THE USE OF POLYURETHANE RESINS IN TUNNEL GROUTING

Grouting is a useful engineering tool for tunnels throughout the world. A wide variety of methods and materials are used, reflecting the broad range of geological, hydrogeological, and structural demands. Most tunnel grouting is conducted with cement, which produces acceptable results in appropriate conditions. However, there are cases where such grouts are not practical, but polyurethane grouts can be extremely useful. Regretfully, these grouts are frequently poorly understood, leading to improper application and therefore poor results. This paper provides a fundamental overview of their application, both used individually and in combination with cement. Case histories from Scandinavian practice are cited.

FUNDAMENTALS OF POLYURETHANE GROUTING

Polyurethane grouts react with water and expand due to production of CO_2. Often, polyurethane grouting has proven successful when other grouts have failed. An experimental study on polyurethane grouts was finalised in 1998 at Chalmers University of Technology in Sweden (Andersson, 1998)). The research was aimed to study polyurethane grouts and observe the factors that govern the reaction process, to increase the knowledge about what influences the course of events during a grouting operation. The conclusions made it possible to give recommendations for the application of polyurethane in rock grouting.

Background for the experimental study

Hypotheses. Sometimes when sealing rock, one faces situations where grouting with cement suspension does not work. One such situation is when the conducted pre-grouting is insufficient and post-grouting has to be performed. The joint openings may be too narrow for the particles in the cement to enter, or flowing water in the rock transports the suspension away and/or dilutes it. The general hypotheses in the research were that (i) chemical grouts have better penetrability, because they do not contain particles, and (ii) they can be used to control the cement propagation, since their gel time can be programmed. The criterion for describing a grouting situation should be whether the water flows in the rock or not (see below).

Conceptual model. A conceptual model was developed for the sealing of a rock tunnel (see Figure 1). Pre-grouting of highly pervious rock, with water flowing towards the tunnel, is similar to post-grouting of remaining water leakage. Then, the grout material is injected into a water flow and the grouting pressure has to be held rather low so that the grout material is not flushed back into the tunnel before hardening. Without flowing water, the situation resembles the pre-grouting of competent rock, and the grout is injected against groundwater under hydrostatic pressure. In the latter case, the grouting takes place well into the rock and higher grouting pressure can be used, which is more efficient than when post-grouting.

Important features for polyurethane grouts. In order to understand and predict the typical behaviour of polyurethane grouts, it is important to be familiar with the following: (i) the time dependency, (ii) the flow behaviour of unreacted as well as reacting polyurethane, and (iii) the influence of the carbon dioxide produced during the reaction. The viscosity of a polyurethane grout is mainly influenced by the crosslinking in the gelling reaction of polyisocyanates with water (see Figure 2). The time dependent behaviour is very important since the viscosity changes in each part of the grout are governed by the time when that specific polyurethane volume came into contact with the water. Consequently, while parts of the grouted volume are still in the liquid foam phase, some of the polyurethane may already have turned into a solid.

Laboratory and field experiments

Expansion tests. The expansion tests aimed to establish a phenomenological understanding of different polyurethanes used for rock grouting, and were performed on four commercially available products, all of the one-component type. The importance of keeping several factors constant was stressed, in order to limit the number of tests. The purpose of the free expansion test was to determine the influence of varying water content, and the controlled expansion test aimed to study the influence of varying counter pressure and size of the measuring vessel. Consistency in the behaviour was of particular interest. The tests provided enough information to enable selection of the most even material to use in the pipe flow tests.

Pipe flow model tests. The pipe flow tests were based on the conceptual model in Figure 1, with stagnant groundwater at a set pressure or flowing groundwater, and aimed to study the behaviour of polyurethane in situations resembling rock tunnel grouting. In the tests against groundwater pressure, the polyurethane pump was stopped when CO_2 was visible at the grout front, i.e. when the reaction between polyurethane and water had started. In this way, the reaction induced penetration and a value of the induction time could be established. In the tests with flowing water, the pump was stopped when a pre-determined amount of polyurethane grout had been injected. A volume criterion was chosen because a consumption limit for the polyurethane grout is regarded suitable in a field situation. The grout was pumped into the water flow and penetrated downstream and upstream, depending on the grouting pressure and the water gradient.

Field tests. The field tests aimed to study the behaviour of polyurethane in a real rock grouting situation. The objective was to predict the grouting process and to observe the reaction between polyurethane and water, by isolating a joint in the rock and grout it with polyurethane. In order to isolate the rock mass to be used, three barriers around the test site were grouted using cement suspension. An artificial groundwater pressure was obtained by pressurising a water curtain in the rock mass and a system for measuring the pressure was installed. The test was successful – the polyurethane grouting was predicted and the reaction was observed through pressure measurements. In conclusion, the flow of polyurethane along a circular-cylindrical fracture was established, and overcoring verified the assumed single water-bearing fracture.

Conclusions for polyurethane grouts

Time dependency. The time dependent behaviour of the polyurethane grout means that it reacts at different times depending on when that specific volume of polyurethane comes into contact with water. When a fracture system is grouted, the penetration due to the gas production is thus promoted to varying extent into different fractures. As a consequence of the time dependent behaviour of the polyurethane grout, the fractures in the rock mass tend to be sealed at varying times. Crucial for the polyurethane penetration is whether the induction time is reached when the grout front passes the fractures, or not.

Newtonian material. The unreacted polyurethane grout can be described as Newtonian, and the viscosity and gel time determine its penetration into a system of rock joints. The penetration rate depends on the viscosity, the fracture aperture, and the driving pressure. An advantage when studying a Newtonian fluid, is that known flow equations and theoretical models can describe the flow of unreacted polyurethane. The penetrability of a polyurethane grout is the same as for other Newtonian fluids, but with its comparatively high viscosity it flows with lower velocity compared with a fluid with lower viscosity (e.g. solutions).

Carbon dioxide gas. CO_2 gas generates when polyurethane reacts with water and contributes to the grout penetration in two ways: (i) by causing the expansion of the foam, and (ii) by increasing the pressure behind the front of reacting polyurethane. No apparent viscosity decrease of the reacting polyurethane, due to the low viscosity of the carbon dioxide gas, could be detected. Probably, the crosslinking during the gelling reaction counteracts such a decrease. However, when a fracture system is grouted, flow of grout is possible in more than one direction and therefore a potential viscosity decrease can be advantageous.

Influence of rock mass character

Active penetration. The blowing reaction between polyurethane and water involves production of urea derivatives and CO_2 gas, which forms the foam. The additional penetration due to the reaction between polyurethane and water is beneficial for the sealing result. The so-called reaction induced penetration of the grout front is linked to the expansion of the polyurethane and the pressure build-up of CO_2 gas behind plugs of hardened polyurethane. The time dependency facilitates the spread of the grout, still in the liquid foam phase, towards zones with lower pressure – the character of the rock mass is an important factor.

Direct communication. Ewert (1992) made a distinction between "direct" and "indirect" communication for fluid flow in different types of rock masses. The main difference for the flow patterns is the amount of possible routes for the fluid and the penetration slows down due to different mechanisms (see Figure 3). To the left, the pressure decrease mainly depends on losses in the many joint openings, while to the right;

the friction between the fluid and the fracture walls governs the decrease more or less completely. The reaction induced penetration is more advantageous in highly fractured rock masses, since flow of grout is possible in several directions. Also, since water is abundant, the polyurethane reaction is complete.

Indirect communication. A rock mass with only a few conductive fractures can give rise to trapped polyurethane grout. An explanation can either be insufficient water supply for the reaction to start or that the surrounding pressure is too high for the polyurethane to release the CO_2. The problem of trapped grout can be solved by one or a combination of the following measures; (i) limit the amount of polyurethane grout, automatically decreasing the risk of trapped polyurethane, (ii) inject cement grout after the polyurethane, supplying the system with water in the suspension, and (iii) create a pressure gradient for the polyurethane to follow (e.g. by use of relief holes), giving the polyurethane reaction a possibility to begin.

Recommendations for application

Volume criterion. As regards penetration, the advantage of long pumping time grows less when the induction time is approached and the reaction starts. Pumping to refusal does result in an increased penetration, but it takes unnecessarily long. Instead, in combination with an awareness of the induction time, use of a volume criterion is advocated for several reasons; (i) the velocity decreases markedly when the reaction starts at the grout front; there is thus no point to continue pumping, (ii) the costs of both material and time are reduced, and (iii) the risk of trapped polyurethane grout is minimised.

Resolute grouting pressure. Since the viscosity of polyurethane is higher than that of water, the polyurethane grout front is stable when it is pumped against groundwater. A resolute grouting pressure should be used when polyurethane is pumped into flowing water, i.e. sufficiently high to cut off the water flow and facilitate grout penetration upstream, thus preventing flushing out of the grout. Then, when the volume criterion is fulfilled and the pumping has stopped, the water fingering into the polyurethane is useful in that it improves the mixing of the two fluids and hence the reaction between them.

Optimal grouting. In the case of large water flows, the polyurethane follows the water flow and mixes effectively with it. To optimise the grouting, the following is recommended; (i) set a volume criterion and employ a resolute grouting pressure, (ii) increase the grouting pressure if the flow of water is not halted, (iii) apply the volume criterion when a stable polyurethane front is achieved upstream, and (iv) shorten the induction time by increasing the amount of catalyst, if the groundwater pressure drives the polyurethane out of the fractures before start of the reaction (other measures to halt the water flow may be required).

Practical use of polyurethane grouts

General considerations. Based on the findings in the study, the following suggestions were made on the use of this type of grout as complement to cement grouts; (i) for sealing of large water-bearing rock joints, in which cement grout is both diluted and transported away by the flowing water, and (ii) for sealing of narrow rock fractures with remaining leakage, e.g. caused by the limited penetrability of the cement suspension used in the pre-grouting. It is advisable to use a volume criterion, depending mainly on the induction time for the material, and a resolute grouting pressure in order to achieve an optimal sealing result. The expansion during the reaction facilitates for sealing of fractures with flowing water, and the CO_2 gas pressure caught behind hardened polyurethane helps forcing the grout into very narrow fractures.

Description of the combination method. Parallel to the experimental study, the so-called combination method was developed by direct application in different projects. The practical experience corresponded well with the findings made in the study, or vice versa. The method makes it possible to adjust the cement grouting to the conditions in the rock mass by combining cement suspension and water reactive polyurethane in the same borehole. The polyurethane grout is transported with the cement grout to the most permeable area in the rock, where the reaction starts after a certain, set time. When a one-component pre-polymerised polyurethane, i.e. TACSS, is used, the reacting polyurethane creates a front against the tunnel surface and the inflow of cement grout into the tunnel is stopped, but the flow in the hole is not blocked.

Why use the combination method? In short, the philosophy of combination grouting can be concluded as: Instead of regarding grouting as a procedure where cement grout is simply forced into fractures from a borehole, a grouted barrier is created by use of polyurethane to limit the spread of cement. Within such a barrier, a cement suspension can then be used without risking for it to be transported away. Post-grouting invariably involves sealing of water flowing or streaming into the tunnel. When only cement grouts are used, there are always situations when the suspension is flushed away by the streaming water or flows out of the fractures before it has cured. It may be attempted to accelerate the cement, but this is regarded a quite complicated process, and experience also shows limited sealing results from that type of procedure.

CASE HISTORIES FROM SCANDINAVIAN PRACTICE

In 1995, polyurethane grouting was performed in the road tunnel Lundbytunneln in Gothenburg. Both to help fulfil the severe leakage demands (down to 0.5 litres/min, 100 m) and to create a barrier to protect a small aquifer, below a clay layer sensitive to settlements, from being flooded with cement suspension. During 1998, a major post-grouting operation was performed in the railway tunnel Romeriksporten near Oslo. Polyurethane was used in combination with cement grout in order to meet the leakage demands. The very positive sealing results were in good agreement with previous experience of the combination method.

Use of polyurethane grouts in Lundbytunneln, Sweden

Project orientation. The Lundby tunnel in Gothenburg, Sweden, is 2050 m long, with two separate carriageways. Each carriageway has two lanes and an average cross-sectional area of 89 m^2. The tunnel leads the traffic along the north shore of the Göta River, below residential areas situated on settlement sensitive ground. The rock mass is mainly granite, but the tunnel also traverses rock with poor quality.
Technical background. Very strict demands were set on the water leakage into the tunnel, varying along the tunnel stretch as shown in Figure 4. Pre-grouting with a cement suspension of grouting cement was performed, starting with a w/c ratio of 3, then lower. Three grouting classes were described for different conditions and the grouting involved many grout holes and a time consuming procedure. The sealing

results were satisfying, but a number of leakages remained in the tunnel roof. Due to possible ice problems during the winter, post-grouting with the polyurethane TACSS was performed. A detailed procedure was established to make sure every type of leakage could be sealed. The basis of the successful post-grouting was systematic utilization of the active penetration of the polyurethane (see also Borchardt, 1993).

Combination method in Lundbytunneln. Polyurethane was also used in combination with cement. For a part of the tunnel, below a settlement sensitive clay layer – Lammelyckan – the rock had poor quality and a cover of about 5 m only, but the demand on water leakage was strict; 0.5 litres/min·100 m. Pre-grouting with cement grout alone was not applicable and TACSS was used to create a barrier to protect the small aquifer from being flooded with cement suspension and to prevent cement from flowing back into the tunnel (see Figure 5). The two different grouts were pumped through a T-piece into the same borehole.

Results of grouting efforts. The strict demands on water leakage were well underway even before the tunnel was completed (see Table 1), and today the total water leakage into the system of tunnels amounts to only 38 l/min. Due to the pollution problems from use of the acrylamide Rhocagil at the Hallandsås tunnel in 1997, the builder then measured possible pollution from the polyurethane TACSS in Lundby-tunneln. The levels of for example DBP were far below the set health and environmental hazard limits.

Use of polyurethane grouts in Romeriksporten, Norway

Project orientation. The tunnel Romeriksporten along the first high-speed railway in Norway, to the new international airport for Oslo, is 14.5 km long (13.8 km in rock) and has an average cross-sectional area of 110 m^2. The rock mass in the tunnel is mainly gneiss of different types, but the tunnel also traverses the major fault between the crystalline basement rock and Oslofeltet. The rock cover is between 20-250 m. For the most part of the tunnel, conventional pre-grouting with cement suspension worked rather well. But the tunnel also traverses weak zones with a large number of water-bearing fractures where pre-grouting with cement was not adequate. Severe depletion of the groundwater level almost emptied a small lake in the vicinity of the tunnel in early 1997 – strict demands were then set on the water leakage into the tunnel.

Technical background. It was attempted to use Rhocagil to seal the large water leakages. The relatively limited use of the acrylamide grout was stopped along with all other chemical grouts, in connection with the pollution problems due to the extensive use of Rhocagil at the Hallandsås tunnel in the autumn of 1997. After that, the post-grouting was performed with accelerated cement grouts, but the sealing results were far from satisfactory. Although the flow into the largest fracture may be stopped when an accelerator is added to the cement grout, much too often blockage is obtained in the borehole as well (see Figure 6). Thus, the spreading of grout into the remaining finer fractures is blocked and new boreholes are required. Chemical grouting was considered again and now very high demands were put on the materials to be used.

Health and environmental aspects. The builder applied with the controlling authority for a trial grouting operation with the water reactive polyurethane TACSS. The purpose of the trial grouting was to study the environmental consequences, as well as to study the sealing effects from grouting with TACSS. Early in 1998, two trial grouting rounds showed that the pollution was well within the set health and environmental hazard limits. A thorough investigation of the polyurethane product TACSS (Aquateam, 1998), comprised a comprehensive survey of the different chemical substances in the grout (DBP, MDI and HDMA) and an evaluation of the possible environmental hazards, as well as the risks associated with the handling of the product. The report concluded that it was acceptable to use TACSS for post-grouting in Romeriksporten.

Combination method in Romeriksporten. By use of a combination of cement grout and polyurethane, the post-grouting performed between February and June 1998 reduced the leakage to 80% of that required. Every one of the 7 grouting teams in the tunnel was provided with equipment for instant use of TACSS, as necessary, combined with cement grout. Combination grouting was used to seal large leakages in the roof and walls of the tunnel without causing blockage in the boreholes. A vast number of concentrated leakages (25-60 l/min) in the tunnel were further sealed effectively by use of polyurethane only. Mostly, when rock with flowing water was grouted, a barrier was obtained at the tunnel surface and the work was terminated. Even so, fractures closer to the grout hole were sealed when still liquid TACSS worked against the water flow. This corresponded well with the results in the study on polyurethane grouts (Andersson, 1998).

Results of grouting efforts. Figure 7 illustrates the marked sealing effect obtained during the first period of the post-grouting in Romeriksporten with the water leakage into the tunnel vs. bored meters of grout holes. Naturally, the remaining leakage was more difficult to come to terms with and needed much effort. Small leakages are more difficult to locate and, as the tunnel is getting tighter, the increasing groundwater pressure also render the sealing more difficult. In Romeriksporten, flushing out of cement grout was a central problem. However, grouting with cement and TACSS was successfully used for sealing of a rock with water leakage through single fractures, albeit high groundwater pressure and large water flow.

CONCLUDING REMARKS

The reasons for using polyurethane as complement to cement grouts may differ – it is recommended for sealing of large water-bearing rock joints and for sealing of narrow rock fractures with remaining leakage. In conclusion, combination grouting with cement and a water reactive polyurethane of type TACSS can be used with success for sealing of a rock mass, albeit high groundwater pressure and large water flow.

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Table 1 Maximum permitted water leakage into the Lundby tunnel vs. measured leakage into the tunnel by February 1997 (in l/min, 100 m)

Sections of the Lundbytunnel	0/600-1/190	1/190-1/780	1/780-2/040	2/040-2/660
Maximum permitted water leakage	2.5	1	2	0.5
Measured leakage into the tunnel	1.1	0.9	1.5	0.85

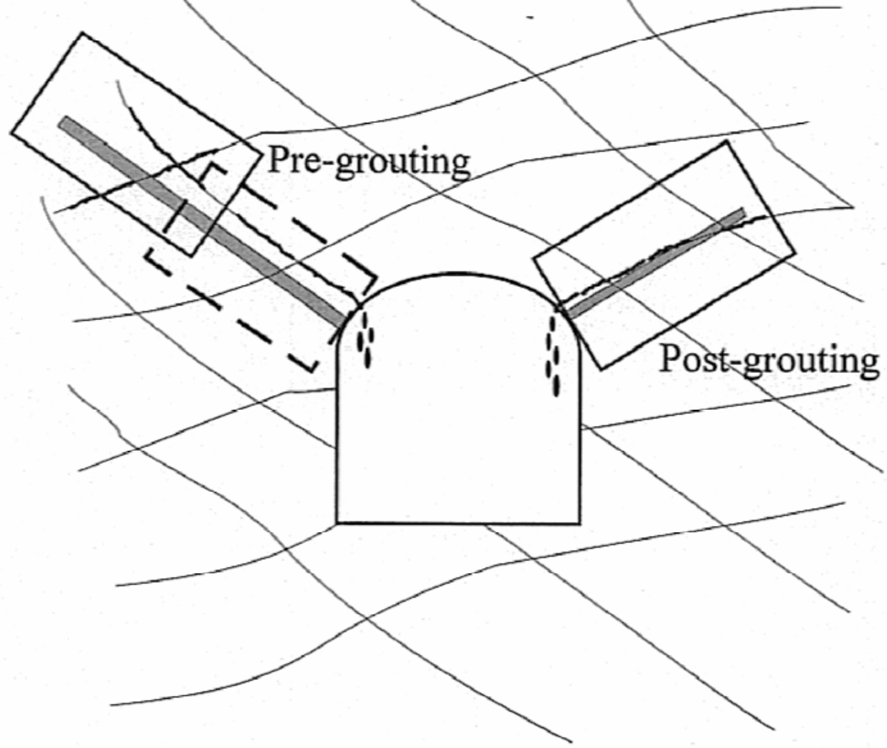

Figure 1. Conceptual model for pipe flow tests – a hypothetical grouting situation *(Andersson, 1998)*

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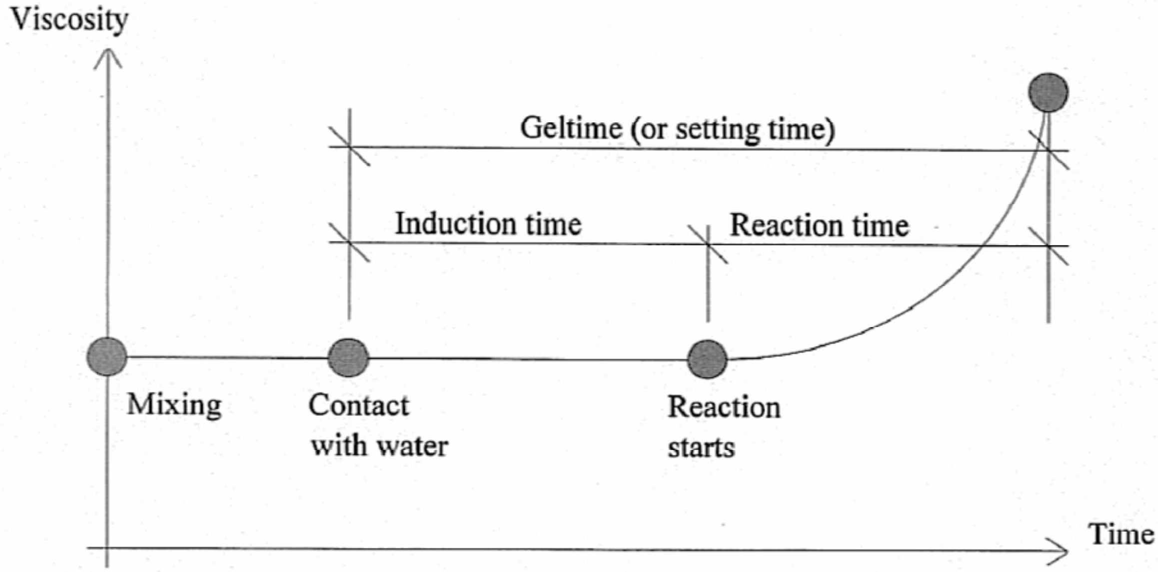

Figure 2. Principle time dependent change in viscosity for one-component polyurethanes

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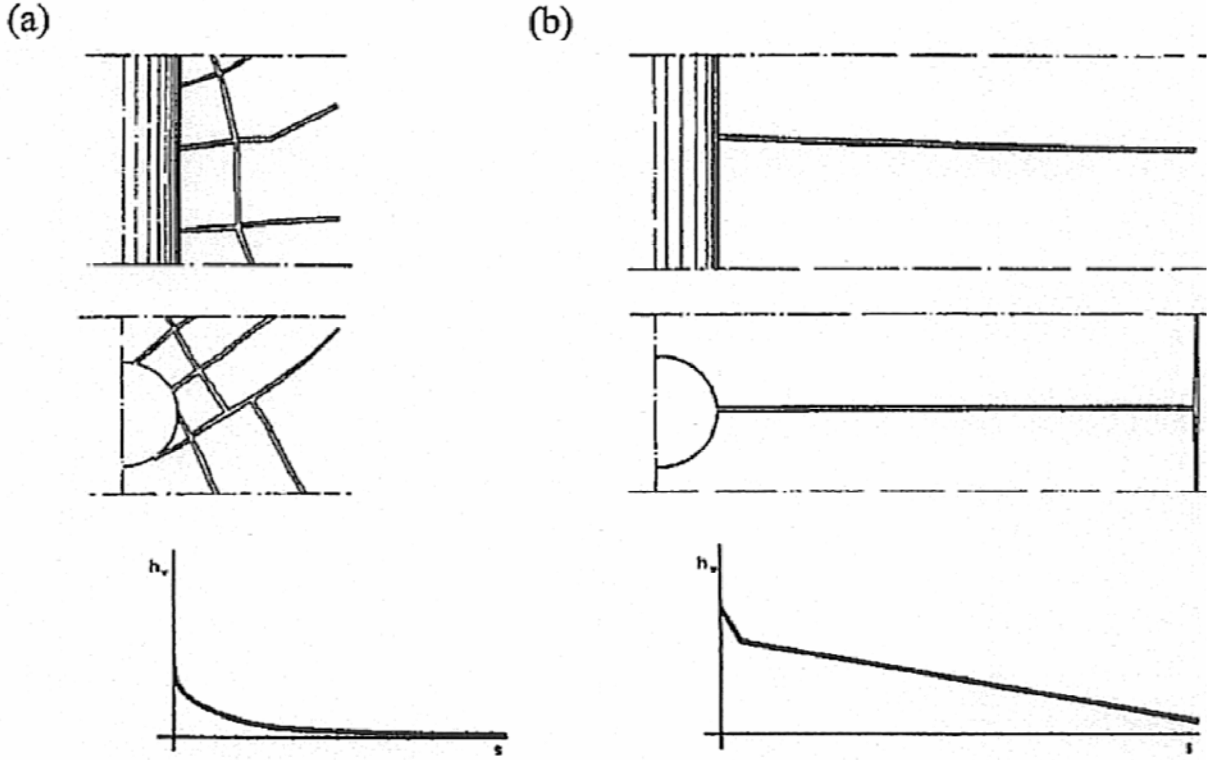

Figure 3. (a) Direct communication, and (b) indirect communication *(after Ewert, 1992)*

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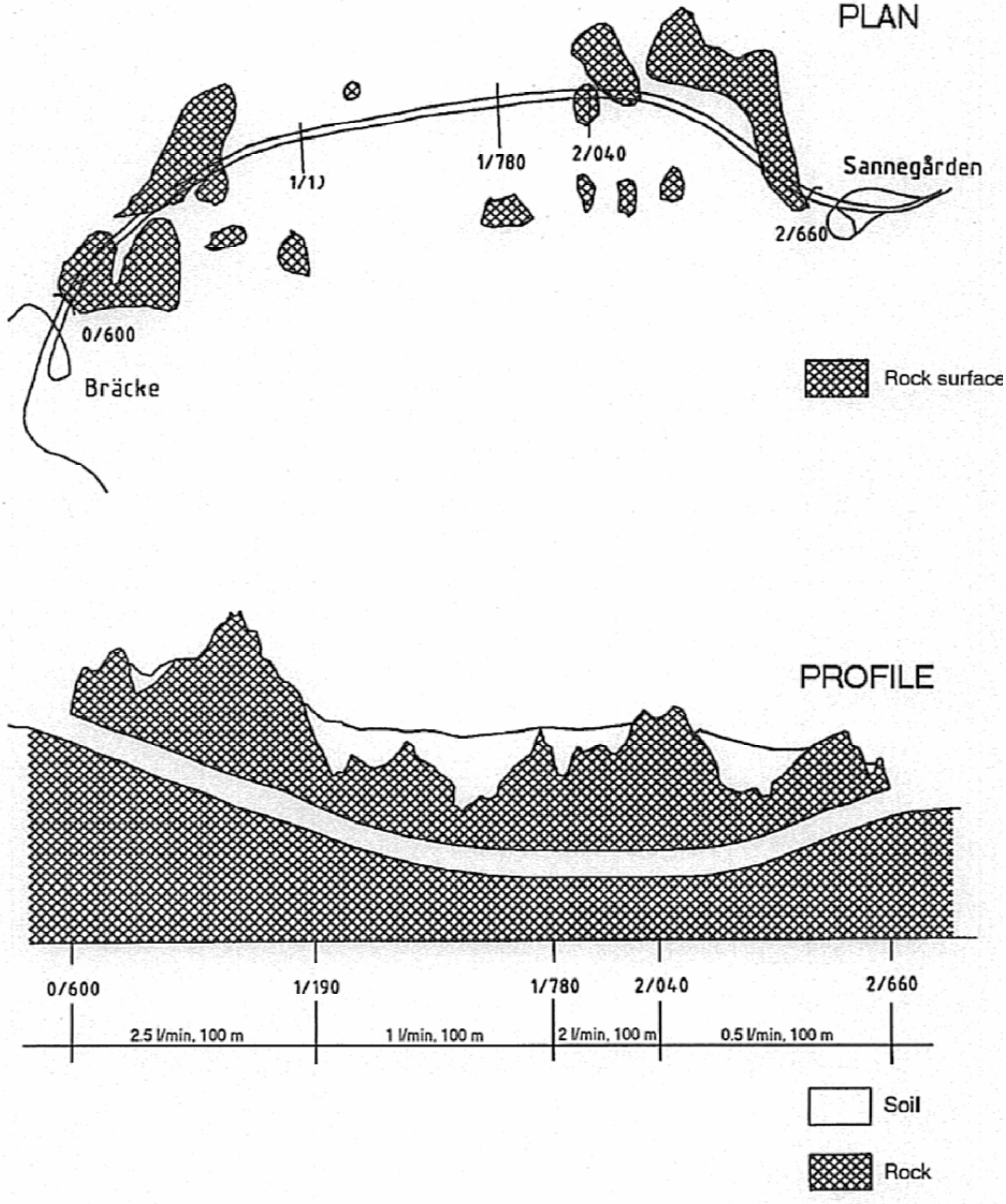

Figure 4. Plan and profile of the Lundby tunnel (exaggerated height scale), including permitted water leakage into the tunnel *(after Eriksson and Palmqvist, 1997)*

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Figure 5. Profile of the Lammelyckan section at Lundbytunneln – combination grouting with cement and TACSS polyurethane

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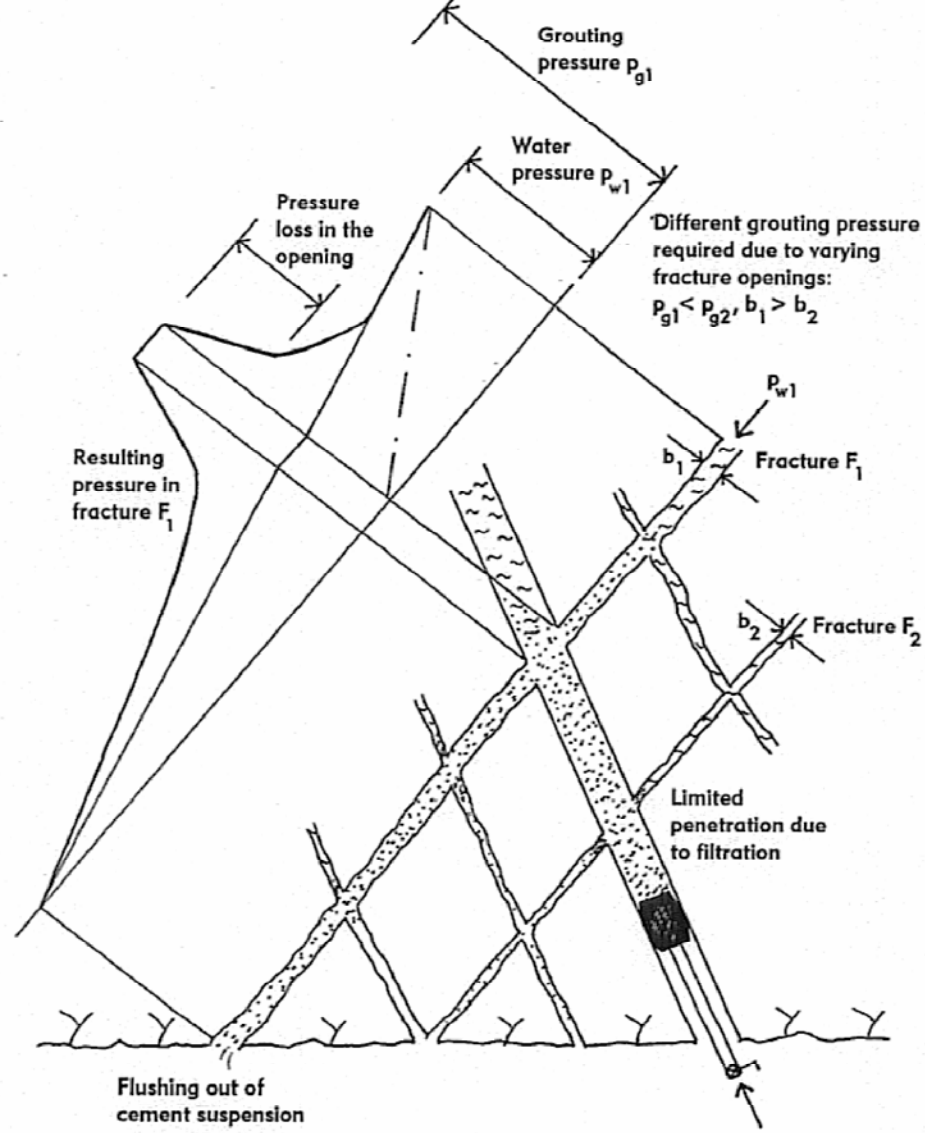

Figure 6. Penetration of the grouting material requires variable injection pressure for different fracture openings *(after Borchardt, 1993)*

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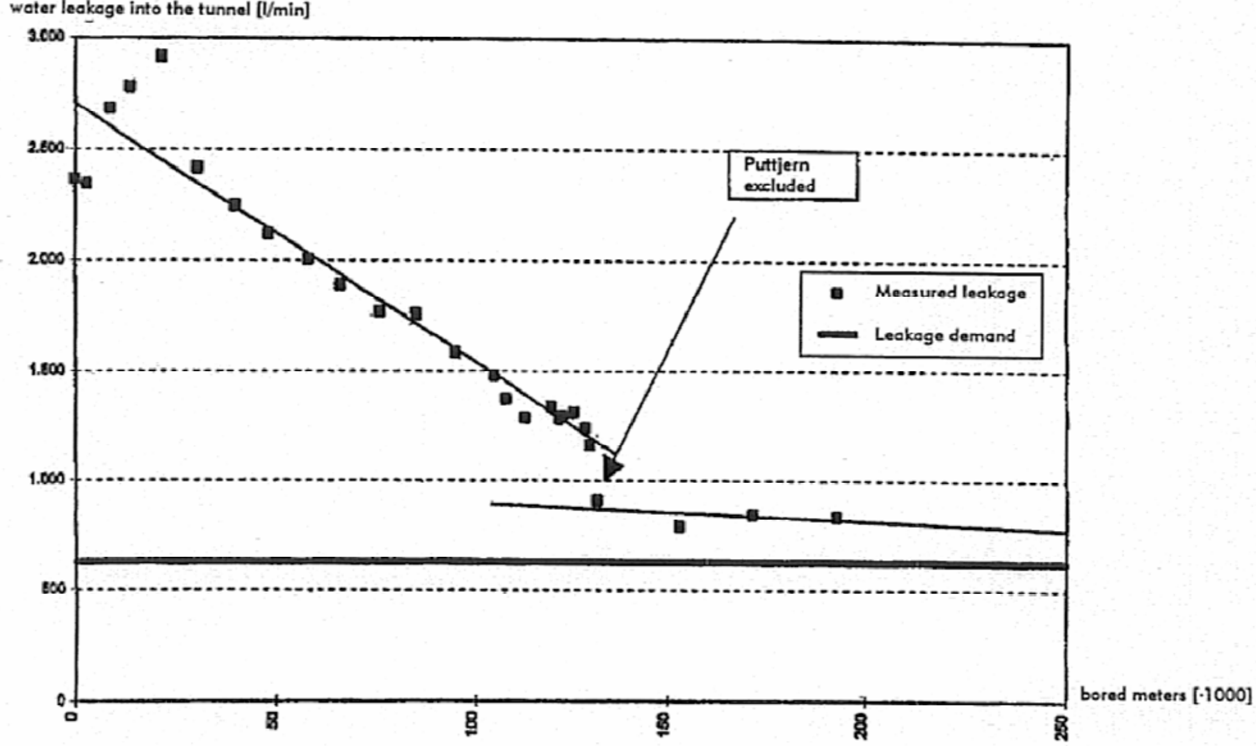

Figure 7. Measured water leakage into the Romeriksporten tunnel vs. bored meters of groutholes

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