INNER LINING IN TRAFFIC TUNNELS

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The standard solution for the inner lining of Norwegian tunnels is the installation of precast concrete elements. Recent incidents in existing road tunnels in Norway due to damages to the inner lining – as a consequence of frost effects, falling rock blocks or gravitational collapses – have led to a reconsideration of the existing design standards and common practise for road tunnels, as documented in the "Modern Road Tunnel Strategy Study" from the Norwegian Public Roads Administration (Statens Vegvesen). The choice of the inner lining concept is very important with respect to reliability, availability, maintenance and safety (RAMS). This is true not only for road tunnels but also for railway tunnels. Most of the newly planned railway tunnels are designed for high-speed trains, where the effects of dynamic pressure and suction loads are an important factor for the dimensioning of the inner lining. Furthermore, for such tunnels a long lifetime and a high availability (in order to face the increasing traffic intensity) are demanded. In account of this, adjustments in the design of railway tunnels are also on-going. This paper describes and compares both the Norwegian precast concrete elements concept and the cast-in-place concrete lining system – which is the standard solution for inner lining, e.g., in Switzerland – showing that the cast-in-place solution is a valuable alternative.

INTRODUCTION

The standard inner lining of Norwegian tunnels consists of precast concrete elements (fixed with rock bolts). Recently, some incidents occurred due to damages to these elements (because of frost effects, falling rock blocks or gravitational collapses [1]). In account of this, the Norwegian Public Roads Administration (NPRA, Statens Vegvesen) reconsidered the existing design standards for road tunnels. One of ten major research and development projects conducted by the NPRA was the sub-programme Modern Road Tunnel Strategy Study, which focused on the NPRA's strategy for tunnels and followed up issues described in two reports [2, 3]. These reports revealed the need for improved tunnel maintenance and geological documentation systems as well as increased professional expertise. Major issues, such as the design of the tunnel profile and of the tunnel lining, life cycle costs, operation, maintenance and, more in general, the harmonisation of the regulations also made up key parts of the project.

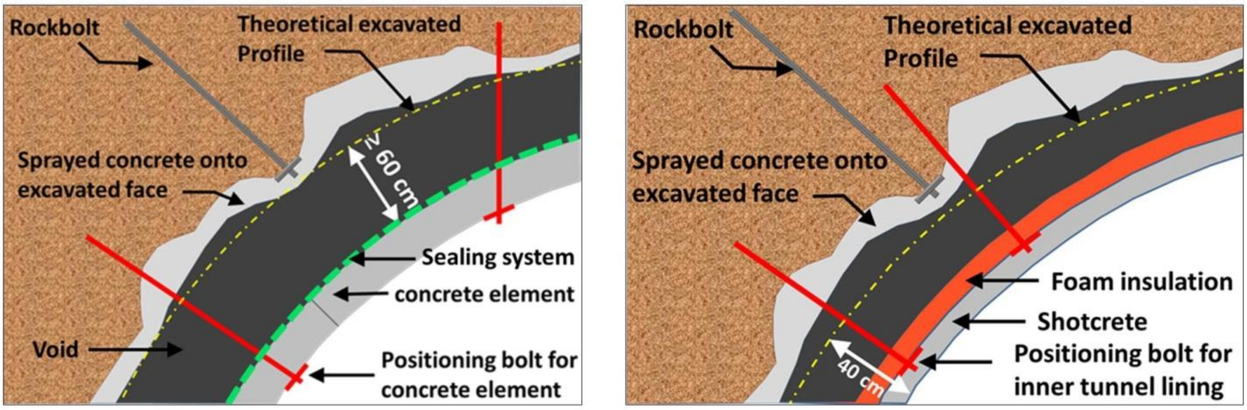
Similar considerations apply for railway tunnels. As most of the newly planned railway tunnels are for high-speed trains, the design of the inner lining is a central issue. In fact, in such tunnels the dynamic pressure and suction loads play a central role for the dimensioning of the inner lining. Furthermore, a long lifetime and (in account of the continuously increasing traffic intensity) a high availability of the tunnel are two of the major requirements for modern railway tunnels. This is because for railway tunnels too (and not only for road tunnels) adjustments in the design standards are on-going.

The present paper deals with the topic "inner lining" for both road and railway tunnels. After a description of the inner lining concepts, the paper compares the classic Norwegian lining concept (precast concrete elements) and the concept with cast-in-place concrete.

INNER LINING CONCEPTS

Inner lining with precast concrete elements

As already mentioned above, an inner lining consisting of precast concrete elements is the standard solution in Norway. In this case, the inner lining is non-structural and is built-in after the final rock support has been installed. The main purposes of the non-structural lining are managing of water ingress and frost protection. Furthermore, there are aesthetic requirements. As shown schematically in Figure 1a, the precast concrete elements are fixed with rock bolts (which are also used as positioning bolts for the installation of the elements). On the outside of the elements, a waterproofing membrane is placed. Between the sealing system and the rock mass there is a void, i.e. the inner lining is not in contact with the rock mass.



a) b)

Figure 1. (a) Inner lining with precast concrete elements; (b) foam isolation – sprayed concrete lining (after [4]).

The temporary and final rock support of the tunnel (e.g. rock bolts and sprayed concrete as sketched in Figure 1a) is installed previously and is independent from the inner lining system. The final rock support and the rock mass surrounding the non-structural lining have to be monitored during the entire lifetime of the tunnel. However, there is generally no easy or practical way for this monitoring. As a rule, the safety inspections consist of random drillings into the concrete lining. It is obvious that such random inspections are unreliable and expensive. Therefore, the so called "Ground Penetrating Radar" has been introduced in the vault walls to map the contours of the void in a more systematic way, as this scanning technology provides satisfactory data and gives an optimal location of the apertures. Additionally, it can also be used in the vault roof to pinpoint potential rock falls [5]. In the future, detection of potential rock falls will be done by means of video cameras installed in the void behind the inner lining, thus allowing for an online supervision. However, the suitability and reliability of such a system is not proven yet.

In addition to the monitoring, regular maintenance for checking the conditions of the rock support and for removing loose rocks is necessary. The void behind the inner lining has to be at least 60 cm (Figure 1a), which is not sufficient for inspections. However, in most cases the void is bigger than theoretically required (due to systematic over profile) and inspections are possible.

Foam isolation – sprayed concrete lining

An alternative to the inner lining with precast concrete elements described above, is the so called "foam isolation – sprayed concrete lining" (Figure 1b). In this system, foam isolation is fixed with rock bolts (which are also used as positioning bolts during assembling) and covered with a layer of sprayed concrete. As for the system with precast concrete elements, the inner lining is non-structural and not in contact with the rock mass. The theoretical minimum dimensions of the void between the rock mass and the inner lining are smaller (40 cm instead of 60 cm).

Inner lining with cast-in-place concrete

The main difference between an inner lining consisting of cast-in-place concrete and the two Norwegian systems described above is the fact that the inner lining is in contact with the rock mass (or with the sprayed concrete of the temporary rock support, if any). In this way, there is no void behind the inner lining (Figure 2) and latter is a structural part of the tunnel construction which, as a rule, consists of two shells: the sprayed concrete layer of the temporary rock support (outside) and the cast-in-place concrete shell of the inner lining (inside). Between the two shells a sealing membrane is installed; both drained and undrained solutions are possible.

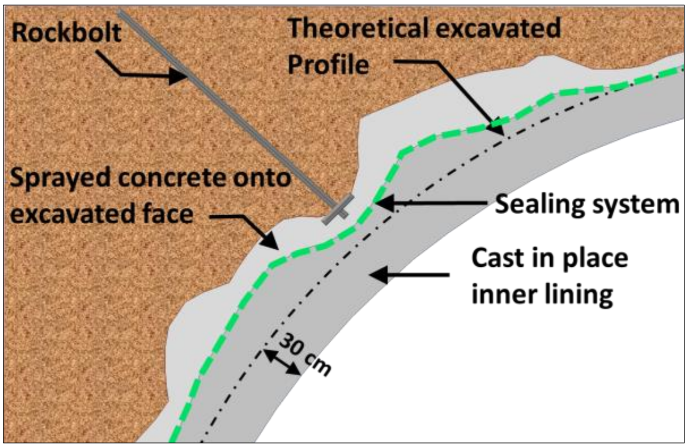


Figure 2. Inner lining with cast-in-place concrete (double-shell lining).

As for the Norwegian systems, the thickness of the sprayed concrete layer depends on the encountered geological conditions. For concreting reasons, the minimum theoretical thickness of the cast-in-place concrete lining is 30 cm. Usually, the inner lining is reinforced only near to cross-passages or niches. Of course, if necessary the thickness can be increased and the inner lining can be reinforced systematically. Furthermore, if required, the inner lining can be enhanced with an invert arch and closed to a ring, thus allowing the accommodation of high rock loads and/or water pressures (undrained solution).

The main purposes of an inner lining consisting of cast-in-situ concrete are manifold:
– guarantee of a lifetime of 100 years for the tunnel construction;
– reduction of the required maintenance;
– increase of the availability of the tunnel;
– provision of an internal finishing for the minimization of the air friction (this is particularly important for high-speed railway tunnels, as the internal friction influences the energy requirements);
– protection of the sealing membrane (in case of fire);
– easy mounting of the tunnel equipment (signals, handrails, ventilation, traction current, etc.);

- easy painting, which allows for a reduction of tunnel cleaning and tunnel lighting (only for road tunnels);
- accommodation of the rock pressure;
- bearing of the external water pressure (undrained solution);
- reduction of the amount of pre-grouting (in the case of an undrained solution and assuming that water inflow is acceptable during construction).

COMPARATIVE CONSIDERATIONS

Dimensions of the tunnel profile

The dimensions of the tunnel profile to be excavated depend, among others, on the inner lining concept (Figure 3). Applying the concept with the cast-in-place concrete inner lining, the excavation surface can be reduced. This is due to the fact that in the Norwegian system place is lost because of the void existing between inner lining and rock mass. According to Table 2, a reduction of the excavation radius of 45 cm is possible, which results in an important reduction of the muck quantity and of the corresponding transports and deposit volume. Assuming an inner radius of 5 m, the reduction in cross-section is of approximately 10 m^2.

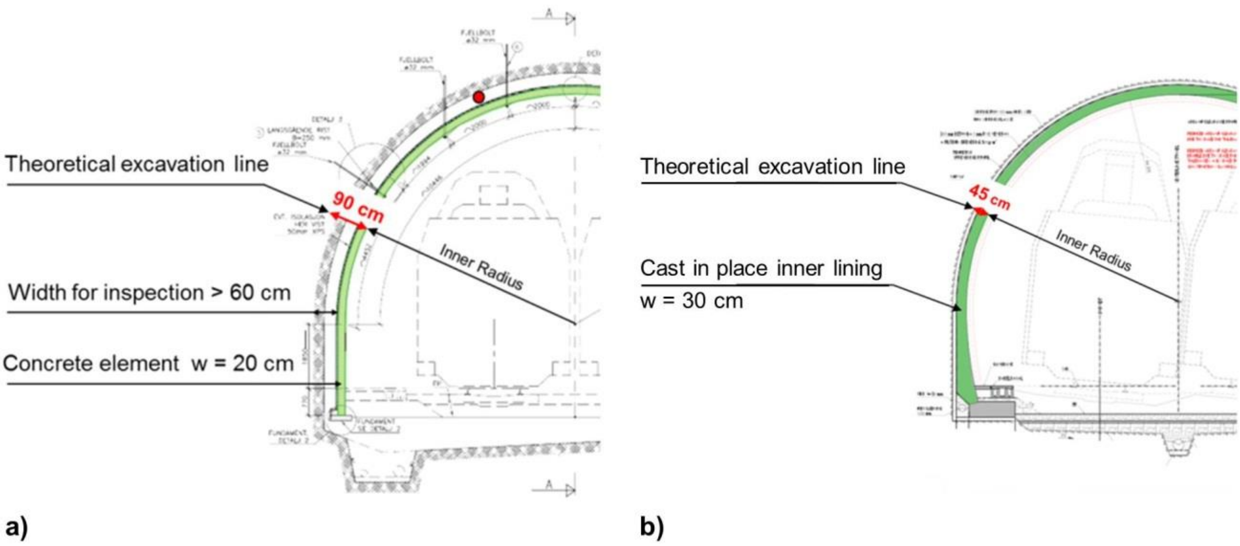


Figure 3. Theoretical excavation line for, (a), inner lining made of precast concrete elements (after [6]) and, (b), inner lining made of cast-in-situ concrete (after [7]).

Table 1. Comparison of the excavation radius for the two inner lining concepts of Figure 3.

Concept	Precast concrete elements	Cast-in-place concrete
Inner lining	20 cm	30 cm
Sealing membrane	0.3 cm	0.3 cm
Inspection space	> 60 cm	--
Leveling layer	0 cm	5 cm
Rock support	10 cm	10 cm
Excavation radius	**Inner radius + 90 cm**	**Inner radius + 45 cm**

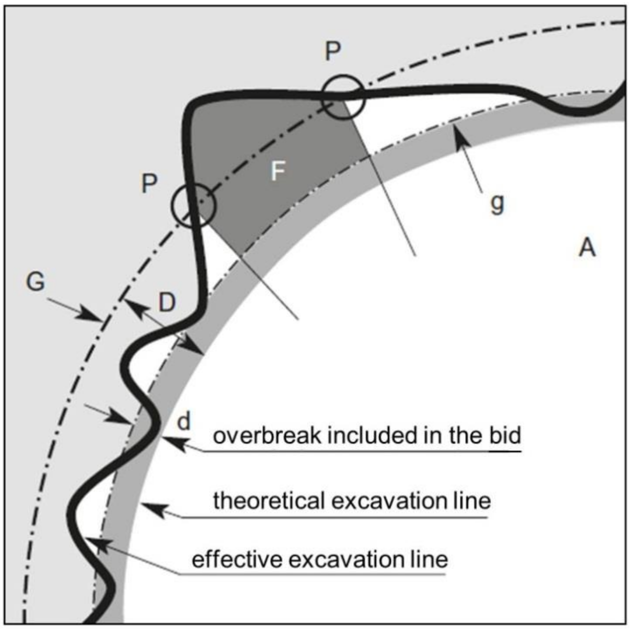
Rock support

A cast-in-place concrete inner lining is part of the final tunnel structure and has a structural action. According to this (and if designed accordingly), it can accommodate the entire or part of the rock loads in the long term. This allows for a reduction of the temporary rock support and, therefore, to a further reduction of the excavation radius compared with the concept applying precast concrete elements (with which the rock support has to accommodate the rock loads both in the short and in the long term and, therefore, has to fulfil higher requirements with respect to bearing capacity and lifetime).

Overbreak regulations

The considerations of above apply for the theoretical excavation radius. However, the effective dimensions of the excavated profile depend also on the amount of overbreak. The Norwegian inner lining concept assumes implicitly that a certain amount of overbreak exists. This in order to have a big enough void between inner lining and rock mass allowing for the assembling of the precast concrete elements and for inspections. On the contrary, in the case of a cast-in-place concrete inner lining more sever overbreak regulations can be applied, thus resulting in a reduction of the excavated volume. The stronger regulations are also advantageous with respect to the required concrete volume, as less overbreak means less volume to be filled with concrete.

The Swiss standards [8] define clearly the procedure for the reimbursement of the excavation volume and of the overbreak, respectively. The principle is depicted in Figure 4. A given overbreak *d* is included in the bid (this has to be declared by the contractor in its bid). The overbreak *F* is additional reimbursed (according to the unit price contained in the offer) if this is due to geological reasons. When the contractor causes itself the overbreak (e.g. as a consequence of inaccuracy of the drill holes, overloading or late installation of the rock support), this is not paid. With this regulation, the contractor is encouraged to blast as exactly as possible in order to minimize the overbreak, which is not paid and which has to be filled with cast-in-place-concrete.



A: Theoretical excavation surface
d: Overbreak included in the bid
g: Boundary line of the overbreak included in the bid
G: Boundary line
D: Distance between the theoretical excavation line and the boundary line G
P: Point of intersection between the boundary line G and the effective excavation surface
F: Overbreak, which will be additionally paid

For drill−and−blast:
$D = 0.07\sqrt{A}$
$D_{min} = 40$ cm

Figure 4. Overbreak regulations for drill-and-blast excavation according to the Swiss standards [8].

Sealing

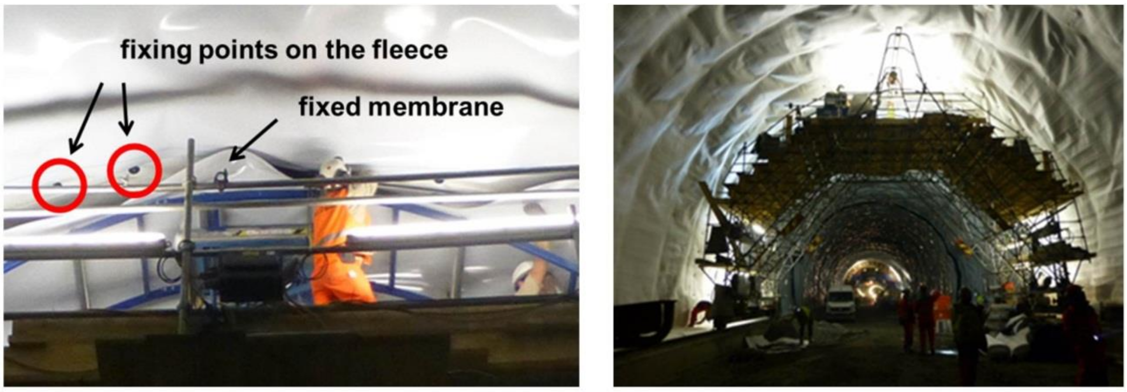
The inner lining of a traffic tunnel is more and more planned for a functional service lifetime of at least 100 years. For this reason, the cast-in-place concrete must be protected extensively against the effects of mountain water. The degree of protection and, more in general, the design of the sealing system depend on the water pressure and on the aggressiveness of the mountain water.

The requirements concerning the waterproofing of the tunnel have to be clearly defined in the design basis. Beside the protection of the cast-in-situ concrete of the inner lining, also the operational requirements of the client as well as environmental aspects (e.g. reduction of the drainage of the rock mass) have to be considered. In the Swiss standards [9], this is handled with so called "waterproofing classes" (Table 2).

Table 2. Waterproofing classes according to the Swiss standards [9].

Class	Description
1	**Completely dry.** No damp spots permitted on the dry side of the structure's surface.
2	**Dry to slightly moist.** Some damp spots permitted. No dripping water permitted on the dry side of the structure's surface.
3	**Moist.** Damp spots limited locally. Individual dripping spots permitted on the dry side of the structure's surface.
4	**Moist to wet.** Damp spots and dripping areas permitted.

As a rule, the installation of the sealing system occurs in two steps. In a first step, a fleece with special fixing points (Figure 5a) is nailed on the sprayed concrete surface. In a second step, the sealing membrane is welded to the fixing points. Both the fleece and the sealing membrane are delivered in 4 m wide rolls (preassembled in the factory). For their installation a special scaffold (Figure 5b) is used. After being fixed, the 4 m wide ribbons are welded together. In areas where reinforcement has to be placed, an additional protection membrane is mounted on the inside. A big advantage of this solution is that there are no elements perforating the sealing membrane and, therefore, reliable waterproofing is easier to realise. The same does not apply for the Norwegian inner lining concept, where the positioning and fixing rock bolts of the precast concrete elements go through the sealing membrane, i.e. there are a number of points which may become leaky.



a) b)

Figure 5. Sealing membrane: (a) welding points on the fleece; (b) special scaffold for the installation.

It has also to be mentioned that the application of a sealing membrane behind a cast-in-situ concrete inner lining requires a given evenness of the sprayed concrete surface. Figure 6 shows the corresponding acceptable geometric values. Normally, in tunnel excavated by means of drill-and-blast an additional layer of sprayed concrete (without fibres) for smoothening is necessary.

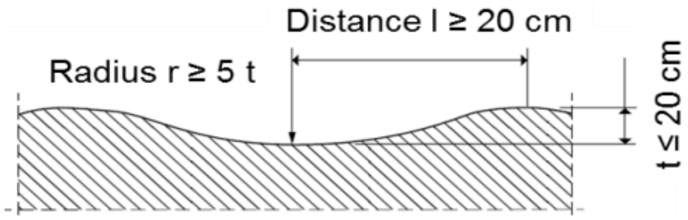


Figure 6. Acceptable unevenness for the sealing membrane [10].

Concreting

A further major difference between the Norwegian system and an inner lining made of cast-in-place concrete regards, of course, the construction method of the inner lining. In the Norwegian solution, the precast concrete elements are prefabricated in a factory, transported to the construction site and installed with the aid of the positioning bolts (Figure 1a). The mounting of the sealing membrane on the outside of the concrete elements is also part of the assembling works. On the contrary, if the inner lining consists of cast-in-place concrete, the sealing system is installed in advance in a previous working step (i.e. the sealing works and the construction works of the inner lining are not coupled, thus allowing for better quality controls). Afterwards, the inner lining is concreted in sections of 10–12 m length using a movable formwork (Figure 7). Before the formwork can be carefully stripped, the compressive strength of the concrete has to reach a minimum value defined in advance (for large tunnels, as a rule, 10 N/mm^2). Compliance with these requirements is verified, e.g., with the Schmidt hammer.

Figure 7. (a) Formwork; (b) steel structure of the formwork; (c) concreting (left: formwork, right; sealing membrane).

With both systems, the inner lining works can be carried out after the tunnel has been excavated or, with appropriate logistic adjustments, in parallel to the tunnel excavation. A common performance for cast-in-place concrete inner linings is of one section (10–12 m) per working day using two formworks. Due to the high degree of industrialization, careful curing and strict quality controls, the quality of the cast-in-place concrete is as good as the one of precast concrete.

Safety and reliability

Particularly in the case of high-speed railway lines, the loads on the tunnel walls due to the dynamic air pressure and suction as well as vertical uplift is very high. The positioning bolts used for fixing the precast concrete elements of the Norwegian system (Figure 1a) are not designed for withstanding such high pressure loads. Furthermore, due to the irregular shape of the excavated rock, these bolts have different lengths, thus leading to an asymmetric bearing (and, therefore, stress) of the entire construction. Another very important aspect is the fact that inner linings according to the Norwegian concepts (Figure 1) are not able to withstand the dynamic load resulting from a heavy rockfall (as incidents, like the one occurred in the Hanekleiv Road Tunnel [1], demonstrate).

For a cast-in-place concrete inner lining, these dynamic loads either not exist (the height of fall of a rock block is equal to zero) or do not represent a problem (as the inner lining is in contact with the rock mass, oscillations of the system are not possible). Furthermore, the rock loads are considered in the structural analysis of the inner lining. Therefore, these loads do influence neither the safety nor the reliability of the system. The safety is better also in the case of heavy road accidents, as there is no risk that parts or even the entire inner lining fall down.

Lifetime

As already mentioned above, cast-in-place concrete inner linings are designed for a lifetime of at least 100 years. This is a major advantage of this system, as time and cost intensive replacing works are not necessary.

Corrosion

Especially for road tunnels, where in winter de-icing salt is used, the risk of reinforcement corrosion is high. This risk is lower for inner lining made of cast-in-place concrete. First of all, such inner linings are, as a rule, not reinforced (i.e. the risk does not exist a priori). Furthermore, the concrete cover is higher than for precast concrete elements (for which, due to the thickness of about 20 cm, the possible concrete cover is limited). For both systems, the use of concrete with a low permeability (to prevent the penetration of salt and water) is recommended.

Corrosion can also concern the rock bolts used for the fixation of the precast concrete elements. These rock bolts can get damaged and lose their corrosion protection. After completion of the construction works, monitoring of the quality of the fixing elements is hardly possible.

Frost

In Switzerland, damages to the inner lining due to ice pressure are not known. This in spite of the fact that several tunnels are located in mountain areas with low temperatures during the winter (for example, the north portal of the Gotthard Road Tunnel is situated at an elevation of 1'150 m a.s.l.). The absence of such damages can be explained considering the dimensions of the elements of the sealing system installed behind the cast-in-situ concrete inner linings. The thickness of the draining layer, i.e. of the layer when water could be collected, depends on the water quantity to be drained. In the maximum case, this thickness is of approximately 1 cm. Therefore, the maximum thickness of the ice layer is also 1 cm. Due to icing, water experiences a volume increase of 9%. This results in an expansion of the water/ice layer behind the inner lining of only 0.9 mm, thus leading to a non-significant pressure acting on the inner lining.

Anyway, one method for protecting concrete against frost is the use of chemical additives to generate air voids. In this way, water inside the concrete can expand into these voids and spalling can be avoided.

Fire

The resistance against fire of a concrete structure depends among others on the characteristics of the concrete. Assuming the same concrete for both cases, an inner lining consisting of precast concrete elements will collapse before an inner lining made of cast-in-place concrete. This is because of a weak point of this system, i.e. the rock bolts used for fixing of the precast concrete elements, which are not able to resist the high temperatures developing already in the first minutes of a fire. It is worth mentioning here that the stability of the tunnel structure is a premise of each safety concept based upon rapid self-rescue of people.

Fixing of installations

Both in road and in railway tunnels a lot of installations have to be fixed to the wall. With a thickness of at least 30 cm, inner linings made of cast-in-place concrete allow the use of dowels without penetrating the waterproofing membrane (Figure 8).

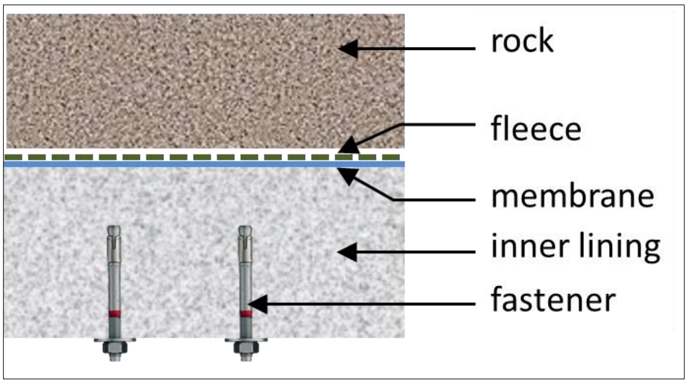


Figure 8: Fixing of installations with dowels.

Costs

One common argument against the solution with cast-in-place concrete is the price, i.e. that the investment costs are much higher than for the solution with precast concrete elements. However, recent comparisons of contractors working on the Norwegian market showed that the two solutions have comparable investment costs, provided that the costs for the temporary rock support can be reduced. As a rule, this is possible. For example, instead of expensive full grouted bolts with corrosion protection, normal friction bolts can be used. Furthermore, comparing the costs, a global evaluation is recommended. In fact, taking into account not only the investment costs but also the maintenance costs and the costs deriving from a reduced availability of the tunnel, there is a clear advantage for the solution with cast-in-place concrete.

CLOSING REMARKS

Both inner lining concepts (precasted concrete elements and cast-in-place concrete) have advantages and disadvantages. However, the tendency for the future is towards inner linings made of cast-in-place concrete (Figure 9), which are the standard solution in Switzerland but not only).

This because of the clear advantages with respect to reliability, availability, maintenance and safety (RAMS) and of the comparable construction costs.

Figure 9: Inner lining of the Lötschberg Base Tunnel (Switzerland) [10].

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