from shorter initiatives of 1 year up to 4-5 years for PhD projects. BeFo takes a positive view of co-funding from other sources, and broader funding normally improves the chances for an application to receive funding even if this is not a requirement. Up-to-date information about BeFo, the call periods and our activities can be found on our website at www.befoonline.org.

2. Priorities of the programme

The programme has been developed by BeFo's Board and Research Council and is based primarily on a workshop with the foundation's principals, a survey for members of the Swedish Rock Engineering Association and a survey for active academic researchers. The programme serves as a starting point for developing project proposals, individually or in collaboration with other experts, for acceptance and prioritisation by the foundation's Research Council and eventual implementation decisions, which are taken by the Board. The programme also intends to transform promising ideas that, in collaboration with BeFo, can be developed into feasible research and development projects.

Vision for 2040

Our society is facing more difficult challenges than ever before. The threat posed by climate change, demands for sustainability including better resource use, pressures from a growing population, and urbanisation – all must be managed as we strive to maintain a high standard of living. In many cases, construction that better utilises underground assets can provide attractive solutions. Tunnels for energy production, underground energy storage, waste management, the cultivation of both plants and fish, and tunnels for communication and supply are just some examples of solutions that are expected to increase in the future. Expanding urbanisation is bringing with it densification even under the ground, placing special demands on planning and implementing underground solutions in densely populated areas. The mining sector is

confronting major challenges, not least because of extensive depths. Special needs can also arise in both the design and construction of disposal facilities for environmentally hazardous substances, such as radioactive waste and mercury. These needs are often linked to processes that have long time horizons and must cause as little damage as possible during construction.

The limits of what constitutes an acceptable workplace environment and environmental impact are becoming stricter, bringing the risk of fewer options for what is feasible to build. In order to achieve and maintain a reasonable, sustainable balance, and for the efficient use of rock as a natural resource, we need to deepen our understanding of mining and building in rock.

We are witnessing a substantial increase in the extent of underground construction. In Sweden today, underground projects in rock are being conducted for several billion kronor every year. Efficiency improvements through research and development therefore have a major impact.

Based on a workshop and discussions with our principal funders on the theme "Future goals and visions", a picture has emerged of the industry's desired progress and status for the long term – in about 20 years – around the year 2040. What do we want the rock engineering industry to look like, and how do we want it to function? Key watchwords have emerged, like sustainability, environmental health and safety in underground facilities and in construction, efficiency and maintenance.

The vision from a 20-year perspective for BeFo's business can be summarised as follows:

– Installing new infrastructure and public facilities underground can support the redirection of urban development and urban planning. Robust, well-maintained and well-functioning underground facilities will become an important part of long-term sustainable development.

– By maintaining global competitiveness around knowledge, education and research in the built environment, civil engineering, rock engineering, and the continued technical development of underground construction, we can promote a sustainable, robust development of society that maintains our national standard of living.

– Well-documented, proven risk-based methods will be used to plan, design, build and operate underground facilities and mines. These methods should balance the needs of the projects from a life cycle perspective in terms of production costs, function, resilience to extreme events, and operation and maintenance. We believe that engineers and town planners will increasingly carry out analyses in collaboration.

– Throughout all areas of society, we are experiencing more rapid technology shifts and pervasive automation and digitalisation, which are driving new skillsets, service production, work practices and entrepreneurship. Robotics, data vision, and measurement and sensor technology will eventually pave the way for automated robot solutions in underground facilities, especially in ageing legacy facilities, in order to reduce risks to humans. Artificial intelligence (AI) and machine learning (ML) are technology fields that have already begun to be used in the rock engineering industry. We envision great potential here, so people with a rock engineering background need to become actively involved in developing tools for more efficient, accurate data analysis and interpretation. Huge volumes of data are already being collected today, and they will be able to be processed in a short time and with good quality.

– Attractive and accessible public facilities in rock will become a natural part of the built environment when underground spaces are planned with consideration for utility, efficiency, ease of access, guidance, safety and aesthetics.

The 2030 Agenda

On 25 September 2015, the UN's member states adopted the 2030 Agenda, a universal agenda that includes the sustainable development goals (SDGs). The 17 SDGs, in turn, have 169 targets and 230 global indicators.

The global goals and 2030 Agenda are the most ambitious agreement for sustainable development that world leaders have ever made. They integrate all three aspects of sustainable development: social, economic and environmental. With the SDGs, world leaders have committed to achieving four great accomplishments by 2030: To eradicate extreme poverty. To reduce inequality and injustice in the world. To promote peace and justice. To solve the climate crisis.

With the help of the SDGs, we are the first generation that can eradicate poverty, and the last that can end climate change.

During BeFo's workshop with its principal funding bodies in May 2020, we discussed how our business links to the SDGs. We found that the rock engineering and mining industries have points of contact with many of the 17 SDGs in one way or another. The goals that are closest to our business are goals 9 and 11, which are reflected in this RDI programme.

Innovation and technological progress are necessary to find sustainable solutions to both economic and environmental challenges. Investing in sustainable industries, research, green technologies and innovation are all vital ways of helping to ensure sustainable development.

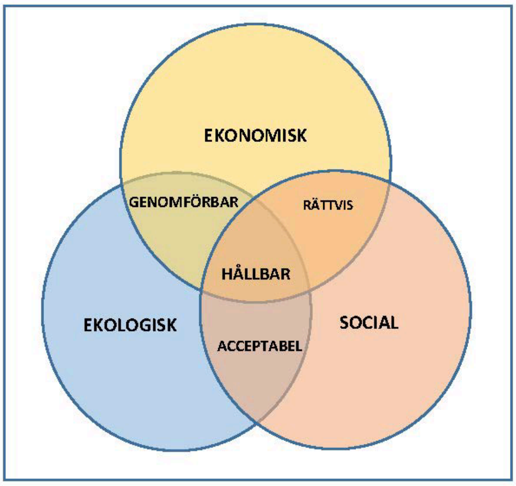
More than half of the world's population lives in urban areas, and this share is expected to rise to 70 percent by 2050. The rapid and large migration to cities places new demands that need to be met in an environmentally, economically and socially sustainable way.

Sustainable urban development includes sustainable construction and planning of housing, infrastructure, public spaces, transport, recycling and safer chemical management, which in turn requires new technologies and cooperation among several sectors. Inclusive and innovative urban planning is needed to make cities safe and sustainable for the future.

A holistic perspective for sustainability

Our industry is expected to take responsibility for social, environmental and economic sustainability. It needs to make an impact on research so that methods and materials are chosen based on a holistic perspective. To achieve this, different experts should step up their collaboration.

Environmental sustainability. In the rock engineering industry, this can involve using climate-neutral methods and materials as well as energy-efficient machinery. With advances like electrically powered machines, mines have come a long way today. But more efficient and thus more environmentally friendly methods for rock mass excavation and tunnelling need to be developed. The choice of building material should also be made taking into account the aspect of sustainability. Here, the development and application of life cycle assessments can offer a way forward to improve environmental sustainability in underground projects. With a sustainability mindset, rock masses from construction projects and mines can be considered a resource and reused.



Social sustainability includes health and safety, justice and equality. Well-planned underground construction can free up land used for roads and tracks for other land uses, such as for homes, workplaces or recreational areas. Even though requirements are in place for limiting the impact on local residents and others during installation of underground facilities, adjacent parties are impacted in various ways including by noise, dust, traffic diversions and more. Creating safe and secure environments in underground facilities is a future issue with a zero accident target. For safe working conditions, automation and robotisation can be necessary to avoid accidents and near-misses. In the longer term this will enable zero entry, meaning that no people will need to enter an underground mine or installation project. Social sustainability also refers to the psychosocial workplace environment from the perspective of employees, including office staff and field workers.

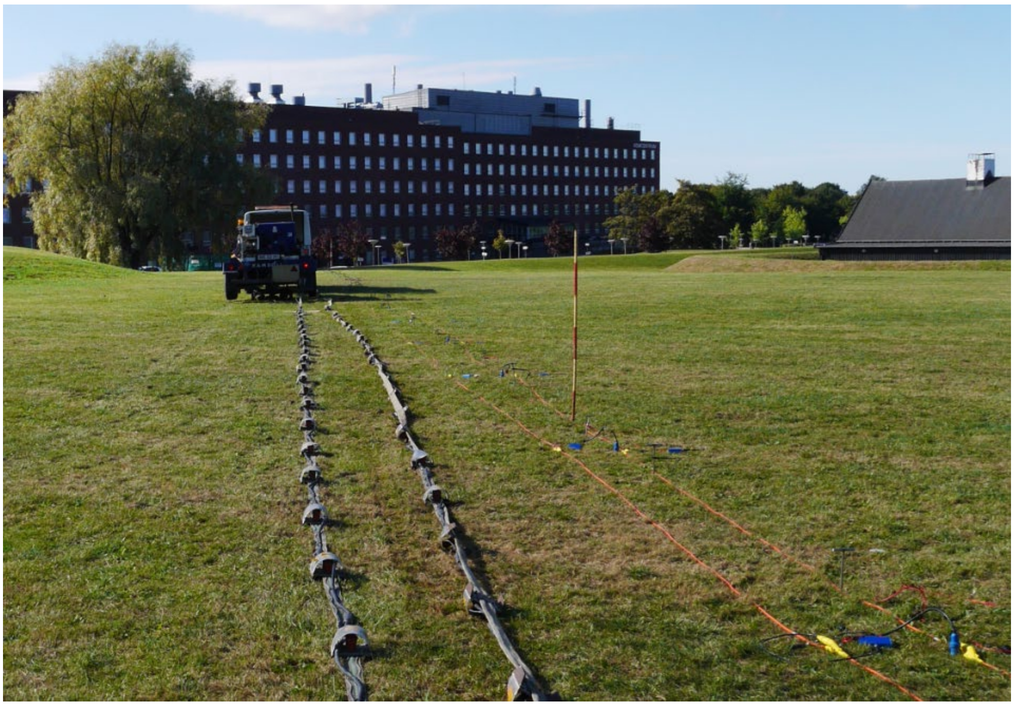
Economic sustainability includes streamlining processes to provide cost efficiencies when building underground facilities, or “more underground bang for the buck”. Here, streamlining means clarifying the processes for planning, design, construction, maintenance and decommissioning, so that the industry can create better tools and practices to achieve well-defined goals with less effort. Here, new forms of contracting, collaboration and compensation can provide a way to increase productivity and efficiency if they are adapted to projects in tunnel and rock construction.

The maintenance aspect is important for securing safe, long-term operations. For assessing the choice of materials and design, a life cycle cost (LCC) analysis can be used. To support their use, input data must be produced, in particular reference tables of historical inputs (such as initial investment costs and maintenance performed), and methods for condition assessments must be developed further. With the help of the LCC tool, underground facilities can be designed for efficient and successful maintenance.

3. Research, development and demonstration infrastructure

New ideas for products, services, methods and processes need to be developed through testing and demonstration under actual conditions. In BeFo projects, this is traditionally often done during a project's construction phase; this usually works very well, so we continue to encourage this approach. Field tests in ongoing projects are valuable and help to guarantee uptake of the research in question. This can entail various restrictions, such as time constraints, lack of options, and accessibility in both time and space, and challenging working conditions, all of which can limit the value of the tests and demonstrations.

One alternative is to use special underground facilities for research, development and demonstration where real-life conditions prevail or can be simulated. BeFo encourages the use of test and demonstration facilities to improve the chances of realising innovations and implementing new technologies in the areas of infrastructure, mines and the power industry.



Measuring with a double-folded geophone land streamer (Ramböll). At the right are cable harnesses for seismoelectric electrodes and geophones (Lund University Faculty of Engineering). Photo: From BeFo Report 194.

4. Research areas

The programme's current research areas, which have some overlap, are described below. In all areas, we facilitate basic research projects for developing knowledge as well as projects that are targeted to direct practical application.

Research areas

1. **Underground planning and development**
2. **Design and construction processes**
3. **Mapping and characterisation during planning, implementation and operation**
4. **Rock reinforcement design**
5. **Sealing, and water and frost protection**
6. **Environmental impact with respect to groundwater, deformations and vibrations**
7. **Rock excavation and mining**
8. **Operation and maintenance**
9. **Function and durability of materials**

The social, economic and environmental aspects of sustainability, including workplace health and safety, inform all areas and are pivotal to the development of industry and society. However, they are not primarily viewed as their own research areas but rather as aspects that are highly relevant to all of our nine specialised research areas. These aspects should therefore always be analysed, taken into account, highlighted or otherwise addressed in each research project in order to give greater weight to a holistic view and sustainability.

The expected results, viewed from environmental, social and economic sustainability, should also be highlighted in research applications. If sufficient expertise is lacking on these sustainability aspects as they relate to the research area, applicants must determine how their project can address them in the application, the project's implementation and the final results. Because we do not expect researchers in a specialised field like rock engineering to be experts on all these sustainability aspects, we encourage collaboration with other experts active in these research areas.

To make a real impact in our industry, it is not enough for developers, planners and contractors to work towards improved sustainability. Such considerations need to be made early on, during research and development, when new approaches, methods, designs and solutions are being developed. In research, emphasising sustainability is expected not only to ensure sustainability proofing of the results, but to stimulate one's own sustainability mindset and promote a holistic view in the industry.

Image by nasidastudio/shutterstock.com

1. Underground planning and development

The signs of global urbanisation, with growing and densifying cities, are in plain view in Sweden and around the world. Although a denser urban structure can help drive sustainable urban development, it puts demands on high accessibility to the city's offerings. This is why providing a good human habitat requires careful planning and installation of underground solutions.

Municipalities shoulder the primary responsibility for land and water use planning. Their goal involves offering an attractive urban environment while achieving national and regional climate and environmental goals. By siting certain functions underground, we can achieve a better use of above-ground land as we build well-functioning communities that enjoy a good standard of living. The regions are responsible for developing comprehensive, long-term spatial plans. These serve as input to municipalities' spatial plans with regard to inter-municipal and regional planning issues.

Needs

Even though it can be expanded to deeper levels, the subsurface is a finite resource. This is why proper planning is vital, including documentation of existing facilities, near-term consideration of planned underground facilities, and reserving space for their intended future use. Without long-term underground planning, the most attractive locations will risk being seized by whoever builds on a first-come, first-served basis. This risks ignoring long-term public interests and allows attractive locations to be consumed and blocked for other, perhaps more important, purposes. Repurposing existing facilities – such as converting non-essential air-raid shelters into museums – is also an example of resource management.

Spatial planning is managed by the municipalities, who have a planning monopoly. This poses some shortcomings in terms of long-term underground planning as well as the necessary integration of the environment both above and below the ground. A common term used throughout the world in this context is "underground master plan". Although we lack an equivalent term in Sweden, other locations have introduced such a planning tool for including underground areas in a city's spatial plan. We see a need for research and development in underground planning and integration with other municipal planning processes that take into account all the relevant geo-resources. Such an integration of existing and planned facilities bolsters and streamlines spatial planning, and draws particular attention to the value of the subsurface as a resource.

Research and development are also needed to develop better data and tools for underground planning. There is great potential here for data and models from the build phase to be successfully used in the subsequent management of underground facilities. Developments in this area have gained momentum, but a uniform methodology for addressing these issues is lacking.

In the planning process, the consequences of the changes need to be described and should include social, economic and environmental aspects. Social impact assessments must shed light on the working conditions of the people who work underground, yet only limited research is available on this in Sweden and abroad. For example, we need to better understand the consequences of the absence of daylight and orientation ability relative to the surroundings and circumstances underground. It is vital to adapt plans and designs to human experiences and create positive, inspiring environments.

It is vital to adapt plans and designs to human experiences and create positive, inspiring environments. At the Triangeln station of the City Tunnel rail link in Malmö, natural daylight fulfils an important design function. Photo: Sweco.

2. Design and construction processes

The design and construction processes refer to the stages from facility design to the completion of as-built documentation through to deployment. Although the industry has many projects underway, it is facing pressures due to time and cost overruns on completed projects. There are several reasons for why making accurate assessments in the early stages is such a struggle. An investigation into key success factors in underground construction showed that success often depends on the relationships between different parties in the planning, design and construction processes. New forms of collaboration among the various parties in these processes have been tested, with the common interest of building facilities that meet everyone's expectations – a final product that meets requirements, stays within budget, and can serve as a reference for suppliers on future projects. Review procedures can also be used to communicate shortcomings and opportunities at an early stage or during execution of the work. Communication and collaboration, within the industry and between the industry and society with politicians and the general public, must be improved.

Needs

Examples of needs include developing better forms of compensation, quality control, and risk assessment and distribution that are targeted to underground projects, which require a more agile process due to the uncertainty around understanding underground conditions in advance. Functional requirements have become a part of industry documents in recent times and guide the construction process. New contractual forms, new approaches to collaboration and new compensation models must be developed to improve efficiencies and collaboration in projects.

Construction using the observational method involves starting from the design of reinforcements and sealants, which are incorporated according to previously designed modifications based on observations of the structure's behaviour that take place during construction. There is a need today to develop forms of compensation that are better adapted to this methodology that clearly clarify risk distribution and responsibilities as the design is modified. How do we define design requirements and how do we validate them? Forms of compensation and risk distribution have proved to be particularly relevant in terms of sealing work. This can involve specifying in construction documents a clearer delimitation of responsibilities between client and contractor during the different stages with regard to function, quantities, time required, etc. We need an overarching discussion of how to plan and implement rock engineering projects based on previous experiences and opportunities to optimise the entire process. This includes the question of acceptance based on well-functioning communication and interaction with the general public that considers the sustainability perspective. The scope and role of feasibility studies in the planning phase, as well as how this information is used in subsequent processes, should be analysed. The sustainability perspective needs to inform the project, and an analysis of methods, materials and impact should

Citybanan, Stockholm. Photo: NCC, from BeFo Report 154.

all be included in the initial project stages. One example could be classifying excavation material for later repurposing, a measure that should be part of the procurement phase. Furthermore, life cycle assessments are needed that can also be useful in the permit procedures for a project.

Visualisation and database models serve as a supplement to quality assurance and documentation of the processes. However, useful methods and routines must be developed for an industry-wide approach and use. Artificial intelligence (AI) and machine learning (ML) can be used during controls and inspections of performed work to streamline tasks and raise quality.

3. Mapping and characterisation during planning, implementation and operation

Rock engineering and underground construction depend on accurate mappings and preliminary assessments of rock conditions at different stages of the construction process, during planning and construction through to operation and maintenance.

Needs

Needs include creating better input for assessments based on geoengineering experiences and well-designed mappings, both before and during construction as well as in the operational stage of maintenance planning. The need is great to systematically collect and store rock engineering and hydrogeological data for use in future projects. Opportunities for better data collection and interpretation, the development and use of new tools, and the visualisation of results urgently need to be tested in order to promote better planning and decisions at different stages of rock engineering projects. Today, 3D and 4D data are already being stored and interpreted in the construction and mining industries, from planning through to construction and operation. Methods must be developed and implemented for better quality assurance, forecasting and documentation throughout projects and for future projects. The ability to obtain real-time predictions of rock content and its properties during excavation can also enable improved production in terms of both working conditions and efficiency.

Several properties are being examined in the field or in the laboratory. These include rock-mechanical and other physical properties that require special technology and processing of primary data. There is a need for better models and technology for data collection as well as data interpretation and visualisation with the aim of providing real-time decision support and accurate accounting. Uncertainty analyses that illustrate data reliability should be developed.

The interpretation and reporting of mapping results is linked to how the data is best utilised in the successive updating of conceptual models for characterisation of the rock mass and its rock-mechanical and hydrogeological properties. No method can provide all the information that is measurable, but different methods complement each other; here, collaborative interpretation provides an improved understanding of geological conditions.

A rough classification of rock slopes along roads, Höga Kusten, 2019. Photo: Yuliya Zhuk/Sweco.

New methods for predicting the internal structure and properties of rock using techniques from other fields of technology are being created and should be tested further, for example for non-destructive testing and quality control of materials and products from other industrial or development activities. These could be based on proven or new technology, and usability should be tested in the field to demonstrate practical benefits.

Better studies are needed at different scales and stages, from general information during the initial planning stages to local site condition assessments (including the effects of blast damage) of a facility, in order to support an assessment of reinforcement and sealing efforts and for subsequent maintenance planning and execution. This research area often involves collecting vast amounts of data that must be structured and interpreted. New technologies like AI and ML can both streamline and increase the quality of efforts in this area.

In deep rock facilities like mines, large rock deformations can require extensive measures and, in worst cases, parts of the mine must be abandoned. Strategies and techniques for measuring deformations in rock and reinforcements thus need to be developed to ensure high preparedness.

4. Rock reinforcement design

Rock reinforcement design is applied to underground facilities at different depths, rock and mountain slope foundations, and reinforcements if erosion problems are present.

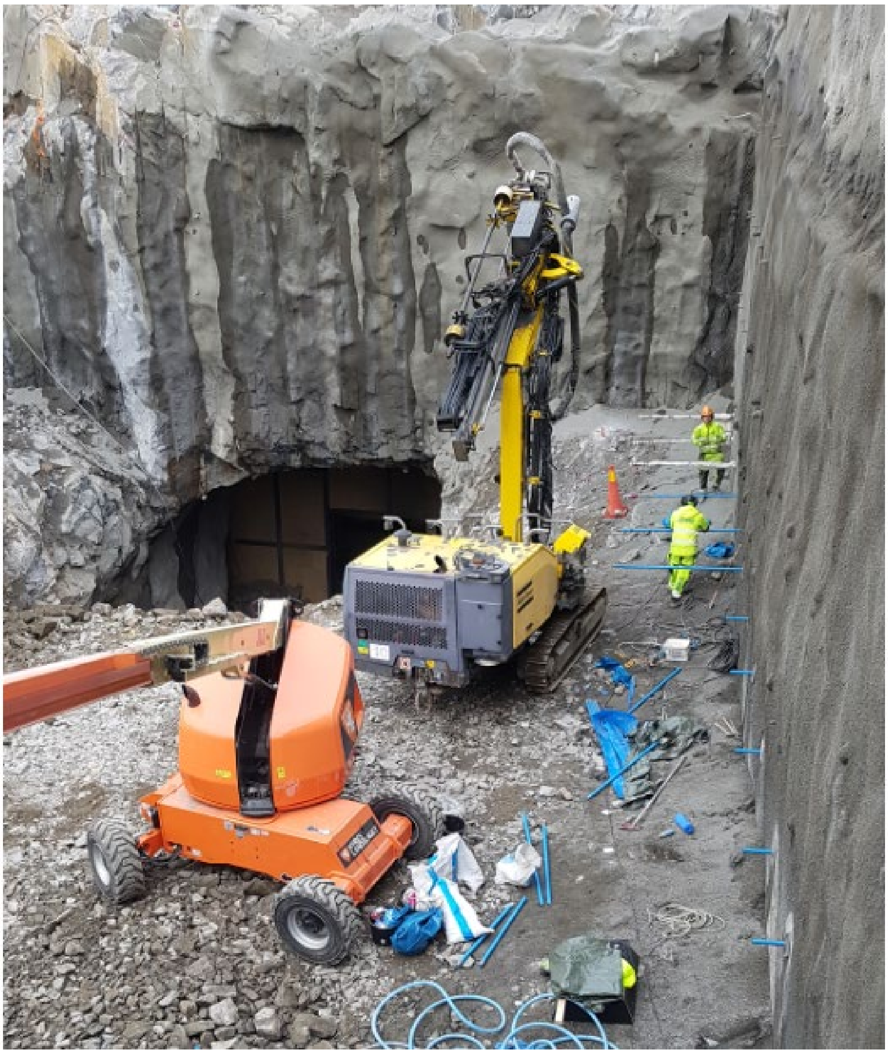
As a rule, the primary load-bearing structure of an underground facility consists of rock mass together with reinforcement. The design cannot therefore be based on the same type of calculations as for other structures built using steel, concrete or similar materials, partly because loading and strength are not unambiguous and independent of each other. Other difficulties arise because rock mass properties are determined by the rock's fracture structure, and these properties and qualities are determined by sampling and are thus scale-dependent. In addition, the installation of reinforcements itself is an uncertainty that needs to be taken into account. Questions about the fire resistance of materials must also be considered in the design and during construction, something that must be developed further.

Needs

Examples of needs include developing methods, technologies and practical pathways to success to ensure the safety of reinforcements and reinforcement inspections over time. A further clarification of design methodology that meets the requirements and conditions of Eurocode 7 are also needed, as is the development of observational method fundamentals for practical application in rock mechanics design. Meeting the code requirements requires an in-depth understanding of mapping techniques and interpretation of results (see "Mapping and characterisation during planning, implementation and operation"), as well as an understanding of how to characterise rock mass properties, use material models for rock and reinforcement, and knowledge of computational and verification methods. Effective and improved review processes for verifying strength, durability, large-scale stability, and the impact of third-party interests (for example, geotechnical category 3) of major construction projects may also need to be studied. When designing reinforcements such as the length and weight of bolts, working conditions must be taken into account. Methods for monitoring the capacity of reinforcements, such as the detection of bolt breakage, are not well understood today and must be developed.

For mines and other deep-sited facilities (storage facilities, for example) or plants with wide spans, reinforcement strategies are needed to manage large deformations. The significant stresses that occur at greater depths can, during rock excavation, induce seismic events that require special measures and products. Reinforcement components and systems that are resilient and can handle dynamic loads, known as dynamic reinforcement, must be developed for these types of facilities.

The question of how rock mass properties are addressed in conceptual models is complex and presents a number of challenges, such as the uncertainty of material models. Calculations can be made using analytical solutions or numerical methods; in both cases, methods are needed to calculate the distribution spread for rock mass behaviour based on stochastic distribution adapted for practical application. Composite structures can be divided into two main types. In the first one, which is most common in Sweden, the rock mass has the primary load-bearing function, and is secured using a composite bolt and shotcrete reinforcement. The second type involves rock mass that lacks sufficient bearing capacity and thus requires reinforcement that is sized based on composite interaction, usually using the ground reaction curve. In connection with the interaction function, there are questions about the bearing capacity of the reinforcing elements in the load and deformation states in question. These include, for example, the deformation properties and load-absorbing capability of fibre-reinforced shotcrete. Understanding the function of reinforcement materials in the event of fire is necessary in order to assess function and fire safety.



A shaft in Henriksdal. Project: Stockholm's future wastewater treatment, 2020. Photo: Yuliya Zhuk/Sweco.

5. Sealing, and water and frost protection

Sealing, and water and frost protection for underground facilities are closely tied to several sustainability aspects in terms of groundwater impact, efficient rock construction, safety, well-functioning operation and maintenance, and the environment in and function of the facilities.

Managing water ingress in rocks during the construction and operation of tunnels, caverns, ponds and certain rock cuts usually involves an object-adapted sealing requirement based on the current groundwater conditions and functional requirements at the facility. The functional requirements can be of a technical, financial or safety nature, and can involve preventing water droplets or ice build-up on installations or roadways, or the cost of pumping out leaking water. Sometimes the functional requirements involve aesthetics, such as preventing stains from dripping water or moisture. The sealing requirement can often be fulfilled in two ways: by sealing fractures in the rock, which minimises groundwater inflow, and by using drains or various forms of permeable or impermeable liners to meet the functional requirement for water and frost protection.

Needs

A need to develop water and frost insulation exists. We thus suggest developing alternative solutions for drains and liners that also take into account long-term operation and maintenance considerations. New materials that are developed must also meet the specific requirements for fire resistance at the site in question.

Sealing, and water and frost protection in underground facilities require a holistic approach that often requires more than one measure for developing a solution. An evaluation of the sealing systems is needed that considers functional, financial and production perspectives. LCC methodology can be used to evaluate different options, such as grouting, drainage, cladding or waterproof lining, from a financial perspective. These options can be weighed against a change to use infiltration. Although a systems approach is sometimes applied today, it would benefit from additional enhancements and better input data.

Bjäsholm Tunnel, Ådalsbanan. Photo: Kari Korhonen/YIT.

6 Effects on the environment with respect to groundwater, deformations and vibrations

Assessing and controlling environmental effects is a natural part of underground construction projects. One environmental impact that can, in some cases, be permanent and entail substantial costs is groundwater drawdown.

Complex hydrogeological relationships often need to be evaluated for a facility installation project, so assessing requirements and selecting measures to reduce groundwater impact require a deeper understanding of the different relationships. Assessing environmental effects is closely tied to sealing requirements or the protective measures that must be taken. This area of expertise provides vital information to other technical areas in a construction project: assessments of water chemistry for material selection, groundwater level impact for input in assessing pore pressure changes and the risk of subsidence, and documentation for environmental impact assessments and permit applications. The environmental court sets requirements based on the permit application and largely regulates the implementation of underground projects and, oftentimes, the operation and maintenance of the facilities.

Mining operations impact the environment in many different ways. The primary environmental impact that must be managed is vibrations from mining-induced seismic events and ground deformations caused by rock excavation when certain mining practices are used. Mines are gradually being expanded and so their environmental impact is growing, causing ground deformation and subsidence that affect an ever larger area both above and outside the active mine. With mining at ever greater depths and the resulting greater rock stresses, seismic events like rock mass vibrations are also on the rise, not infrequently in areas located far from the mine itself. Another environmental impact of mines as well as construction projects involving blast rock excavation is the discharge of explosive residues to the groundwater or water recipient.

Needs

There is a need to better manage uncertainties when predicting groundwater drawdown, the effectiveness of protection and sealing measures, and hydraulic parameters. Uncertainties are present in both the raw data and in the construction and operation stages.

Research that takes a holistic systems approach is needed, one that links hydrogeological properties and the technical solutions in order to prevent drawdown near facilities. This includes improving the LCC analysis for sealing or infiltration work as well as assessing the overall impact of ambient effects with regard to finances, adjacent structures (including the impact on groundwater in the soil layers and pore pressure in clays that can cause subsidence), and the environment.

Changes in water chemistry and their environmental consequences have an impact on construction conditions, corrosion and concrete degradation. These consequences should be better understood with regard to groundwater abstraction, seepage and infiltration during a facility's implementation as well as operation.

In the permit process, a key consideration is the environmental impact on groundwater resources and surface water systems. A subsidence of merely a few decimetres in groundwater levels can have an impact on the water balance of a catchment. A better understanding is needed of hydrogeological systems and discharged water from underground facilities, as well as of infiltration. Likewise, we need to understand how rock excavation and deformation influence deep groundwater flows and what knock-on effects they cause close to the ground surface. For all types of rock excavation involving the use of explosives, we need to be able to understand, forecast and influence water flows in order to minimise the release of explosive residues into the groundwater or water recipients. The current permit process is perceived as being confusing and unclear, entailing a potential work burden in relation to true needs. The process must provide clearer guidelines on which types of input and documentation is required for a permit application in order to develop the envisioned framework – simply put, a more predictable process is needed.

We should be able to understand, forecast and influence vibrations and deformations based on an understanding of the rock mass, stress conditions and seismology in particular.

Water quality testing near an underground facility
Photo: Shutterstock.

7. Rock excavation and mining

In excavation and mining, efficiencies are sought to achieve successful time and cost management. With increased demands, the organisation, processes, staff skillsets and machinery all need to be developed.

Two tunnelling methods dominate underground rock construction in Scandinavia today: drill and blast, and mechanical excavation. The conventional method of drilling and blasting has evolved thanks to increasingly efficient methods and equipment. For example, the rate of penetration has increased significantly.

Alternative methods for rock excavation include wire sawing and hydraulic fracturing, which have been successfully used in urban environments that have special requirements due to the thin soil cover of nearby underground spaces. These methods, together with the tunnel boring machine (TBM) method, are more gentle on the rock. Gentler methods result in less cracking and limited damage zone. This in turn limits the reinforcement needed, reduces the amount of muck to be removed, and likely also limits the amount of water ingress through the remaining rock. On the other hand, in an environment with high rock stresses, which is becoming increasingly common in mines due to greater mining depth and competent rock mass, a large damage zone can have a dampening effect on rock burst, with increased safety and reduced reinforcement costs as a result. In other deep rock facilities, such as those used for the final disposal of environmentally hazardous substances, minimising the damage zone is of great interest. A deep understanding of how the damage zone arises and develops is needed in order to steer towards the desired result.

The methods used should be assessed from a sustainability perspective in terms of economic, environmental and social aspects, such as workplace health and safety. This can mean that what used to be the “right” method no longer measures up, which places demands on research and development in this area.

Needs

The advance rate for a tunnel or shaft represents high value, so time management is an essential economic factor. One need is streamlining the production process in order to reduce the cost per metre of tunnel, a cost that is steadily on the rise, and minimise long-term environmental impact. Development of the organisation or training can also lead to efficiencies. Construction should have minimal impact on the remaining bedrock and adjacent facilities. The chosen tunnelling method affects working conditions, the external environment, operation and maintenance, and sealing and reinforcement requirements. This entails the need to develop methods, techniques and pathways to success for the advance rate in order to minimise time and costs for the tunnelling operation itself as well as for sealing and reinforcement. To generate the best possible results for the completed facility, its costs and safety must be considered from a life cycle perspective. In terms of working conditions, safer methods might need to be developed for manual steps performed during reinforcement operations, such as greater automation. The vibration impact on surrounding structures and adjacent parties should be considered in order to achieve an optimal drill and blast operation in terms of environmental impact. Improved analytics tools are needed in this area.

More research is needed on the design and geology of underground spaces and their relationship to the occurrence of seismic events and deformations. Great depths, which are needed to store radioactive waste and mine tailings, bring increased rock stress and more frequent seismic activity caused by excavation. These induced seismic events pose both a health and safety risk and an environmental risk that must be better understood in order to assess the risk of their occurrence. Methods for predicting risk, monitoring and systematically collecting data need to be further developed. The effect of the damage zone on rock stability combined with high stresses must be further investigated, and intelligent technologies for monitoring fracture propagation developed.

Sustainable mining practices must be developed in terms of working conditions and the environment, as well as improved profitability. Developments in mining can also lead to similar developments in the construction industry. Rock excavation methods for facilities intended for storage of environmentally hazardous substances require production methods that minimise the damage zone and have high accuracy. Here, too, cost-effective methods need to be developed. The development of machinery, including electrification, automation and communication with other devices, brings new opportunities to develop more efficient processes and improved working conditions. In some mines, excavation can be carried out without the need for any human being to enter the work area. This “zero entry” vision is becoming more and more realistic.

Drill rig from the construction of a new ramp in the underground repository in Rönnskär. Photo: Boliden. From BeFo’s 2016 Annual Report.

8. Operation and maintenance

As the operating and maintenance costs of underground facilities increase, it is essential to determine the right efforts early on, during construction and installation, rather than focusing on subsequent operation and maintenance phases. The costs of such efforts are a key consideration, and several methods are available to guide balancing capital expenditure with expected operation and maintenance costs. A systematic LCC analysis should be carried out during the initial stages of the design process, when time and materials are determined. This method has already been applied in several underground and tunnelling projects. The LCC analysis should be followed up with project actuals and with any repairs or replacements so that it is kept up to date.

Many existing facilities have reached an age that might require more thorough maintenance efforts. This is especially true of hydroelectric power plants, many of which have been in operation since the mid-twentieth century, but it also applies to many road and rail tunnels. Yet age or time alone does not determine the need for maintenance. Condition-based maintenance is a modern strategy that requires a solid understanding of how to measure the facility's condition. What information is necessary for planning, following up and managing maintenance operations? How can an optimal balance be achieved between the costs of investment, maintenance and risk? These questions reveal that operation and maintenance questions should be raised during both the design and construction stages so that a planned facility can pass inspection and be built to optimise maintenance requirements.

Needs

To meet legal as well as business requirements, models for analysing life cycle costs serve as indispensable tools. Application of these models requires reliable input data. Requirements for such data from underground facilities must be specified and tested before these models are applied. One example of needs is to develop strategies and methods for determining a facility's status with regard to maintenance requirements. Effective methods are needed for an assessment of rock condition and reinforcement following exposure over a longer period of time and under different external influences. Degradation processes and the durability of the main load-bearing system (composite of rock and reinforcements), as well as grouting and sealing, must be grasped in order to assess maintenance and repair requirements. Condition-based maintenance methods for underground facilities and effective maintenance information management should be investigated and developed. Repair and reinforcement methods are needed that are adapted to limited accessibility in space or time, especially in transportation tunnels. There are specific needs around status assessments for water-filled tunnels and the subsurface at dams, rock cuts, and discharge channels that show the progression of erosion, as well as condition assessments and measures for rock cuts. Methods for inspecting facilities using drones and other remotely operated craft should be developed to minimise workplace health and safety risks. Experience feedback from documented rock falls in tunnels, slopes and other cases of damage should be utilised.

Artificial intelligence can be leveraged in various ways here if equipment for condition assessment is developed, such as sounding hammers, which today is a relatively subjective process.

9. Function and durability of materials

This section refers to testing of established materials as well as new materials based on their function and durability.

Several of the materials used for rock reinforcement, sealing and cladding are well proven and established in civil engineering works. In some cases, however, the properties are less well documented and specified, for example in terms of durability and fire resistance. New materials must be compared with conventional ones and specified based on functional requirements. Quality assurance of facilities should be developed for conventional as well as new materials, reinforcing elements, grouting, sealing and more.

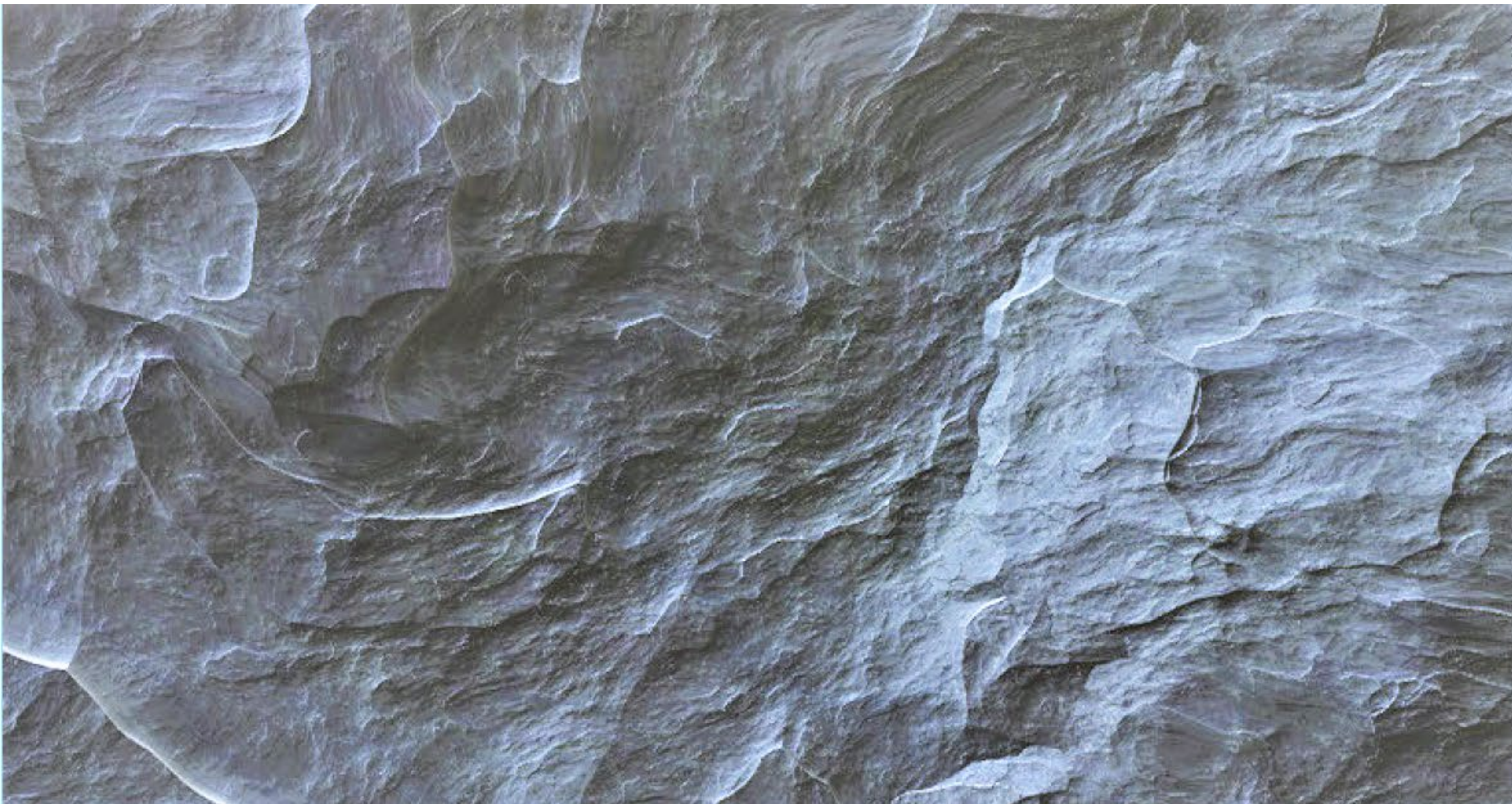
Material selection for underground facilities is typically done based on work environment, function, durability and economy. Environmental sustainability needs to be assessed for the entire facility, meaning that the materials and products chosen should function properly as part of one whole sustainable system.

Needs

One development need is to meet the functional requirements for fireproof water and frost insulation. Different materials and combinations must be tested in prototype scale and in full scale. Shotcrete, often fibre-reinforced, is often used as rock reinforcement. Nevertheless, more knowledge is needed about shotcrete's properties in order to obtain better design input, taking into account load-bearing capacity and durability. These can include deformation properties using different types of fibre reinforcement, the potential for strain hardening, shrinkage properties, waterproofing and leaching, resistance to frost and fire, alternative additives and ballast, as well as fibre and mesh reinforcement corrosion. A potential area worth investigating is the use of thin spray-on liner as an alternative to shotcrete. For bolt reinforcement, it is interesting to look at and test new materials for rock reinforcement in different shapes and applications. Material failure for loads under breaking load and in fatigue, for example, are also worthwhile subjects of investigation. Over the years, fully grouted rock bolts have dominated bolt reinforcement options, but we do not yet have an in-depth understanding of the bolt's mode of action, a factor that can probably reduce bolting work. Questions of grouting durability can involve pure rock grouting as well as contact grouting between the rock face and concrete. Specific problems are associated with grouting fan seepage over time, something that affects the otherwise long service life.

One advantage of underground facilities is their very long service life, an environmental advantage that should help to offset the carbon footprint from the use of steel and concrete. There is a great need to develop new materials that are highly durable yet have a small climate impact, both in the rock engineering industry and the entire built environment sector.

Partly exposed grouted bolt in carbon steel, after eight years of exposure in the Muskö Tunnel. Photo: From BeFo Report 193.



BeFo
STIFTELSEN BERGTEKNISK FORSKNING
ROCK ENGINEERING RESEARCH FOUNDATION

www.befoonline.org