In-situ Rock Stress and Tunnel Stability

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Abstract

Stability and potential failure mode of tunnels and underground rock caverns are directly related to the magnitude and orientation of the in-situ rock stress. In some cases, the high horizontal in-situ stress is essential in maintaining cavern stability, whilst in other cases the high rock stress may bring forth additional difficulties in tunnel construction and rock support design. It is crucial to take into account the in-situ rock stress in designing of the shape and orientation of underground works and selecting of excavation methods and rock support. With a number of examples of real projects the paper describes the impact of the in-situ rock stress on the tunnel/cavern stability and corresponding rock support design. The hazardous effects resulting from spalling and rock burst associated with very high in-situ rock stress are addressed with the example of the world longest road tunnel – the Lærdal tunnel.

Keywords: In-situ Rock Stress,Tunnel, Rock Cavern, Stability, Rock Support

1. Introduction

Stress-induced instability is one of major concerns for the safe construction and operation of tunnels and caverns. This is true for both soft rocks and jointed hard rocks. Jointing controlled rock falls are also controlled by the stress condition in addition to the jointing geometry since the sufficiently high normal stress will prevent the rock block from falling even the geometry is not favourable.

The high horizontal stress may play a crucial role in maintaining stability of tunnels and caverns, which is particularly true for underground openings situated close to the ground surface. The Gjøvik Mountain Hall, which is 61m wide, 25m high and 95m long with the lowest rock cover of only 25 m, is an excellent example of using in-situ rock stress to maintain the cavern roof stability. Numerical analysis has demonstrated that it is the high horizontal stress that makes it possible to excavate such a large span cavern at such a shallow depth.

In some situations the high in-situ rock stresses may also bring forth additional difficulties in the tunnelling working environment and the rock support design. This is particularly relevant to the deeply seated openings. The high in-situ stress resulting from high overburden may cause extremely high stresses at cavern/tunnel roof and/or in the pillar that may considerably exceed the rock strength leading to rock failure and tunnel collapse. Heavy rock support might be needed in such conditions. In addition such high rock stress may also cause rock burst and spalling threatening the safety of the personnel working on site.

It is important to orient the longitudinal axis of large caverns with consideration of the orientation of the major principal in-situ stress as well as the major joint set. In areas with high and anisotropic in-situ stresses the most stable orientation is obtained when the length axis of the underground opening makes an angle of 15º - 30ºto the horizontal projection of the major principal stress (Nilsen & Thidemann, 1993). Potential failure mode of rock caverns is directly related to the magnitude of the major and minor principal rock stresses. For instance, for the power house cavern of a hydropower project, which has usually very high walls, a large horizontal stress component may cause instability of the walls rather than the roof.

In general the in-situ rock stress increases with depth resulting from gravity, however, a high horizontal stress may well occur close to the ground surface due to the historical tectonic processes. The gravity components can be computed, but the tectonic components have to be measured, one way or another. It is therefore crucially important to measure the in-situ rock stress, both magnitude and orientation, before any underground construction starts.

2. Shallowly Seated Underground Works

2.1 Tunnels and large span rock caverns

A reasonably high horizontal in-situ stress is in some situations essential to maintain a stable arch for large caverns. This is particularly the case for the shallowly seated large caverns. Without the help from the high horizontal stress the arching effect is hardly formed and consequently the instability becomes a problem for the roof safety. The Gjøvik cavern in southern Norway is a typical example. The cavern was constructed in 1992-1993 for the ice-hockey matches of the Winter Olympic Games in 1994. The cavern is 61m wide, 25m high and 95 m long, by far the largest man-made rock cavern in the world for public use. Figure 1 shows the cross section of the cavern. It is constructed in jointed granitic gneiss of Precambrian age. The joints are generally rough and well interlocked and have rather irregular orientations. The joint spacing varies from tens centimeters (a frequency of several joints per meter) for non-persistent joints to several meters for persistent ones. In short, the host rock is well jointed rock mass containing rough and randomly situated joints. Compared to the cavern scale, the rock mass can be categorized as 'closely jointed'. On the other hand, it is unlikely that the block failure involving large deformation would take place. Shearing along massive small joints may be the dominating potential failure mode. Many laboratory tests and field mapping were undertaken in order to gain the rock mechanics properties of the intact rock and the rock mass. Evaluation of the rock mass classification indexes was also made. The rock properties are summarized in Table 1. As can be seen from the table, the Q-value ranges from 1 to 30 corresponding to “Poor” to “Good” classes.

In addition to the large span it is amazing that such a huge cavern can be constructed only 25-55m below the ground surface, i.e. the overburden is much less than the cavern span. Then the question is: what makes it possible? The commonly accepted answer is the sufficiently high horizontal in-situ stress, which ensures the establishment of the arching effect and makes the roof basically a self-standing arch structure without the need of heavy rock supports (Grøv 2006; Myrvang 2006). Having realized the crucial importance of the horizontal in-situ stress a measurement program by the 3-D overcoring technique was followed at the early stage of the site investigation. The measurements were carried out in an existing tunnel on the site. The measurements showed dominating horizontal stresses in the range 3 – 5MPa at a depth of 25 – 50m, and the vertical stress is less than 1MPa, which coincides with the gravity stress. The horizontal stress pattern was later confirmed by the hydraulic fracturing tests performed in vertical boreholes drilled from the surface above the proposed location. Based on these findings it was decided to go ahead for the 61m span cavern.

Table 1. Mechanical properties of intact rock and rock mass and rock mass classification indexes.

Parameter	Value
E-modulus of intact rock	50-55 GPa
Uniaxial compressive strength of intact rock	70-77 MPa
RQD	70 (mean)
Q-value	1-30 mean 12
GSI index	45-75 mean 66

Numerical modelling with both continuum analysis (FEM) and discontinuum analysis (DEM) was then carried out for studying the stability and the rock support requirements. It was finally concluded with given rock quality and favourable in-situ stress condition it was feasible to construct the proposed huge cavern at such a shallow depth without a need for heavy rock support. Figure 2 shows the yielding area and deformed geometry of the result of a FEM modelling in which the in-situ rock stress estimated based on the measurements is used, i.e. the horizontal stress is about 3 times of the vertical stress. As shown in the figure the rock almost remains in the elastic state after the final excavation without application of any rock support. The maximum roof subsidence is about 1mm. Under the extreme case when the tectonic component of the horizontal in-situ stress is omitted, i.e. only the gravity stress field is considered the computation simply could not convergent and the large yielding takes place above the roof and below the floor. The computed roof subsidence is 2cm, which is obviously underestimated due to the divergence of the computation, as shown in Figure 3. This clearly demonstrates the necessity for the relatively high horizontal stress in maintaining the cavern roof stability. However, a high horizontal stress result in high differential stress σ_1 - σ_3 at the cavern roof leading to the instability in the form of slip of joints in the unfavourable orientations. Further modelling with a moderate horizontal stress, $\sigma_h = \sigma_v$, shows no yielding around the cavern and more uniform distribution of the displacement of the cavern periphery. The actual measured cavern roof subsidence is about 8mm.

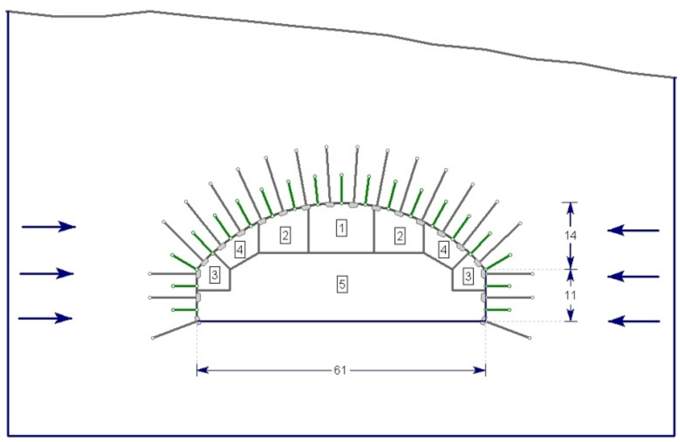


Fig. 1.Cross section of Gjøvik cavern and sketch of the excavation sequence and in-situ rock stress.

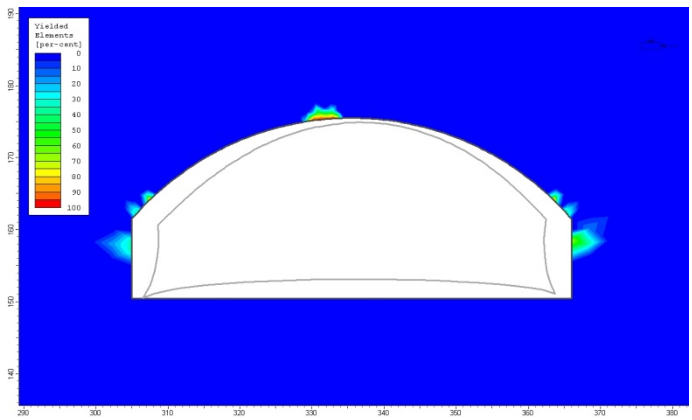


Fig. 2. Yielding of modelling result for high horizontal stress.

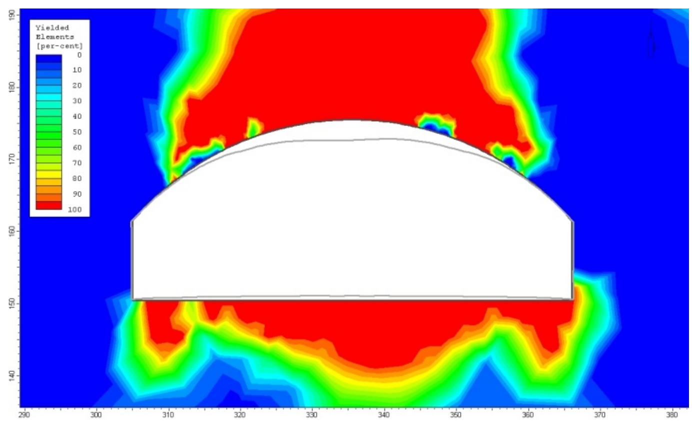


Fig. 3. Yielding of modelling result for extremely low horizontal stress.

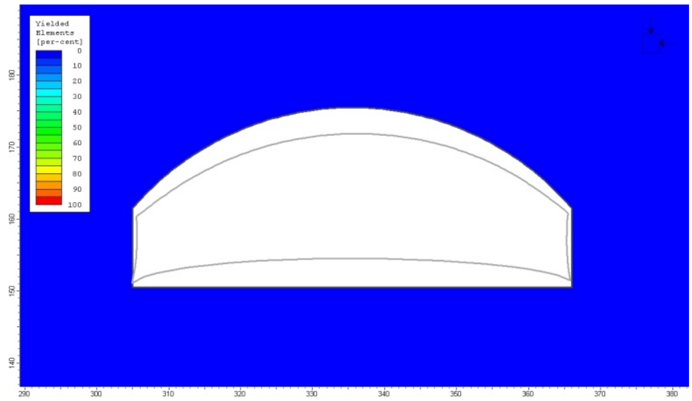


Fig. 4. Yielding of modelling result for moderate horizontal stress.

2.2 Silos and High Wall Caverns

Different from the large span caverns where the roof stability is the major concern the shallowly seated silos and caverns of high walls may have the essential failure potential located at the walls. This occurs very often when the tectonic component of the in-situ horizontal stress exists and the jointing orients unfavourably. For most storage silos this is not a so critical issue since the circular cross section is favourable in many cases in the stress redistribution after excavation. However, for the power house of the hydropower project where the walls are often very high the magnitude of the horizontal stress then plays an important role in instability of the cavern walls.

The Xiaolangdi Multipurpose Dam Project is constructed in the middle reach of the Yellow River, China, with an installed capacity of 1800MW. The powerhouse cavern is 22.3m wide and 61.5m high, and located in sedimentary rocks of fair to good quality (Q = 8~12, RMR = 59~66) with overburden of 85 to 115m. The horizontal to vertical in-situ stress ratio is about 0.8. However, some clay intercalations are oriented parallel with the almost horizontal bedding planes in the powerhouse area. The existence of these clay intercalations became a major concern for the stability of the cavern crown. This lead to the decision to install a total of 345 pieces 1500kN tensioned 25m long cable anchors with a spacing of 4.5m × 6m (circumferential × longitudinal) in the powerhouse cavern roof. This came in addition to 8-12m long rock bolts installed in a pattern of 1.5m × 1.5m, and 20cm thick wire mesh reinforced shotcrete, which was the original design (Huang et al. 2004). Both cable and bolts are also used in the rock support for the cavern walls. Figure 5 shows the cross section of the power house and transformer caverns with rock support design.

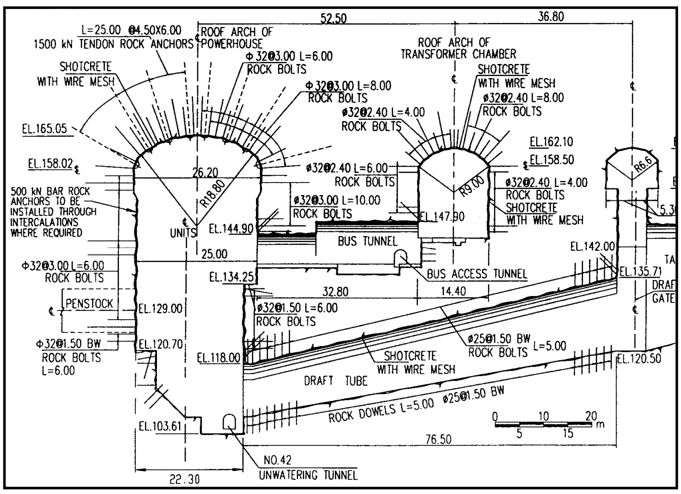


Fig. 5. Cross section of the Xiaolangdi power house cavern and rock support design.

Huang (Huang et al. 2004) performed numerical simulations by using software DIANA and UDEC respectively. The analysis result indicates the displacements in the walls are greater than that in the roof and plastic zones extend to a maximum depth of about 20m in the walls, whilst there is only a very limited plastic zone in the cavern roof, as shown in Figure 6. Huang also conducted a sensitivity study with the horizontal to vertical in-situ stress ratio varying from 0.4 to 1.0 and found the high horizontal stress helps roof arch forming, but results in larger deformation of the walls. In this situation the walls are more critical than the roof in terms of the cavern stability, and a too high horizontal in-situ stress is not favourable to reach stable cavern walls. The optimized rock support design may be reached when a moderate in-situ stress regime exists.

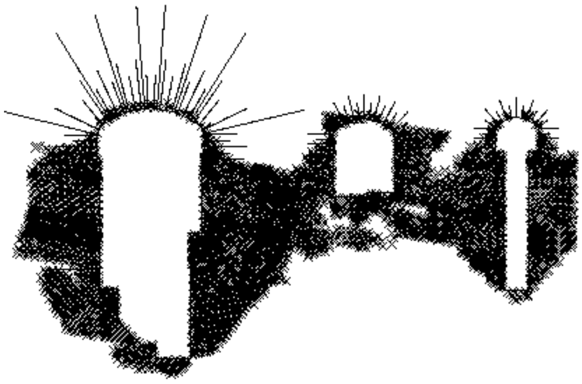


Fig. 6. Plastic zones in the rock mass of the powerhouse complex.

3. Geo-Hazard Associated with High Rock Stress

3.1 Spalling and Rock Burst

Normally in-situ rock stress increases with depth. In the common range of engineering the in-situ rock stress may reach up to 40 – 50MPa at an overburden of 1500 – 2000m. However, high rock stress may also occur as the tangential stress close to valley-sides, or even at low cover depending on the tectonic conditions. Especially in the mountainous fjord landscape of western and northern Norway, such conditions are common. When the high stress is released by, for instance excavation of a tunnel, it may cause rock spalling or rock burst as violent fracturing. This results in dangerous working conditions during excavation, manual scaling may become impossible to perform safely and mechanical scaling by a hydraulic hammer has to be taken. In the worst situation the working face has to be supported by rock bolts and sprayed concrete in order to drill the charge holes. It is reported that every year roughly 20 miners are killed by rock burst solely in South Africa.

The more intense spalling and rock bursts may be accompanied by crackling or gun-shot sounds, providing a dramatic effect and sometimes acting as warning signals. However, moderately high rock stresses may also be very dangerous, as there could be a lack of the warning signals that may follow the high rock stresses. Fatal accidents have occurred in circumstances where rock stress problems are not intense, providing a false feeling of safety. The effect could also be delayed; in the less brittle rocks the deformations may go on for a long time (weeks, months) and could cause potentially dangerous situations further out in the tunnel (Blindheim 2004).

The high rock stress is included in a list of major geohazards presented by Blindheim (2004). In addition to the bolting and sprayed concrete he mentioned drilling of stress release holes as a preventive action. Wang et al. (2008) studied the mechanism of rock burst and proposed the prevention by means of rock softening by water injection. It is unknown to the authors of this paper if this measure has been successfully utilized in any tunnelling project.

3.2 Stress Consideration in Rock Mass Classification

In-situ rock stress has been taken into account in the Q-system for rock mass classification (NGI 1997).

$$Q = \frac{RQD}{J_n} X \frac{J_r}{J_a} X \frac{J_w}{SRF} \quad (1)$$

The parameter SRF is Eqn (1) is the Stress Reduction Factor, describing in general the relation between stress and the rock strength around a cavern/tunnel. According to NGI (1997) for the competent rock with stress problems that “with very high stresses spalling and rock burst may occur in a tunnel, and SRF-value up to 400 may be used in some situations”. This implies that a rock mass categorized as “very good” with a stress-free Q’-value of 50 may fall into the category “very poor” simply due to the high in-situ rock stress. The magnitude of the reduction may be discussed, but anyhow this is a clear demonstration of the importance of the in-situ rock stress.

3.3 Experience from the Lærdal Tunnel

The 24.5km long Lærdal tunnel in Norway is the world longest road tunnel. With the high rock cover up to 1450m the in-situ rock stress is high, and the gravity stress resulting from the overburden is estimated to be about 40MPa. The dominating rock type is banded or veined gneisses. Jointing is moderate, but some weakness and fault zones exist. Figure 7 shows the longitudinal cross section of the site geology. Due to the extensive experience of the similar projects in the region the pre-construction site investigations were basically geological survey and rock mass classifications based on the Q-system. No core drilling and in-situ stress measurement were performed (Blindheim 2003).

Tremendous difficulties were encountered from the beginning of the excavation due to stress-related problems. Moderately intense spalling and slabbing accompanied with sound from cracking to gun shot occurred frequently. In the worse situation rock flakes could fly up to 20m away from the rock surface, and spalling occurred at the work face during explosive charge. The work face had to be supported with rock bolts and sprayed concrete. Other stress-related problems include: drilling jumbo jumped due to spalling in the floor; drilling robs got stuck during blast and probe hole drilling due to crushing and cracking in the holes; increased spalling during rock surface washing before spraying of concrete and so on (Blindheim 2003).

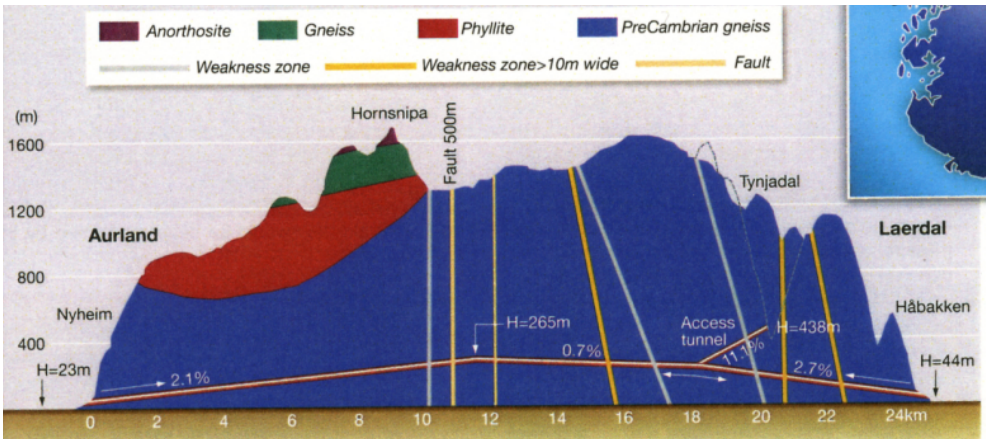


Fig. 7. Longitudinal geological cross section of the Lærdal tunnel.

As a result the anticipated progress of 60m per week was not maintained. Then stress measurements were conducted at two locations indicating a sub-horizontal in-situ stress of 30-33MPa and the rock deformation was monitored at two locations with multipoint extensometers. In order to identify the depth of the stress release crack in the surrounding rock the endoscope measurements were performed in more than 100 boreholes.

A revised work procedure and rock support was then worked out including the use of mechanical scaling before application of sprayed concrete in roof and abutment after mucking out half of the much pile; rock bolting through fresh concrete; the heavy use of end-anchored rock bolts and fibre-reinforced concrete. The experience indicates the end-anchored rock bolts behave better than the full grouted bolts in high-stressed rock condition due to the larger allowable deformation. The tunnel was open to traffic after 5-year construction and has been operated normally.

The experience gained from the Lærdal tunnel may be summarized as (1) the use of the mechanical scaling instead of the manual scaling, (2) applying of sprayed concrete and followed by bolting through fresh concrete and (3) use of the end-anchored bolts instead of the fully grouted bolts.

4. Unlined Pressure Shaft/Tunnel for Hydropower Development

As shown in Fig. 8 the layout of the hydropower projects in Norway has dramatically changed after the end of the Second World War. Powerhouses are located underground whenever the rock cover is sufficient. Associated with the underground location two techniques were developed, namely unlined pressure shaft/tunnel and the air-cushion surge chamber. The major portion of the pressure shaft/tunnel remains unlined leaving only a short section of 20-50m next to the powerhouse being lined with steel plate. The main condition imposed is that the minimum rock stress (σ_3) should be higher than the internal water pressure every point along the unlined tunnel to avoid the risk of failure by hydraulic fracture, see Fig. 9. This may require continuous measurements of the in-situ stress during the tunnel excavation. The air-cushion surge chamber is an unlined rock cavern designed to replace the conventional open surge shaft by using compressed air injected into the cavern. The condition is the minimum in-situ rock stress must be higher than the maximum operation air pressure inside the cavern with a sufficient factor of safety. This concept was later used in the underground storage of pressurized gas in unlined rock caverns.

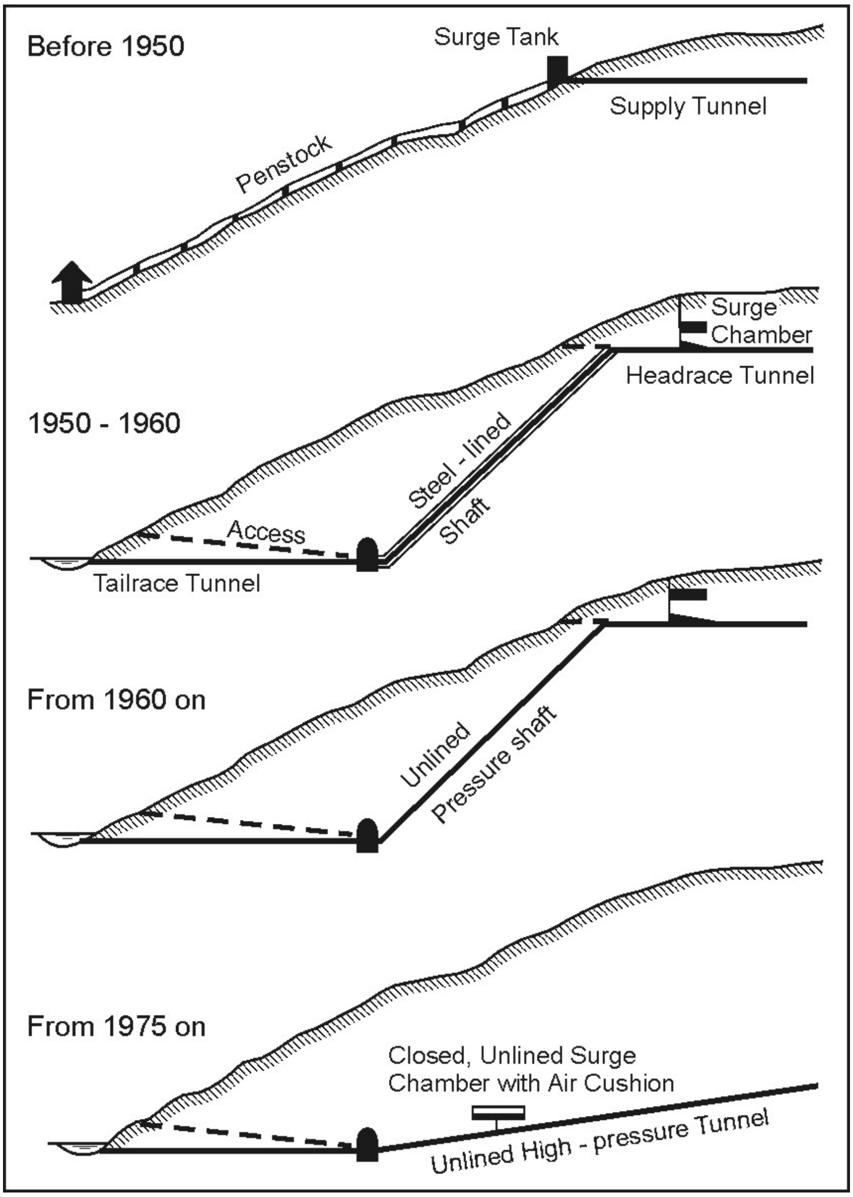


Fig. 8. Development of general layout of hydroelectric plants in Norway.

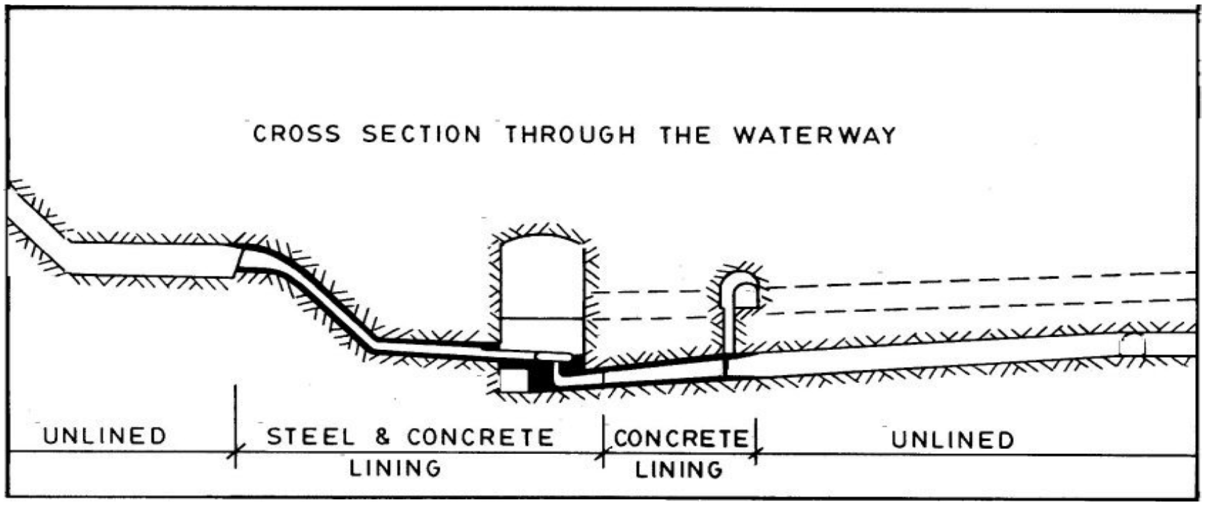


Fig. 9. Cross section of an underground hydropower plant with unlined waterways.

5. Rock Support for Tunnels in High Stress Rock

The Qinling Zhongnanshan tunnel, Shaanxi, China, consists of four tunnels: two railway tunnels and two road tunnels. With a length of 18.02km the road tunnel is currently the longest double tube road tunnel in the world. The gross cross section of the road tunnels is 12.8x10.5m, accommodating three driving lanes. The tunnels were open to traffic in January 2007. For special lighting and driving safety purpose six caverns are designed in the road tunnels, see Figure 10. The idea is when a person drives in such a long tunnel he or she may feel monotony and anxiety, and lose concentration. As a result the potential of traffic accidents increases. Special and bright lighting is designed in the caverns such that the driver will be woke-up and has a perception of being outside the tunnel. In this way, the driving safety is increased.

The tunnels penetrate the Qinling Mountain Range, where the major rock type is mainly granitic gneiss of good quality and the maximum rock cover along the tunnel route is about 1800m. Rock bursts and spalling were frequently encountered during tunnel excavation. With a strong anticipation of high in-situ rock stress and reorganization of its significant impact on the cavern stability, a field stress measurement program by overcoring technique was carried out in two boreholes close to the cavern sites. The overburden for the boreholes is 400 and 1600m, respectively. The measurement at the low overburden hole was successful, whilst great difficulties were encountered in the high overburden hole. Severe core disking was observed (Figure 11). Finally, the 3D overcoring was replaced by doorstopper (2D overcoring). The measurement result indicates the highest major principal stress may be as high as 45MPa (Lu et al. 2006).

The rock support was designed with empirical means and verified by 2-D and 3-D numerical analyses, and the experience gained from the Lærdal tunnel was referenced. Having realized the restrictions by the very high rock stress and the small pillar width in comparison to the cavern size (the minimum pillar width is 8m and the cavern span is 22m) the design was very cautious.

The designed rock support system consists of rock bolts and fibre-reinforced sprayed concrete, a clearly defined construction sequence and a monitoring system. For the caverns under extremely high stresses a flexible support is proposed which is composed of temporary support and permanent support. The idea is to allow rock deformation to partially take place before the permanent reinforcement is applied, such avoiding failure of the support elements. The use of the end-anchored rock bolts with polyurethane cartridge is particularly specified. The length of the bolts was such designedthat the anchorage ends must be located at the competent rock, in other words, the bolts must be anchored in the non-yielding rock, which was ensured by the numerical analyses. Figure 12 shows the details of the modelling of the construction sequence for the caverns at relatively low stress conditions.

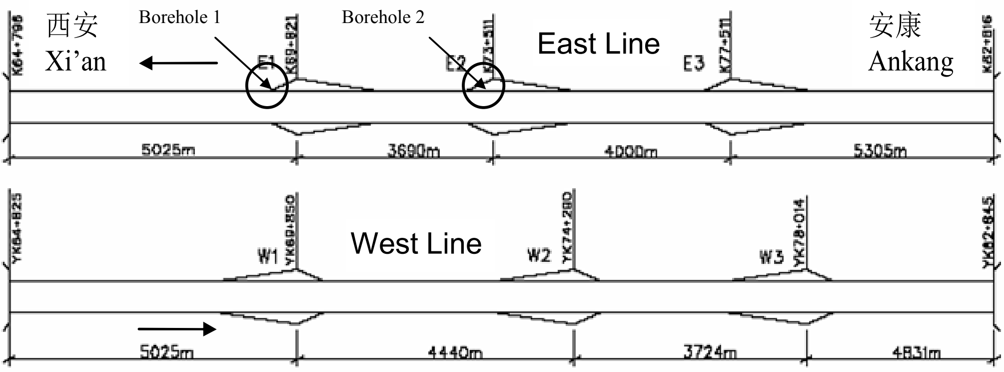
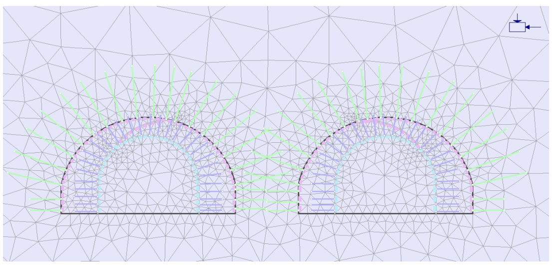


Figure 10. Illustration of location of measurement boreholes and caverns.

Figure 11. Illustration of core disking: 23 disks observed in a 27 cm long core.

Stage 1



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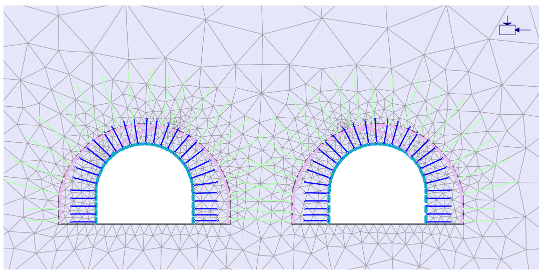

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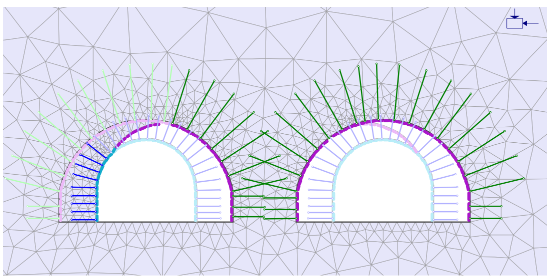

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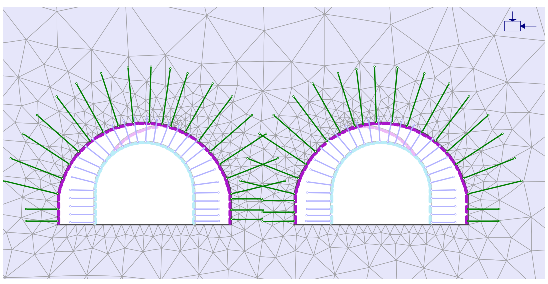

Stage 5 Stage 6

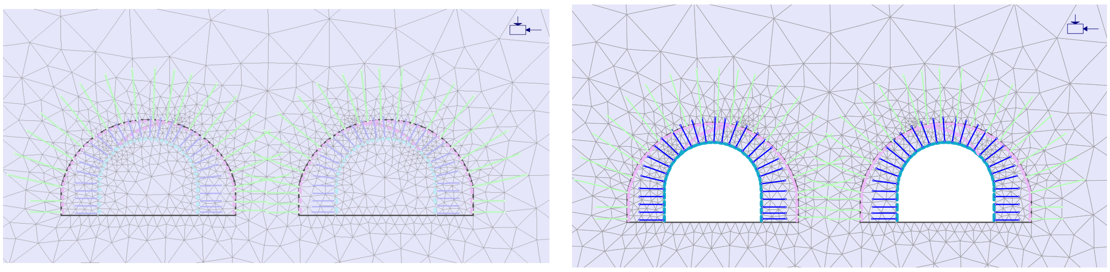

Fig. 12. Numerical simulation of the complete construction sequence.

6. Conclusions

The importance of the in-situ rock stress for the underground tunnels and caverns has been recognized since a long time ago. Reasonably high horizontal stress plays a crucial role in maintaining the roof stability of shallowly seated large caverns by arch forming mechanism. However, for the silos and caverns with high walls a high horizontal in-situ stress may have negative effect on the stability of the walls. It is generally accepted a moderate stress regime is preferred for most underground works.

High rock stresses may appear in great depth or can be caused by the tectonic process, which may become hazardous to the environment of underground construction with potential for spalling and rock burst. In particular the rock burst with its violent nature threatens the safety of the personnel working at the site. Special engineering measures have to be taken in preventing, reducing and/or handling the rock burst.

Great caution is needed in rock support design in high stress rock. In general attempt to prevent rock deformation by using of heavy and stiff support should be avoided. A certain level of deformation should be allowed and flexible support such as end-anchored rock bolts should be used. The yield bolts developed in recent years may fit the specific requirements for the high stress condition.

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