1 Introduction

Sprayed concrete is a method of concrete placement that offers unique advantages and flexibility for different practical applications. To spray concrete, different methods may be selected and they all have their specific advantageous and disadvantageous. For this article, the background is underground construction of caverns and tunnels in hard rock, primarily by the drill and blast method and in this field, state-of-the-art means placement by robotic equipment, use of the wet-mix method and mostly with fibre reinforcement.

The development from hand-held nozzle operation using the dry-mix method to today's modern wet-mix placement is outlined below. This is done to explain the reasons for the rapid change that took place, especially in Norway and why practically all of international mining and civil construction has adopted the same approach.

Even with such a narrowed down focus, the subject of sprayed concrete in hard rock tunnelling would require a brick of a textbook to cover all aspects of the subject. This article is only aiming at outlining some main parts of this wide subject, to provide an overview and to present what is considered the right approach for the prospective user of sprayed concrete in hard rock D&B tunnelling.

1.1 Sprayed concrete methods

The sprayed concrete approach, originally called Gunite, was invented more than 100 years ago by the Cement-Gun Company, Allentown, USA as early as 1907. Carl Ethan Akeley needed a machine to spray onto mesh to build dinosaurs. His company protected the brand name «Gunite» for their sprayed mortar process. This mortar typically contained fine aggregates and a rather high percentage of cement and the name Gunite is still being used.

Today there are primarily two application methods for sprayed concrete:

1. The dry-mix method where mixed natural humidity sand, aggregate and cement is conveyed through a hose by compressed air (thin-stream conveyance) and water for hydration is added in the nozzle.
2. The wet-mix method where ready pre-mixed concrete (sand, aggregate, water and cement) is pumped through the conveyance hose (thick-stream) and compressed air (with set accelerator) is added in the nozzle to create the spraying jet.

For many reasons, the wet-mix process has practically taken over all application of sprayed concrete underground and today this is the case worldwide. It may be useful to understand the background for this development, that first took place in the Norwegian market.

1.1.1 Wet-mix sprayed concrete development

Before 1970, the dry-mix method was practically covering 100% of the sprayed concrete volume in Norwegian tunnelling, like everywhere else. However, due to low output, high rebound of materials and problems with dust development, experiments with wet-mix were started. During the 70'ties, the volume of sprayed concrete placement per year increased rapidly and due to the much heavier hose and nozzle required for wet-mix, the hydraulic manipulators (robots) took over more and more.

Because of the success of the implemented changes, during this period the sprayed concrete market in Norway turned from 100% dry-mix spraying to 100% wet-mix spraying and practically all of it placed by robotic equipment.

1.1.2 Economy

Economy at the tunnel face is very closely linked to time spent and even though the investment cost of integrated wet-mix sprayed concrete equipment increased dramatically, the efficiency improved drastically to cut time related cost to a fraction. Typically, a truck-mounted unit carries the concrete pump, the hydraulic arm for the nozzle operation, a compressor for spraying air, accelerator tank with dosage system, high-efficiency working lights and high-pressure water cleaning equipment. Because of this, spraying can be started just minutes after arrival of the spraying unit at the face (together with the concrete delivery truck) and typical output when spraying being 5X that of the dry-mix method, the cost per m^3 placed reduced drastically. Of course, the fact that materials lost to rebound was reduced by more than 80% was an important part of this.

1.1.3 Working environment

The working environment when using the dry-mix method would routinely produce dust measurement results even 3X above hygienic limit values (even at the normally low output), which required breathing protection of all personnel in the workplace and even for people located elsewhere in the tunnel. Dust could also be a significant problem for visual control of the application process, thus influencing the quality of work. The amount of rebound *removal and disposal* could additionally become a significant cost item.

Wet-mix application is not dust-free but represents still an important improvement compared with dry-mix (or even hybrid methods of wet-mix placed using thin-stream compressed air conveyance hose transport).

1.1.4 Application aspects and resulting quality

The final quality of wet-mix sprayed concrete is often questioned when intended for permanent lining. Generally speaking this is often based on the fact that most sprayed concrete is being used for temporary support, which has specified low requirements on quality and there would consequently be no reason to expect a top-quality product. When considering permanent linings, lack of knowledge and experience is sometimes main reasons for the scepticism.

By use of modern water-reducing admixtures (allowing low w/c ratio) and added microsilica, peak compressive strength of wet sprayed concrete can be as high as 100 MPa. Furthermore, the spread of compressive strength test results is typically quite limited and certainly a lot better than for the dry-mix method.

With the wet method, a ready mixed concrete from a concrete plant is delivered to the concrete pump. The concrete is therefore prepared in the same way as for normal concrete. It is possible to check and control the w/c ratio and concrete consistency and thus the quality at any time. The consistency can be adjusted e.g. by means of admixtures. With the wet-mix method it is easier to produce a uniform quality throughout the spraying process. The ready mix is emptied into the pump and conveyed through the hose in thick-stream by the pump pressure. At the nozzle end of the hose, air is added to the concrete at a rate of 7–15 m^3/min at a pressure of 7 bar depending on whether the spraying is performed manually or by robot. The air is added to increase the speed of the concrete so that good compaction is achieved as well as good bond to the surface. A mistake sometimes made with the wet spraying method is that not enough compressed air is used. For robot spraying, up to 15 m^3/min should be used.

Set accelerator is automatically added at pre-set dosage together with the compressed air in the nozzle. It is sometimes claimed that frost-safe concrete cannot be obtained this way and that sprayed concrete with set accelerator gives a poorer bonding. Several well documented tests from public institutes and practical experience have shown that better frost proofing has been obtained than without accelerator. This may be surprising but has to do with favourable size and distribution of micro air voids in the placed concrete. The bond strength will naturally depend on the quality of the rock or other substrate but is not reduced by controlled dosage of modern accelerators.

1.1.5 Summary of wet-mix method properties

The maximum output of sprayed concrete placement depends on and is mostly limited by practical aspects of the given site. However, when conditions are favourable, it is important that the equipment and application method can take advantage of this. With robot application on sufficiently large available surfaces (like in caverns and larger tunnel cross sections), average production of 50–100 m^3 in an 8-hour shift may be achieved (with less than 10 % rebound) using the wet-mix method. This can be done by just one robot operator and the necessary concrete truck drivers.

The advantages of the wet-mix method compared to the dry-mix method can be summarized as follows:

- Very low rebound. A loss of 5–10 % is normal with use of correct equipment, materials and trained personnel. These figures also apply to the spraying of fibre reinforced concrete.
- Better working environment; dust problem significantly reduced.
- Thick layers may be applied because of effective concrete admixtures and accelerators.
- Controlled water content (constant, defined w/c ratio), which is the primary concrete quality parameter.
- Improved bonding strength.
- Compressive strength as high as required and specified with very small variation in results.
- Much higher output and consequently improved total economy.
- Use of fibres produces a reinforced sprayed concrete structure of better strength and quality than mesh reinforcement, without the extra time and cost of mounting the mesh and splitting the application in at least 3 stages.

There are also some minor disadvantages compared with dry-mix application, but for the purposes covered in this article (tunnels and caverns in hard rock), they are quite marginal and only of importance in very few special cases and consequently not covered here.

1.1.6 Concrete mix design for wet-mix concrete spraying

The modern use of wet-mix sprayed concrete depends on the implementation of concrete admixtures, additives and accelerators. This is of course a very complicated subject for many reasons and there is no one solution that fits all purposes and applications, so adjustments and optimizations are part of the process. The main aspects of this important subject are also complicated by the fact that construction chemicals manufacturers are marketing individual ranges of similar products, but they are not identical and may not even be interchangeable or mutually compatible.

In general, such products are used to produce a best possible combination of concrete properties, both in the freshly mixed state and after spraying:

1. Concrete contains in any case sand, aggregate and water and the primary quality parameter for the end-product is the w/c-ratio, which should be low (certainly below 0.45 and frequently below 0.40). Such a concrete mix will be too stiff and not pumpable or sprayable, which is why a water-reducing concrete admixture must be used.
2. The pumpable mix created under item 1 should have a Slump measure of about 200 mm at the time of spraying (see Fig. 1). If this consistency is sprayed on wall or roof, it will run down the wall and mostly fall off the roof, which is one reason why an accelerator is added in the nozzle. The purpose of the accelerator is to make the concrete stick, as well as to speed up the early strength development to provide support effect as fast as possible (without destroying the final strength potential of the mix design).

Fig. 1 Slump measure left and Flow table right.

Spraying of concrete will unavoidably cause some of the material to bounce back and fall down (termed rebound) and obviously this is a loss that needs to be minimized. Under item 1, this is achieved by using the correct particle distribution of sand/aggregate, high enough quantity of cement and other fines and avoiding maximum particle size above 8-10 mm. The largest particles will always bounce back more than the fines and more the larger they are.

If rebound is measured to 10% or more, all parts of the application needs to be checked to identify what action to take to reduce rebound. Rebound should typically be in the range of 5-10% and never above 10%.

As pointed out in chapter 4.2, the piston pump for wet-mix concrete conveyance to the nozzle must have a shortest possible stop in concrete flow at change-over from one cylinder to the other. However, there is one more related important factor to be aware of. The degree of cylinder filling (filling ratio). When the piston is sucking concrete into the cylinder, concrete will not fill 100% of the maximum cylinder volume reached when the piston turns around to push concrete to the nozzle. If the concrete consistency is too stiff, the filling ratio could be < 60% and the piston would have to move part of the stroke length before any concrete movement occurs. The stop of concrete flow at the nozzle will be caused by the concrete pump properties, but also will increase with reducing filling ratio of the cylinders. The mentioned Slump measure of as high as 200 mm is needed for an acceptable filling ratio.

The use of fluid concrete mix showing Slump of 200 mm seems counter-intuitive and frequently, with the *purpose* of reducing rebound and lower the dosage of accelerator, operators will try Slump measure in the range of 100 mm and less. Such an approach will *increase* the dosage of accelerator, increase rebound and lower the quality of the concrete. The low cylinder filling ratio will cause increased stop time of concrete flow, causing layering of the concrete through intermittent spraying of pure accelerator without concrete. The accelerator flow rate must be set high to satisfy the concrete flow rate between the flow stops. Furthermore, the stiff thick-stream concrete flow is harder to disintegrate by compressed air to create the spraying jet and the mixing efficiency to distribute the accelerator will suffer. The poor accelerator mixing requires again a higher dosage for a given effect. This will typically cause layering of the placed concrete as shown in Fig. 2.

Fig. 2 Concrete layering produced by too low cylinder filling ratio.

2 Design of rock support

Sprayed concrete offers practical flexibility and adaptability to a wide range of different problems and practical situations in tunnelling, both for immediate and permanent support. With modern robotic equipment, placement is done by remote control, avoiding that personnel gets exposed to risk of fallouts from unstable ground. These advantages and the speed of execution are the reasons behind the extreme increase of sprayed concrete volumes in tunnelling over the last few decades.

Sprayed concrete usage for permanent lining has not increased as rapidly and it seems to be linked to issues of rock support design. The interaction and composite effect between the hard rock substrate and a relatively thin skin of reinforced sprayed concrete combined with rock bolts is evidently working very well. It is still a problem to theoretically document this effect by numeric or analytic methods, which partly has the effect that the offered time and cost advantages are not utilised. The final permanent lining design will often be based on partly over-conservative in-situ concrete lining solutions.

Aspects of rock support design that are important when considering sprayed concrete for permanent lining are presented below, to illustrate the offered possibilities of cost and time saving.

Rock support design is a highly specialized field, and it is fundamentally different from the design of other civil structures. The design procedure for rock support therefore must be adapted to this situation.

The main reasons are the following Facts of Life:

- The primary «building material» is the rock substrate with its observable material properties that are given by the local conditions. However, relevant parameters are only partly known.
- The «building material» is highly variable, often within short distance.
- There are severe limitations in what information can be provided from geological pre-investigations or sampling and testing during excavation.
- There are general limitations in accuracy and relevance of rock material parameters that can be tested and even more significant limitations in rock sampling, parameter testing and timely presentation of results.
- There are severe limitations in accuracy and reliability of calculation- and modelling methods.
- The stability behaviour of excavated openings is time dependent, and also influenced by changes in ground water conditions.
- There is an incompatibility between necessary time for parameter testing for calculations and modelling, compared to available time: Progress of excavation is far higher than the capacity in the mentioned activities.

It is therefore obvious that any successful design approach for underground openings must be, or should be, adapted to this situation. Some sort of «design as you go» system is the only reasonable basic method.

Most tunnel support solutions are still designed in a different way. The designers sometimes produce a support design based on pre-investigations of the rock mass and the traditional anticipated load – support load capacity - safety-factor approach. This unavoidably leads to a «worst case» design, which may be necessary in only a small part of the tunnel.

2.1 Analytic and numeric calculations

Calculation tools are an important part of rock support design. To be able to calculate loads, stresses, deformations, support capacity, etc., quantified parameters must be input to relevant formulas and numerical modelling programs. To a varying degree, this will require:

- Sampling and testing for the different rock material parameters.
- Testing of discontinuity (joint) parameters.
- Measurement of in situ rock stresses, often in long boreholes.
- Investigations of ground water conditions.
- Analysis of geometrical data (tunnel shape, intersections etc.)
- Analysis of scale effects on laboratory parameters.
- Analysis of the openings to be excavated and influence of the excavation sequence.
- Identification of rock support material parameters.

Analytical calculations can be quickly performed and are well suited for rough preliminary estimates. The possibilities are quite limited in more complex situations.

Numerical analysis (Finite Element Modelling) is normally run as 2-dimensional models in computers. Even relatively simple situations may take days of preparation and run-time, before results are available.

Once some basic work for a given project has been carried out, sensitivity analysis and re-calculation based on new, or updated information, can be more quickly performed. Numerical 3-dimensional modelling is normally so demanding that only mainframe computers can cope with such tasks.

2.2 Evaluation of empiric and calculation design methods

Empirical methods for the design of rock support can be used as a design tool by classifying the rock immediately upon exposure. The classification system's recommended rock support can then be installed. This approach takes care of the variation in rock quality as it is encountered and is not dependent upon presumptions concerning rock quality. The Q-method developed by the Norwegian Geotechnical Institute (Dr. Nick Barton et. al.) is probably the best-established method of this kind.

Calculation methods on the other hand are generally too slow to cope with tunnelling progress and the frequent variation in rock quality. Sampling, testing and calculations for a given situation in the tunnel, would take days. Obviously, the immediate tunnel support is generally working very well and face advance cannot wait for completion of these steps.

In the case of a more specific location like a cavern for a powerhouse, railway station, etc., calculations can be very useful and can more easily fit into the job site progress. The basic limitation that all input data, formulas and numerical models contain a lot of uncertainties and approximations does still remain. The accuracy of results is therefore questionable and it is hard to tell when and where that will be the case.

A special feature of blasted rock surfaces is the extremely complicated geometry. A relatively thin (50 to 200 mm) layer of sprayed concrete cannot smoothen this contour into a defined arch geometry. The complicated interaction of ground response over time, compared to the sprayed concrete hydration and strength gain over time, variation in sprayed concrete thickness and variation in bond strength, also increase the complexity of any calculations.

2.3 The Observation Method

The Observation Method (OM) has been used since humanity started constructing tunnels and caverns. In the beginning, as well as today, this approach is being used out of common sense and sometimes bare necessity and it reflects the consequences of the above described Facts of Life.

The basic elements of the OM should be as outlined below:

- Rock support solutions must be designed for the range of expected rock conditions of the tunnel, each solution defined as a rock support prognosis. In this design work, any suitable empirical- and calculation method can be used, as considered necessary and useful.
- Verification of the support prognosis shall take place after excavation and installation of the support, by visual inspection, monitoring of deformations, stresses, loads, water pressure

and any other means as considered necessary. Adjusted or added support may become required locally, also subject to verification.
- The prognosis (installed support solution) shall be updated by feedback of data from previous steps, to decide about any need for design adjustments.

The advantages of the Observation Method are obvious. The mountain is being used as a full scale «laboratory», where known and unknown parameters are involved and covered. It allows a flexible work procedure, immediate action when necessary and support adapted to the locally encountered conditions. Normally, this gives more balanced and less costly solutions.

The Observation Method is today an accepted basic approach for support design in tunnelling, as given in e.g. Eurocode 7. The presentation above, is of course only a framework that needs a lot of detailed decision making in a real tunnelling case. It is still important to understand why this approach is the most reasonable way of making support design underground. The pre-designed solutions based on the normal structural design approach with codes and standards, as for steel and concrete structures like bridges and buildings, are simply not practically applicable.

In Eurocode 7, there are four requirements that shall be covered before construction is started:

1. The limits of rock mass and support behaviour, which are acceptable, shall be established.
2. The range of behaviour shall be evaluated and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits.
3. A plan of monitoring shall be devised which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage; and with sufficiently short intervals to allow contingency actions to be undertaken successfully. The response time on the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system.
4. A plan of contingency actions shall be devised which may be adopted if the monitoring reveals behaviour outside of the acceptable limits.

During construction the monitoring shall be carried out as planned and additional or replacement monitoring shall be undertaken if this becomes necessary. The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put in operation if this becomes necessary.

The very well-known New Austrian Tunnelling Method (NATM), is a procedure covered by the more general approach of the Observation Method.

2.4 Active mechanisms of sprayed concrete on rock

Also, when implementing the Observation Method for rock support, it is useful to understand why and how thin layers of sprayed concrete can have such an outstanding stabilizing effect. Such understanding is an important basis for evaluating combinations with other support measures and the limitations that may apply.

There are some important characteristics of the sprayed concrete application process which one should keep in mind:

- Concrete is blown against the rock surface at high velocity (20 to 100 m/s depending on spraying method and equipment).
- The rebound consists mainly of coarse particles. The amount of rebound is highest at first impact. At later stages of spraying, when semi-soft concrete covers the surface, more material will stick. The effect of this is an increase of fines directly on the rock surface.
- The placed concrete is compacted by impacts from the immediately following layers.
- The placed concrete layer will stick to the rock surface with a bond strength (adhesion) of up to 3 MPa (but typically about 1.0 MPa).
- The rock surface gets completely encapsulated.
- Fines are, to some extent, squeezed into open cracks and joints.

The stabilizing effects which can be identified as a result of the above characteristics, are:

- Mortar and fines get somewhat squeezed into open cracks and joints in the rock contour, producing a wedging effect similar to mortar between bricks in a wall or arch.
- Punching resistance, which means that a loose block of rock can only fall by shearing through the sprayed concrete layer, or by debonding sprayed concrete around the block edges
- Thin layers on a blasted rock surface will only create local arches between individual blocks
- Insulation against changes of moisture, effects of air and temperature, washing effect from running water etc.
- Extension of the stability that existed at the time of spraying concrete
- Simultaneous and combined effect of the above listed mechanisms

For thin sprayed concrete layers, it is obvious that the way it influences stability is much more like a rock reinforcement than a rock support. Along the rock surface there will be a composite action between the rock substrate and the hardening concrete. Practical experience shows that even a 30 mm thin sprayed concrete layer can be very effective in some situations. This observation clearly supports the basic idea of a composite action, since a fresh and limited strength “sprayed concrete membrane” cannot alone offer much support capacity.

2.5 Sprayed concrete on jointed hard rock

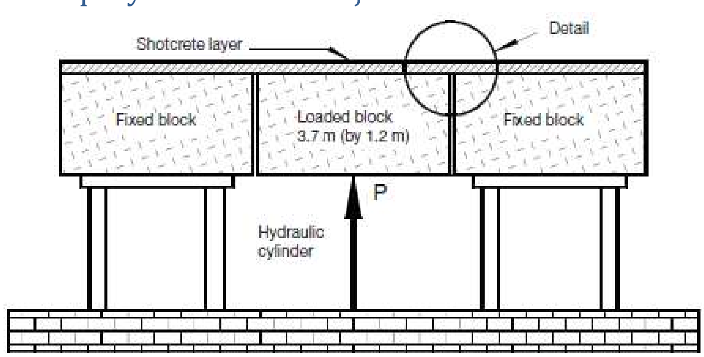


Fig. 3 Large test rig for sprayed concrete.

During the 70'ties and beginning of the 80'ties, a number of large-scale model tests were carried out in Scandinavia and North America. It is beyond the scope of this publication to present all these results. However, some tests and their results are considered very illustrating.

Dr. Jonas Holmgren in Sweden used a test rig as shown in Fig. 3. The sprayed concrete layer was flat (no arch effect) and concrete material was prevented from entering the opening between the blocks (no brick mortar effect in the "joints"). By varying the layer thickness of sprayed concrete and measuring loads and deformations, Dr. Holmgren was able to pinpoint some important effects.

Up to a layer thickness of about 30 mm, the moving block would simply punch through (shearing through) the sprayed concrete layer. This result is hardly a surprise and the load taken is directly linked to the shear strength of the sprayed concrete and its thickness.

For layer thicknesses above about 30 mm (basically irrespective of the thickness), the tests showed that the bond strength was decisive. The basic behaviour of the model is illustrated in Fig. 4 (refer to the detail on Fig. 4). For normal, sound granitic rock, back-analysis of the test results indicated that the width of the loaded bond zone at peak load, was about 30 mm.

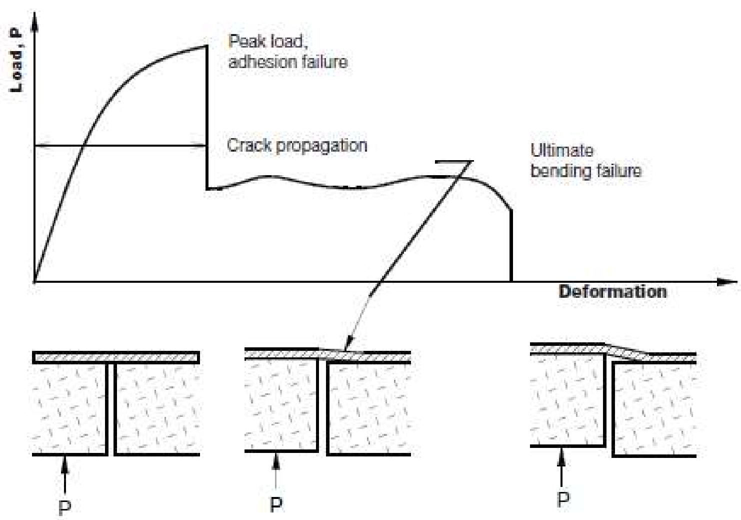


Fig. 4 Bond failure of planar sprayed concrete layer (not to scale)

For a normal bond strength of 1.0 MPa, the above results can be used for an illustrative calculation:

- Volume weight of rock set to: $\gamma = 27000\ N/m^3$
- A cubic block of rock is chosen, with edge length: λ m
- Bond strength as mentioned above: $\tau = 1.0\ MPa = 10^6\ N/m^2$
- Bond zone width at peak load: $\beta = 0.03$ m (as found by Dr. Holmgren)

Driving force is the weight of the block: $\mathbf{W = \gamma\lambda^3}$

Resisting force is created by the sprayed concrete bond along the four block edges over to the stable side-rock: $\mathbf{F = 4\lambda\beta\tau}$

At peak load, the driving force equals the resisting force and we may calculate the maximum theoretical block size, that can be held by the bond strength alone:

$$\lambda = \sqrt{4\beta\tau/\gamma} = \sqrt{4{*}0.03{*}10^6/27000} = \mathbf{2.11\ m}$$

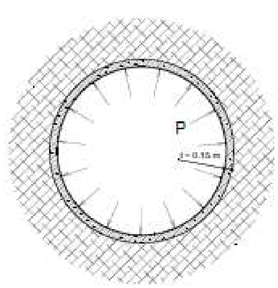
Expressed in terms of volume and weight, a block of more than 9 m^3, weighing 25 tons, could be kept in place. The effects of local arching, brick mortar effect and shear resistance along joint surfaces within rock, have *not* been considered. Obviously, this calculation is just an example to illustrate an order of magnitude and should not be taken as a statement that 35 mm of sprayed concrete would be sufficient support to safely secure such a block.

2.6 Sprayed concrete on soft or crushed rock

In many cases it is not possible or correct to envisage single blocks and wedges, locked in place by a thin layer of sprayed concrete. When tunnelling is carried out in generally crushed and weak materials, experience again still shows a remarkable short-term effect of stabilization, even with thin layers. In such situations the block and wedge theory and support mechanisms are not applicable. It is a bit more complicated to illustrate why and how it works under these conditions.

The most obvious reason for the immediate and short-term effect is the extension of existing stability at time of spraying. Sprayed concrete produces a skin effect on the rock surface, preventing to a great extent differential movements in the contour. An inward deformation (convergence) will take place more generally and evenly, not as local, differential stepwise deformations. As the contour moves inwards, the length of the contour tends to decrease, which means compressive forces in the rock/sprayed concrete composite. In this way the sprayed concrete is helping the rock material to carry itself. Again, we are looking at a reinforcement effect, rather than a load support. For this process to take place, the sprayed concrete shell needs to be of reasonable compressive strength with a good bond to the rock surface.

If the relation between rock stresses and rock strength does not allow a thin-layer, composite-action support solution, a structural sprayed or cast concrete ring may become necessary. The example of a TBM tunnel with a full, circular sprayed concrete lining is given in Fig. 5. In this case, the arch effect can be calculated and the bond strength is no longer the primary factor.



Shotcrete compr. strength	$\sigma_c = 35$ MPa
Thickness of shotcrete	$t_c = 0.15$ m
Tunnel radius	$R_i = 2.0$ m
Radially distributed load	$P = ?$

Maximum support pressure:

$$P = \frac{1}{2}\,\sigma_c \left[1 - \frac{(R_i - t_c)^2}{R_i^2}\right]$$

$$= \mathbf{2.53\ MPa = 253\ t/m^2}$$

Fig. 5 Circular lining subjected to uniform radial load.

2.7 Basic rock mechanics

Excavating a tunnel will initiate changes in the stress field around the opening. If the stress is high enough and/or the rock is weak enough, the surrounding rock will move slowly into the free space (in addition to the small effect of elastic relaxation). This inward radial deformation (convergence) may be controlled and stopped by support measures, or it may continue until a broken zone of rock collapses into the tunnel.

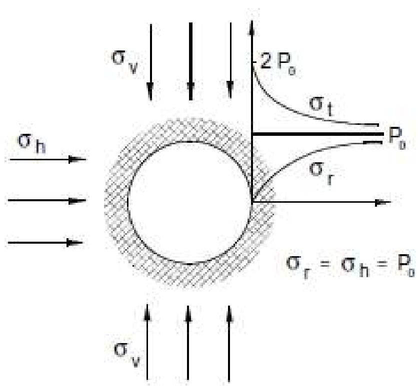


Fig. 6 Stress situation before excavation.

Fig. 6 shows a circular tunnel in a stress field where $\sigma_h = \sigma_v = P_0$. The radial stress σ_r and the tangential stress σ_t just before excavation are also shown. The rock material is considered elastic.

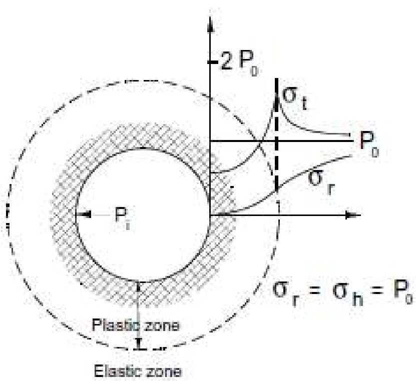


Fig. 7 Development of crushed, plastic zone after excavation.

A short time after excavation, the stress situation will have changed and if the rock is weak enough, a crushed zone will develop as shown in Fig. 7. The radial deformation resulting from such crushing (plastic deformation) is also termed squeezing. In this simplified case the plastic zone is circular and concentric to the tunnel. If some support is established, the Pi of the figure represents the support pressure against the rock surface.

The magnitude of deformation and the thickness of the plastic zone depend on the inner friction and other strength parameters of the rock material. The stress magnitude is also an important factor.

When designing the rock support necessary to limit and stop deformation, the ground reaction curve and the support response curves are useful. This is a different way of illustrating what is happening, from what is shown in Figures 6 and 7. A ground reaction curve is shown in Fig. 8. This is an idealised load/deformation curve, describing the radial deformation depending on the support pressure. The ground reaction curve expresses the necessary support pressure to balance the load and stop further deformation. Line no 3 in Fig. 8 shows a case where the rock is overloaded and a plastic zone is created.

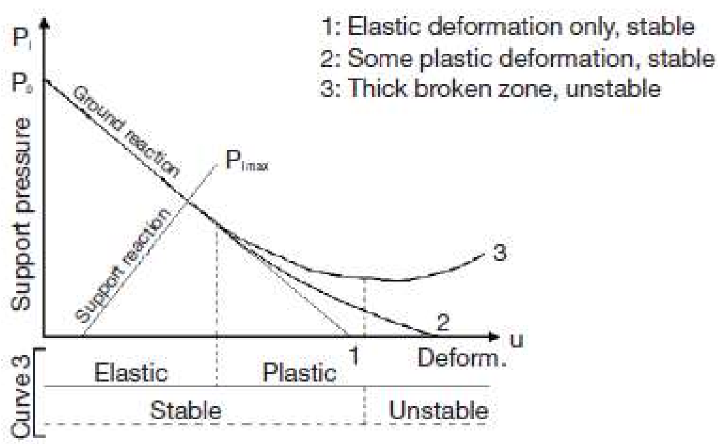


Fig. 8 Ground reaction after excavation and installed support load reaction.

In the elastic part the load decreases when deformation is allowed to take place. At a low stress situation, the straight elastic line could continue to zero load, as shown by the broken line no 1. In this case, no support would be necessary.

At a slightly higher stress level a thin plastic zone would develop, indicated by the broken line no 2. If the stress level is high, we may follow the solid line no 3. The reason for the load increase is the weight of the broken material in the plastic zone of the roof. This gravity effect does not apply to walls and floor.

Installed support measures will be loaded by the rock deformation along a given response curve. Figure 8 illustrates that the support has been installed after some initial deformation has already occurred. The maximum load and deformation capacity of the support is also shown. The intersection point between ground- and support reaction curves defines the final support load and the total rock deformation.

The diagram illustrates the combined effect and interaction between the rock itself and installed support measures. It is important that support measures be installed at the right time, with high enough load capacity and with the correct stiffness.

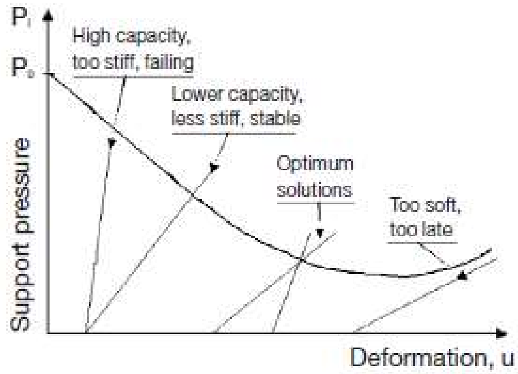


Fig. 9 Various support reaction curves and times of installation.

Figure 9 shows some support characteristics which illustrate the principles. A strong and stiff support may be overloaded and fail, while a weaker and more ductile support stops the deformation at a lower load, without failing. It is also possible that the stiff support works well, if not installed too early. The focus should be on optimising the support, which means letting the rock material carry as much of the load as possible.

2.8 Some points on NATM

NATM can be classified as an Observational Method. This becomes evident through the practical steps normally performed when using NATM:

- Collection of geological data, rock mechanics data and processing of this information in combination with tunnel dimensions etc. Processing means producing a load and deformation prognosis for a set of rock quality cases, covering the tunnel alignment. Any calculation tool which is regarded as helpful and necessary may be used in the prognosis development.
- A preliminary support plan is produced based on the previous step. Thickness of sprayed concrete, number, length and strength of rock bolts, type and spacing of ribs etc., is part of this plan. Prognosis of deformation speed and magnitude for different situations is important information in order to decide on the excavation/support sequence and the interpretation of monitoring data.
- The tunnel excavation proceeds according to the preliminary plan with necessary adjustments for observed rock quality.
- Monitoring instrument sections are installed at intervals in the excavated tunnel. These may include extensometers, convergence measurement bolts, load cells in the lining, load cells on rock bolts etc. The behaviour of the support members and the combined system of rock and support shall be monitored according to a pre-set plan.
- The final support is decided after monitoring the tunnel for a sufficient time. Depending on the design requirements and philosophy, this might give no additional support or in some cases a full concrete lining.

The NATM philosophy aims at allowing a controlled deformation to take place, so that the support system carries a load as small as possible. In practical terms this will normally lead to using sprayed concrete as a first support measure. Normal thickness may vary between 50 and 300 mm. It is normal that also sprayed concrete reinforcement (wire mesh or steel fibres) and rock bolts are used. In weak rock and/or in tunnels of more than 50 m^2 light steel ribs or lattice girders are frequently mounted.

One sometimes very important detail in the NATM application is the closed ring support. As can be easily understood, a closed ring of anchored sprayed concrete support is a lot stiffer than a horse shoe shape. The total load capacity is also higher. The same applies to all kinds of rib support. Again, the timing of such a ring closure against deformation speed and magnitude, is very important.

This discussion of mechanisms and principles of sprayed concrete for rock support is only a brief illustration of a very wide and complex subject. Regardless of which name tag (Q-method, NATM, RMR etc.) the designer will use for a chosen set of principles and procedures, it is recommended to use the general principles of the Observation Method.

In urban areas, tunnelling often means very shallow excavation depths with severe consequences in cases of failure. It may therefore be necessary and reasonable to shift the design focus in the direction of pre-decided support solutions, with less or no emphasis on load transfer to the ground itself. In many cities the ground conditions are well known in advance and will often consist of some type of soil rather than rock and rather than allowing deformations, the target will be prevention.

2.9 Important properties of sprayed concrete for rock support

The relative importance of different material parameters for sprayed concrete depends on the type of stability problem. Thin layers applied to hard rock to prevent loose fragments and wedges from falling out, depend mostly on adhesion. The compressive strength in such a case is of minor importance. The compressive strength, on the other hand, is the main factor when a thick closed ring support in soft ground is considered. In this situation the adhesion is of close to no interest at all.

Compressive strength can be used as an indirect indication of durability factors. The concrete shall be of satisfactory long-term durability in the environment where it is applied. There may be a difference between a road tunnel with heavy traffic and a water transport tunnel in this respect. In most cases the sprayed concrete must meet a 35 MPa strength class according to a normal national standard test procedure. In Norwegian sub-sea road tunnels this requirement is now a grade 45 MPa concrete.

Adhesion to the rock surface is generally an important parameter. The problem is that it is complicated to measure it accurately and it may vary a lot within short distances. Often people are reluctant to specify the required adhesion in a contract, because the control results may cause formal and contractual problems. For routine construction control, the primary focus on compressive strength is a good starting point, followed by careful checking of correct application technique and cleaning of the surface in advance. In this way, the best possible adhesion that the surface allows, can be achieved.

The tensile strength of sprayed concrete is not so important. In design considerations this strength parameter cannot be included anyway, because there is always a chance of shrinkage cracks in critical sections. Across a crack there is naturally no tensile strength. The same applies to the flexural strength of the sprayed concrete.

It is important that the required compressive strength is achieved by a mix design that gives a lowest possible shrinkage. There are two reasons for this:

- Low shrinkage improves adhesion.
- Low shrinkage reduces cracking and improves durability.

To produce low shrinkage, the content of fines and cement should be low, the w/c ratio should be low (generally less than 0.45) and application technique must be correct (good compaction and spraying at right angles). Shrinkage also depends on curing of the concrete, which is a subject mostly neglected for sprayed concrete execution and control.

The thickness of the sprayed concrete layer is a design question. The contractor shall distribute the necessary concrete volume to meet the requirement as closely as possible. This is a practical problem, especially if the specified thickness is large (200 mm and more) and the full thickness is placed on a limited area during one operation. Under such circumstances the tendency is that the walls get more concrete than required and, of course, the roof gets less. This is the opposite of what is wanted, from a stability point of view.

This leads to a very important parameter in sprayed concrete application, the short-term strength development. Safety and economy are improved if the strength gain within the first minutes and hours is high. High early strength is possible when using accelerators. Economy is improved to a maximum if it is possible to build full thickness in one continuous operation, even on a limited area.

3 Design and execution of the Gjøvik Olympic Cavern

Observation Method (or a approach)

Design by observational method (approach) is based on a preliminary design that is reviewed or revised during construction (with planned measures).

- **Ground model** This should be based on most probable conditions of the site and most unfavorable deviations from these conditions should also be defined
- Design for the most probable conditions
- Sensitivity analyses to established critical material properties and geometrical deviations
- Then limits for acceptable behavior of the structure should be established
- Contingency actions should be established (for deviations)
- Limits for alarm and actions
- During execution: Monitoring Observation
- Final structure

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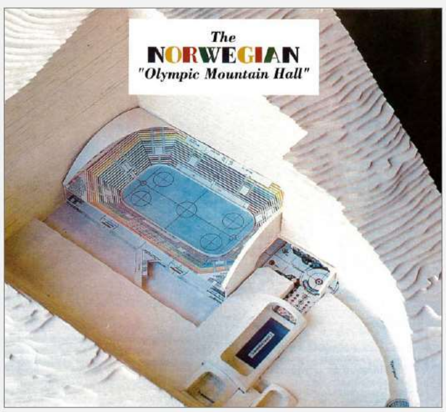
The Gjøvik Olympic cavern

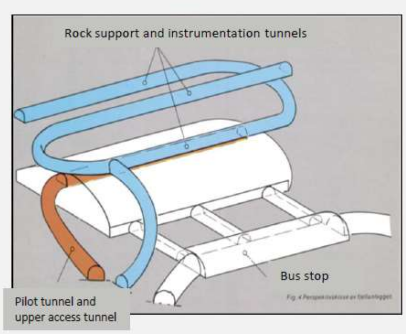


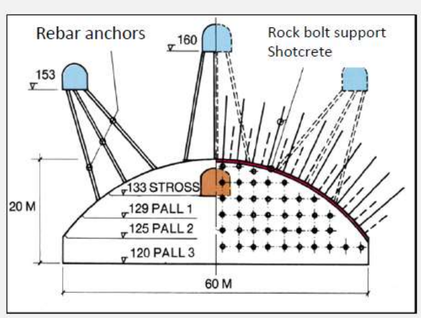
NGI Book: Gjøvik Olympic Mountain Hall

- Winter Olympic games 1994
- Ice hockey hall in rock cavern
- First sketches 1989
- 62x90x25 m cavern
- Experience from earlier planned projects

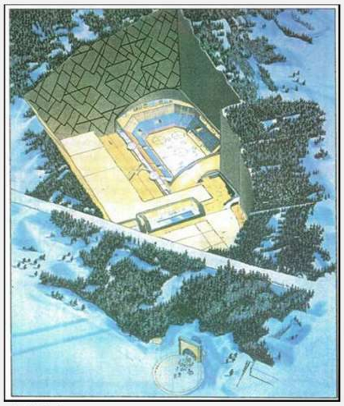
Start of development project for large rock cavern in Norway

- Feasibility of underground siting for nuclear power plants, 1970s
- In the late 70s, the Liåsen development project was performed

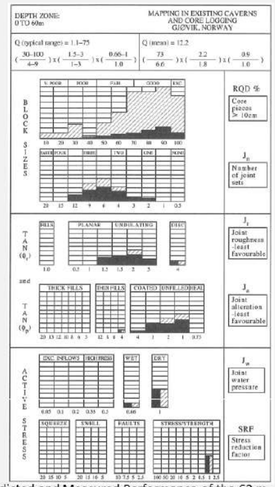




The Gjøvik Olympic cavern



- Feasibility phase (I) 1991 – cavern and tunnel mapping, rock mass classification, UDEC-BB
- Phase (II) – four core holes, rock mass classification, cross-holes seismic tomography, rock stress measurements, UDEC-BB
- Phase (III) – field mapping, measuring of deformation, UDEC-BB



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(Barton *et al.*, Predicted and Measured Performance of the 62 m Span Norwegian Olympic Ice Hockey Cavern at Gjøvik. 1994)

Phase (I) (feasibility-study)

Rockmass mapping at a:
- Nearby swimming pool cavern, finished 1974
- Parallel cavern housing the changing rooms
- Telephone Exchange cavern
- Tunnels
- Over-coring stress measurements, σ_H = 4 MPa with an E-W orientation

A first simple UDEC-BB with K_0 = 0.5, 1.0 and 3.0 (σ_H/σ_v):
- Maximum 19.2 mm de deformation with low K_0

- Precambrian gneiss
- 2-3 joint sets
- Many short, irregular joints
- Irregular jointing, moderate to rough walled joints, quite large variation in dip and strike
- No clay filling
- Foliation, poorly developed, strikes app. E-W with a dip of 35 to 55°
- 25 to 50 m rock cover
- Typical rock mass quality; Q = 30

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Phase (II)

Rockmass mapping at a:
- Four core holes (50-70 m)
- Rock Mass Classification
- Cross-hole Seismic Tomography
- Rock Stress Measurements
- Modelling UDEC-BB

A first simple UDEC-BB with K_0 = 0.5, 1.0 and 3.0 (σ_H/σ_v):
- Maximum 19.2 mm de deformation with low K_0

- Precambrian gneiss
- Five different joint sets, described as sporadic
- Most typical dips was 50-65° and some 40-45°
- Many short, irregular joints
- Irregular jointing, moderate to rough walled joints, quite large variation in dip and strike
- No clay filling
- Foliation, poorly developed, strikes app. E-W with a dip of 35 to 55°
- 25 to 50 m rock cover
- Weighted average; Q = 12.2
- Typical best Q = 30 and typical poorest Q = 1.1

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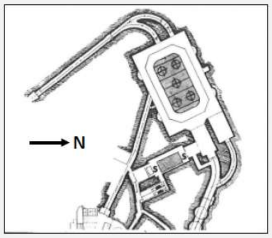
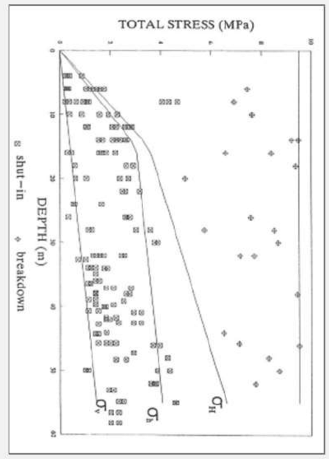
Phase (II)

- Rock stress measuring using hydraulic fracturing and Joint Jacking-shut-in. Some lower σ_h = 3.5 MPa, but oriented N-S





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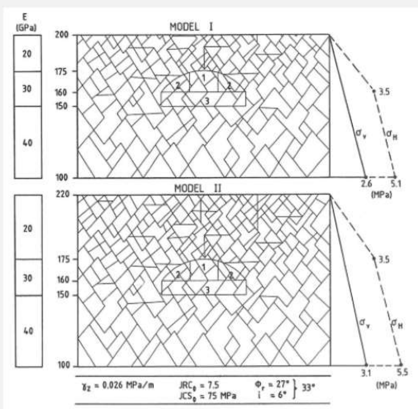
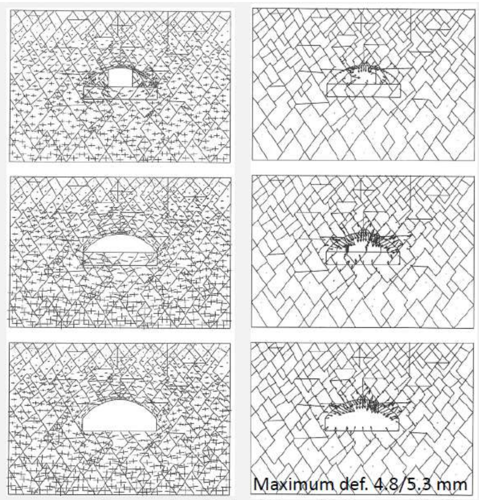
(Barton *et al.*, Predicted and Measured Performance of the 62 m Span Norwegian Olympic Ice Hockey Cavern at Gjøvik. 1994)

UDEC-BB model



25 m and 45 m overburden



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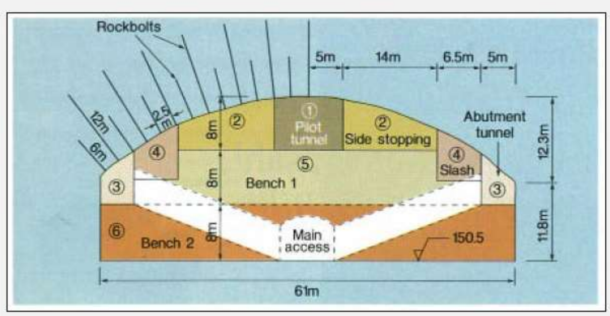
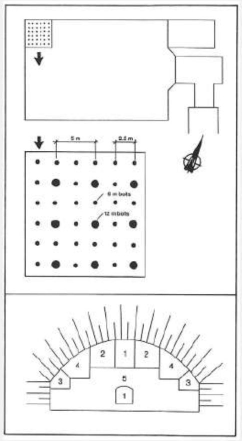
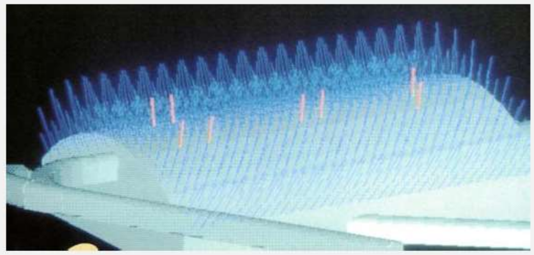
(Barton *et al.*, Predicted and Measured Performance of the 62 m Span Norwegian Olympic Ice Hockey Cavern at Gjøvik. 1994)

Excavation sequences



Rock support





- 5 m and 6 m rebar bolts (dia. 25 mm) fully grouted
- 10 and 12 m twin-stranded cable bolts, fully grouted
- 5 + 5 cm steel fibre reinforced shotcrete

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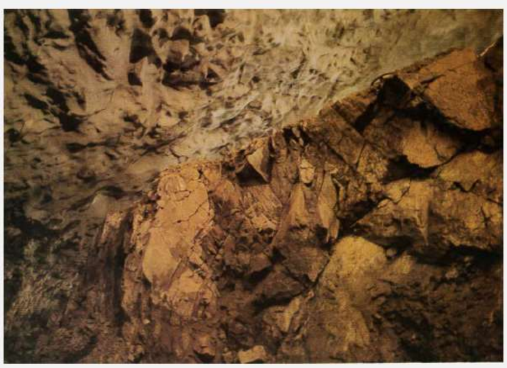
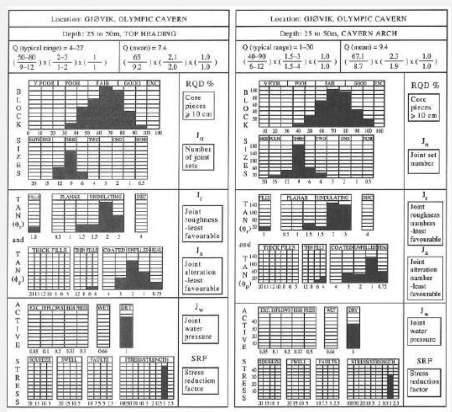
Mapping of rock mass





Design values

- $Q_{average}$ = 12.2
- Q_{best} = 30
- $Q_{poorest}$ = 1.1

(Barton *et al.*, Predicted and Measured Performance of the 62 m Span Norwegian Olympic Ice Hockey Cavern at Gjøvik. 1994)

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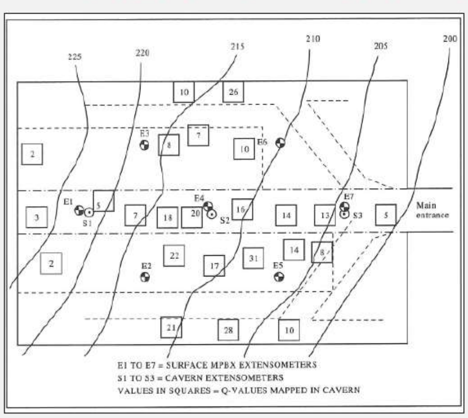
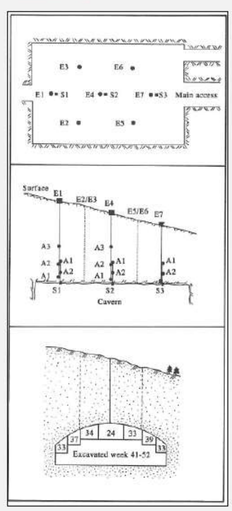
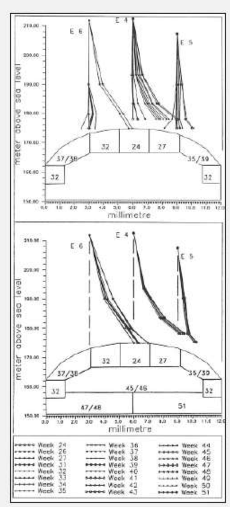
Location of instrumentation







(Barton *et al.*, Predicted and Measured Performance of the 62 m Span Norwegian Olympic Ice Hockey Cavern at Gjøvik. 1994)

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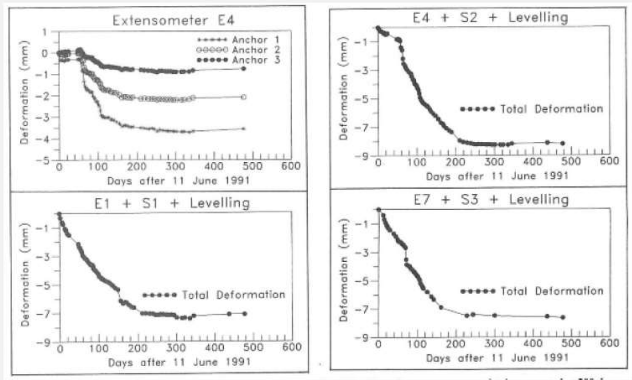
Deformation results along centre-line



UDEC-BB

- Phase (I) 19.2 mm
- Phase (II) 5 mm
- Phase (III) 8 mm

(Barton *et al.*, Predicted and Measured Performance of the 62 m Span Norwegian Olympic Ice Hockey Cavern at Gjøvik. 1994)

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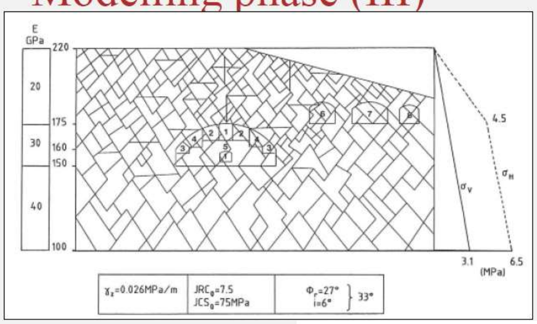
Modelling phase (III)



(Barton *et al.*, Predicted and Measured Performance of the 62 m Span Norwegian Olympic Ice Hockey Cavern at Gjøvik. 1994)

Table 5. Summary of Phase III Gjøvik Ice Hockey Cavern modelling (with Postal Service caverns as steps 6, 7 and 8 of excavation)

	Olympic cavern					Postal caverns		
Modelled parameter	Step 1	Step 2	Step 3	Step 4	Step 5	Excav. of 1st cavern	Excav. of 2nd cavern	Excav. of 3rd cavern
Max. stress (MPa)	9.29	11.5	9.91	8.39	8.37	8.56	8.71	8.83
Displacements (mm)								
• maximum	1.85	1.80	2.63	6.99	8.16	8.28	8.43	8.65
• wall	—	—	—	1.33	3.78	3.88	3.92	3.97
• crown (vertical component)	0.50	1.08	2.62	4.05	4.33	4.39	4.87	7.01

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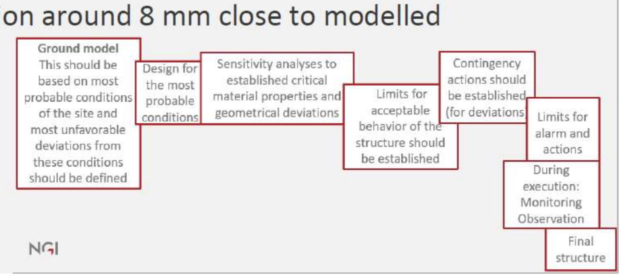
Summary

- Precambrian gneiss with favourable jointing
- High normal stresses
- Rock mass classification value Q decreased from 30 to 8-10 in the different phases (I to III)
- Measured deformation around 8 mm close to modelled deformation



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4 Spraying equipment

4.1 Introduction

Wet-mix equipment delivers almost all the sprayed concrete volume currently being used for rock support underground. However, the dry-mix method has an important role where it offers clear advantages. The wet-mix method cannot be used in cases of no access for any equipment and/or where concrete must be supplied to the nozzle through very long delivery hoses. Special cases like this are not covered here and only normal wet-mix applications are discussed below.

4.2 Development of the wet-mix equipment

At the start of wet-mix application in the 70'ies, a set-up for start of spraying involved bringing in position a number of separate equipment units:

1. The concrete pump
2. Tank for accelerator with supply pump
3. Often a separate compressor for spraying air
4. Flood-lights on stands (2-3 units)
5. Working platform for the operator of the manually handled nozzle for any tunnel higher than about 3 m, or a separate hydraulic nozzle manipulator (robot)
6. Connections, cables, hoses for supply of electricity, compressed air and accelerator and the concrete hose between pump and nozzle

When all was properly arranged, the concrete truck would deliver concrete to the pump and spraying could be started. As soon as there would be a need for moving the equipment to cover a new application area, even a short move would easily cost an hour or two.

From the above situation, typically operating at low pump output of plain concrete (say 5 to 10 m^3/h), during the next about one decade, the integrated sprayed concrete units were developed. All of the above listed functions were built into one truck-mounted unit which would need hook-up to electricity only. See Fig. XX. The concrete output jumped to 10 to 25 m^3/h of pumping and mostly with the reinforcement included in the concrete mix (with structural fibres). Accelerator would be automatically and accurately dosed regardless of concrete pump output and set-up and moves would only take minutes. The overall efficiency effect was dramatic and the cost of sprayed concrete in place dropped to less than 50% at a fixed value basis.

Fig. 10 Integrated sprayed concrete robot units (courtesy of Andersen Mek Verksted AS)

The use of integrated units as shown in Fig. XX had significant effect on quality of the sprayed concrete and the most important factors are:

- The concrete delivery hose diameter increased from typically 50 mm to 64 mm and partly 100 mm, allowing optimization of concrete mix design with more sand and aggregate as well as structural fibres for reinforcement. The hydraulic manipulator (robot) was the key in this respect, since manual nozzle handling would otherwise be impossible.
- The sprayed concrete nozzle design was improved to provide better mixing and distribution of accelerator into the air stream and the concrete, while the spraying jet speed and delivery distance increased. Nozzle wear resistance and ease of cleaning also improved greatly.
- Dosage of accelerator as percentage of cement weight in the concrete became electronically controlled and easily adjustable to conditions. This is important both for quality control and cost of sprayed concrete in place.
- Proper amount of spraying air (also at high concrete output) became possible, ensuring well compacted placed concrete, while furthermore reducing concrete rebound.
- Excellent work area lighting and good viewing angles for the operator, made it much easier to ensure concrete jet direction perpendicular to the rock surface, which again is crucial for compaction, low rebound and final quality.
- The hydraulic robot allows the operator to move the nozzle and application area around on the section being sprayed to avoid too fast build-up of large thickness that may cause concrete fall-down (sloughing). It also allows accelerator dosage to be kept at a minimum.
- Pre-wetting of the substrate and proper washing away of dust and grime using water and compressed air through the sprayed concrete nozzle became highly efficient. This is very important for good adhesion to rock or previous layer of sprayed concrete.

As a “free” bonus, the remote control of sprayed concrete placement means that nobody needs to venture under unsupported rock, which in case of serious weakness zones has significant benefit of improved safety.

It should be noted that high quality sprayed concrete cannot be produced by just using any high-output piston pump. Most pumps will show a far too long stop of concrete flow when change-over between cylinders takes place. During such a break in concrete flow, compressed air and accelerator will *not* stop, causing a local spray of pure accelerator. This effect will result in over-consumption of accelerator and layering in the placed concrete.

5 Cost saving lining approach for D&B in hard rock

5.1 Introduction

For many tunnelling projects the approach to lining concepts is linked to tradition, conservatism and lack of overview and analysis. The current status may also illustrate an element of fear of responsibility for changes *perceived* as risky among the parties involved. New approaches may increase the risk of getting blamed or made economically responsible if results are not as expected.

The tunnel lining is first and foremost viewed as necessary for rock support and stability. This is the case both during excavation (immediate support) and even more so for the permanent operation stage. Still, there are many other functions that must be considered, like control of ground water ingress, prevention of environmental effects in the surroundings, humidity and drip control in the tunnel and requirements that depend on the location and type of tunnel or cavern. In any case, project economy including life-time overall economy is very important and should probably be given more focus than what seems to typically be the case.

The problem of economy is that when design principles are pre-fixed, economy can only be influenced by efficiency during execution of construction and later during operation of the tunnel. However, if analysis is started *before* anything is fixed, much larger potential savings may be identified and possibly implemented.

All the steps of potential cost saving project execution outlined below will not be possible for all kinds of projects but will still illustrate why it makes sense to do the analysis. It should be possible to agree that if quality and functionality can be maintained at a substantial cost reduction, then some limited level of perceived risk would be acceptable. If the risk may even be mitigated (if necessary) at much lower cost than the additional cost of a more traditional and conservative solution, then it should be a no-brainer approach.

5.2 Favourable project requirements for an alternative solution

- Drill and blast tunnelling in hard rock
- Environmental restrictions require limitation of ground water ingress to tunnel both during construction and after commissioning
- Partially drained lining is acceptable
- Free water on lining surface, or drips from the roof not acceptable after commissioning
- No frost protection required
- Operation lifetime requirement for the lining is 100 years

5.2.1 Frequently used conservative solution

- Immediate support for most of the tunnel length by rock bolts and sprayed concrete
- Water ingress during construction is taken care of by gravity drainage and/or by pumping, but this may easily violate environmental protection requirements during construction stage
- Permanent lining by in-situ concrete with a polymer sheet membrane on the rock side. Before mounting the membrane, depressions in the profile must be evened out by spraying concrete as “dental filling”. Rock bolt ends may have to be cut and covered by sprayed concrete. Then a geotextile fleece must be installed for protection of the sheet membrane. Finally, after hanging the membrane, joints must be welded (often double welds) and tested by compressed air.
- The theoretical minimum thickness of concrete lining is typically 300 mm, but overbreak caused by drill and blast, not filled by temporary support sprayed concrete, will be backfilled by extra in-situ concrete. The overall concrete thickness (temporary sprayed concrete and in-situ concrete lining) will typically be between 2X and 3X the minimum theoretical thickness of 300 mm
- Because of normal experience that leaks through the membrane will occur and to make it easier to mitigate resulting drip problems, short compartments of membrane protection may be established (every 10 m or so). The point is that an observed leakage location will

not coincide with where the leakage in the membrane is. Repair without making compartments may therefore become very difficult and time consuming.

If water ingress during construction must be limited, there would be a requirement to execute probe drilling ahead of the face to identify too high leakage locations. In case too much water is encountered in probe holes, pre-excavation grouting (PEG) would have to be executed. It must be noted that the later installation of a polymer sheet membrane, even if also covering the invert (sub-marine undrained solution) would *not* solve the ingress problem during the construction stage.

Depending on the risk level and the targeted maximum allowable water ingress, execution of PEG could be just occasional and along a small part of the tunnel, or in stricter and more difficult cases require PEG practically all the tunnel length. There are examples of ingress requirements of < 10 L/min/100 m of tunnel causing extensive full-length PEG, followed by sub-marine membrane solution and in-situ concrete lining, which in sum represents many different processes and unique work steps, high overall quantity of concrete and resulting long construction time. No doubt, the overall cost will reflect these aspects of such a decided solution.

5.2.2 Alternative cost-saving strategy

The savings potential will depend on how many of the above listed presumed requirements that apply, but starting with execution of ground water control, pre-decided probe drilling and some level of ingress cut-off may pay off even if *not* required by contract or specification. The point is that too much water in a tunnel will quickly represent practical problems and slow down of all operations both during construction and after commissioning. If the tunnel is located in very favourable and dry ground, probe drilling and possibly some PEG may not make much of a difference, but it is typically not possible to know in advance. On the other hand, in very wet ground, the cost of PEG may be well worth the effort because of advantages during later construction steps.

If a decision is made to use combined immediate and permanent support based on rock bolts and sprayed concrete, proper ground water ingress control will create very good conditions for execution of support works and the use of drip prevention by spray-on membrane. To describe the alternative solution under a set of favourable circumstances and requirements, the steps may be shortly listed as follows:

- Probe drilling and PEG is required due to strict environmental limitations on maximum allowed water ingress to the tunnel, valid also during construction. Limit specified: < 10 L/min/100 m of tunnel. Such a limit will produce a practically dry tunnel (visual impression) with just some humid spots in the applied sprayed concrete and occasional drips from the roof.
- Immediate support using combination rock bolts (expansion shell anchorage, hot dip galvanized and epoxy powder coated with system for getting fully grouted to satisfy 100 years life span) and fibre reinforced sprayed concrete, also satisfying permanent lining quality requirements. Spiling rock bolts, pipe umbrella, reinforced sprayed concrete ribs, lattice girders and other special measures to be used where needed depending on local ground conditions.

- Design of final support to be based on the Observation Method (OM), where observation means monitoring of radial deformations as needed and with combination of devices (extensometers, convergence measuring sections, load cells etc.) as required.
- The final lining supplementary spraying of concrete, possibly with additional rock bolts or other measures to be decided and executed based on pre-design compared with monitoring results, which for a major part of hard rock tunnels will typically require total sprayed concrete thickness of 100 to 200 mm thickness (rather than closer to 1000 mm of concrete for the traditional approach).
- Humidity and drip control by spray on membrane (typically horse-shoe protection with open invert) will require its own detailed planning and the first step will be temporary drainage of local drips and other leakage points. Drilling of short 10-15 mm diameter bore holes for insertion of open packers where free water and drips through the sprayed concrete occur, must be executed. Application of spray-on membrane is next step, using the sprayed concrete robot, allowing 100 to 200 m^2 finished per hour of spraying. Then the packers can be grouted to seal off the ingress points and the protective cover layer of sprayed concrete can be applied to finish the process.

  Note that the designer may include the cover layer of sprayed concrete and the membrane as part of the final lining structure, considering the total thickness of concrete as one monolithic composite member. If preferred or required, application of membrane and the sprayed concrete cover layer of 30 mm may alternatively be a last step *after* the permanent lining is in place, only considered as drip protection.

The adaptability to varying rock conditions along the tunnel and use of the OM will prevent the installation of an over-conservative support solution for the whole tunnel, that must take care of the poorest ground conditions encountered in the tunnel. If 90% of the tunnel is passing good and medium quality ground, there is no good reason to use the same support required in the poorest 10% for the full length of the tunnel.

The above outlined approach will save substantial construction time on top of drastically reduced quantities of concrete. The savings potential is primarily linked to the reduced construction time, since time-related cost is the dominating part of overall cost. In today’s world, with increasing focus on the carbon footprint of human activity, reduction of cement-consumption by more than 50% is an important bonus and major improvement in this respect and not just a cost factor.

6 Use of spray applied water proofing membranes

The International Tunnelling Association has published the report “Design Guidance for Spray Applied Waterproofing Membranes” through its ITAtech Activity Group, Lining and Waterproofing. The report was issued in April 2013 and should be read in its entirety by anybody considering the use of the technology and it is recommended to furthermore look for updated information in this rapidly developing field. For the benefit of convenience, selected parts of the report have been copied below.

6.1 Introduction

There are different types of spray applied waterproofing membranes. They may be produced by means of non-reactive systems (curing by hydration or air-drying), or reactive systems (curing by polymer reaction). Typical and final thickness will be about 3 to 4 mm.

Spray applied waterproofing membranes are produced and installed in situ against the primary tunnel lining and typically covered later on by a secondary tunnel lining or a non-structural protective layer (e.g. mortar or sprayed concrete) according to the design requirements.

Generally, the membrane can be applied in one stage directly onto the concrete lining or substrate. Some membranes require first the application of a primer layer before application of the membrane in one or two consecutive layers.

When installed between the primary and secondary concrete linings, spray applied membranes may bond to both primary and secondary linings (double-bonding) or only to one lining (single-bonding), depending on the design requirements and the product chosen. In the case of a spray applied membrane with double bonding properties, the resulting sandwich-structure (concrete-membrane-concrete) may act as a quasi-monolithic structure, depending on the bonding characteristics and properties of the membrane.

Many tunnels, cross-passages, stations and shafts have been successfully completed using spray applied waterproofing systems over the last years, under quite different conditions and design requirements. The use of spray applied waterproofing membranes is not the panacea for all waterproofing requirements for sprayed concrete tunnels, but it does offer a viable solution for a specific window of ground and hydrological conditions that are quite regularly found on tunnelling projects.

6.2 Important features

Spray applied waterproofing can offer benefits in geometrically complex areas such as lay-by niches, cross passages, rail tunnel turn-outs and crossover caverns, where installation of conventional waterproofing membranes is inherently difficult and testing or locating of possible leaks can be challenging.

Spray applied membranes lend themselves to the use of sprayed concrete secondary linings, as they negate the need for customised shutters traditionally used for cast-in-situ linings to line these complex shapes and junctions. They also do not require mesh to allow the build-up of sprayed concrete on a non-rigid substrate such as with the use of a sheet waterproofing membrane.

A key feature of spray applied waterproofing membranes is their simple application by means of equipment often already available on site for sprayed concrete application, thus freeing up time and space for other activities. Typically, 50 – 100m^2/h can be manually sprayed by 3 operators. Robotic spraying can reach application rates up to 180m^2/h.

Spray-applied membranes can be applied to limited sections to provide isolated waterproofing, such as in the crown sections of tunnels, or as a continuous waterproofing system.

Further features of spray-applied waterproofing membranes are:

- *Continuity without discrete joints; confinement measures (injection, tubes, weld links, compartmentalisation with waterstops etc.) are not required as the bond between the membrane and the substrate prevents water paths developing between layers.*
- *Spray applied membranes do not have any welded seams and are simply connected by spraying a short overlap zone onto the previously applied membrane section.*
- *Easier and quicker location and repair of leaks. A seepage point through the membrane can be easily resolved locally precisely where the seepage occurs since this point corresponds to the seepage channel in the concrete behind the membrane.*
- *They can be combined with other waterproofing systems. Standard joint details between spray applied and sheet membranes are available, making the system totally flexible.*
- *They are compatible with all concrete placement techniques, allowing placement of a sprayed concrete inner lining, and reinforcement types (mesh, rebars and fibers) on either side of the membrane. The membrane can be sprayed straight onto many types of penetrating items (e.g. anchored reinforcement).*
- *There is no folding and stretching of the spray applied membrane during the casting or spraying of the secondary/permanent lining as it is in intimate contact and fully bonded to the primary lining*

The complete report covers a lot more than the above, like trials and testing, application requirements, quality control, training, design aspects and example specifications. Appendix D presents additionally eight very interesting case studies executed in eight different countries (N and S America, Europe, Far East and India). One of the cases from the report has been copied below for convenient access.

6.3 Gjevingåsen railway tunnel, Norway

Fig. 11 Finished lining water proof lining, Gjevingåsen, Norway.

6.3.1 Project details

The Gevingåsen single track horseshoe-shaped railway tunnel is 4 km long and was built between Hommelvik and Hell on the Nordland Line between the city Trondheim and the Trondheim airport. See Fig. qw. Prevailing ground conditions were hard rock with mica and green schist. Tunnel excavation was done by drill - and - blast method (30-100 m overburden). The tunnel was put into *operation by the Norwegian National Rail Administration in 2011. It reduces travel time by five minutes and has contributed to increased capacity from 5.4 to 8 trains per hour. Tunnel costs are about NOK 635 million (approx. EUR 86 million). This was the first full-scale use of a spray applied waterproofing system in a Nordic country.*

6.3.2 Design approach adopted

The tunnel lining consists of permanent sprayed concrete with a waterproofing layer in - between two concrete layers. Any groundwater approaching the finished tunnel is diverted through to the tunnel invert and channeled to a main pumping station. Following its successful application to a short section in 2009 and tests at SINTEF the spray applied waterproofing membrane MASTERSEAL 345 was installed with a thickness of 3 mm in the central part of the tunnel (45,000 m^2). Conventional waterproofing with PE-Foam insulation and drainage shield was used in the portal zones and in two zones with very high water ingress.

6.3.3 Application approach and control

MASTERSEAL 345 application was done by manual handheld nozzle, as described below:

1. *Installation of a smoothening layer onto the primary sprayed concrete lining (substrate)*
2. *Temporary drainage of seepage spots*
3. *Application of MASTERSEAL 345 in one pass*
4. *Inspection and eventual treatment of water seepage and membrane application*
5. *Installation of the secondary (inner) sprayed concrete lining onto the membrane.*

Quality control was done mainly by measuring the membrane curing status, achieved membrane thickness and coverage. Systematic inspection of the cured membrane surface was carried out before application of the secondary (inner) concrete lining.

6.3.4 Project benefits

The related project benefits include:

- *Faster installation of the waterproofing system, with reduced construction time.*
- *Reduced maintenance over service lifetime.*
- *Simple routine inspection of the final lining.*
- *No use of inflammable materials (no PE-Foam insulation), where the membrane was applied.*
- *Longer service lifetime than the originally tendered technical solution.*

7 Conclusions

Wet-mix sprayed concrete with added structural fibres applied by integrated robotic equipment is currently the clearly dominating placement method in drill and blast hard rock tunnelling world-wide. The reasons are many, both linked to high quality, placement efficiency and overall economy. However, the much more significant savings potential can only be achieved if sprayed concrete is used as one element in a package of changes compared with the currently dominating over-conservative approach.

Lining design based on the Observation Method (OM) allows adaptation of installed support elements to the varying actual local ground conditions along the tunnel, primarily by adjustments in bolt length and patterns, thickness of sprayed concrete, tailored use of spiling bolts, reinforced sprayed ribs, lattice girders and other special measures if and where needed. When installed immediate support has quality specifications and durability to also satisfy requirements for permanent support, obviously, both time and materials usage can be saved.

The Gjøvik Olympic Cavern, with its 60 m free span is presented above as just one of many existing examples of the approach outlined above (design by OM, immediate and permanent support by bolts and fibre reinforced sprayed concrete), using less than 20% of the concrete quantity of most traditional solutions. It should be noted that the cavern has now been in problem-free operation for 24 years.

To ensure that required concrete quality is sprayed and to achieve the best possible economy, integrated robotic equipment is necessary as well as proper use of modern concrete technology and controlled dosage of set accelerator. Such units are available in different sizes and layouts, for small and very large tunnel and cavern cross sections. To properly utilize this technology, well-trained operators are required and the concrete mix design must be fully pre-tested and verified.

For all tunnel projects, ground water conditions are typically one of the main uncertainties and for some projects, to keep ground water ingress within strict limits during construction as well as after, will be imperative. Such cases offer the ultimate savings potential by implementing the above design and support package, when also including probe drilling and pre-excavation grouting (PEG) and water proof spray-on membrane integrated into the sprayed concrete lining.

The traditional approach typically involves immediate support (disregarded at the permanent stage), installed sheet membrane requiring several complicated work operations and final lining in-situ concrete. All of this producing an average total concrete thickness of close to 1000 mm. It may still require full treatment by probe drilling and PEG. In such a case, the bolting and sprayed concrete solution with spray-on membrane will typically amount to less than 200 mm average concrete thickness and the whole solution is executed much faster than the traditional approach. The overall cost savings potential is significant.

The ITAtech Activity Group - Lining and Waterproofing has issued the document "Design guidance for spray applied waterproofing membranes", which provides necessary information about this evolving technology.

Norwegian Tunnelling Network

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