INJEKTERING I TEORI OCH PRAKTIK

Grouting in theory and practice

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Sammanfattning

Stora satsningar har gjorts av BeFo, Trafikverket och SKB de senaste 25 åren för att fördjupa kunskapen om berginjektering. De har inneburit att de grundläggande mekaniska och hydromekaniska teorier som styr flödet av bruk i bergets sprickor har kunnat kartläggas och beskrivas. Många har deltagit i detta arbete. Speciellt bör nämnas all de doktorander som med sina avhandlingar har aktivt bidragit till fördjupningen. Svensk forskning inom hydrogeologi och injekteringsområdet har sammanfattats i två böcker. Den ena är ”Hydrogeologi för bergbyggare” från 2009 av Gunnar Gustafson och den andra är ”Rock grouting - theories and application” från 2015 av Håkan Stille. Detta föredrag bygger i huvudsak på dessa två arbeten.
Det är författarens förhoppning att denna fördjupade kunskap inom berginjektering skall öka förståelsen om brukets spridning i bergsprickor och utgöra ett naturlig redskap för varje ingenjör som arbetar med bergfrågor.

Summary

BeFo, Swedish Traffic Administration and SKB have greatly contributed the last 25 years in order to develop the art of rock grouting. This has implied that basic theories about spreading of grout in rock fractures and jacking of rock fractures have been developed. Many have taken part in the research work. Especially all the doctoral students ought to be mentioned. The results of the Swedish research in this field have been summarized in two books. One is ”Hydrogeology for rock engineers” by Gunnar Gustafson (translated into English 2012 from the Swedish publication published in 2009) and the other is ”Rock grouting - theories and application” from 2015 by Håkan Stille. This presentation is mainly based on this two works.
It is the hope of the author that this development will provide the international geotechnical society with a better understanding of the basis for rock grouting and be valuable tools for all rock engineers.

Introduction

Groundwater-related problems are common in rock engineering. Changes in groundwater levels can have a considerable impact on the environment. Seepage may wash out the material filling the rock fractures and erode the rock, which may in turn have a long-term effect on the strength and stability of rock structures. The flow of water induces seepage forces and a change in pressure modifies the natural effective stress, which may have an immediate effect on the strength and stability of rock structures. Rock tunnels, rock slopes and dams founded on rock are typical constructions that are exposed to the adverse effects of water flow and a change in water pressure, both during excavation and the operation of related facilities.

Drained structures are often used. The water ingress and flow could be channelled and pumped out or flow out unaided. However, this must be avoided if it results in operational problems, negative environmental impact and if it has a negative effect on the longevity of the installations. Groundwater reservoirs are important societal resources and cannot be exploited without serious consequences. Water leakage must be prevented or reduced by cutting off the groundwater flow.

A common technique to reduce groundwater flow is to seal the water-bearing fractures of the rock mass by means of grouting. Boreholes are drilled and grout is injected under pressure to fill the open parts of the fractures. Cement-based grout is commonly used as it is relatively cheap, sustainable and has limited environmental impact.

Grouting techniques are described in many textbooks, including Houlsby (1990), Weaver (1991) and Evert (1985). These books are based on the authors' long and deep experience of grouting. Grouting technology is often explained using empirical rules. Grouting is complex and many different disciplines and issues are involved. Successful grouting must be based on good knowledge about the geology, the water-bearing fractures of the rock mass and the material properties of cement-based mixtures. It is also important to know about the technology behind mixing and injecting the grout into the rock. The maximum grouting pressure is of particular interest since jacking of the rock can often result in damage to the structures above and have a negative impact on the sealing effect of the rock mass.

Until now grouting has mainly been regarded as a handicraft. The design – establishing the drill pattern, grouting pressure, suitable grout recipes and the stop criterion and completion criterion – are all based on experience. Verification of the grouting design is based on the adoption of prescriptive measures.

Stricter requirements in combination with the fact that the grouting work is normally time critical, e.g. on the critical line of the tunnel excavation work and thus directly affecting the time it will take to produce one metre of tunnel. This has caused the focus to shift to more effective grouting processes. Grouting has been studied from a more scientific perspective in order to complement the empirical rules.

In recent decades extensive research has been conducted to acquire a better understanding of the complex mechanism that governs the spread of grout in fractured rock. The focus has been on the theories of grout spread with a particular emphasis on physics in relation to mass, momentum and energy constraints. This has produced theories and analytical solutions for grout spread with account taken of pressure and flow rate control. Hydraulic jacking has also been studied theoretically, based on mechanical principles, resulting in equations describing the opening of the fractures due to grouting pressure and grout spread. The importance of restraints on the volume and pressure has been emphasised. The properties of cement-based grout have also been studied as well as the relationships between flow properties and the type of cement, the water-cement ratio and the additives. The ability of cement-based grout to penetrate rock fractures has been investigated and it has been shown that it is not only the relationship between the size of the largest cement grains and the fracture apertures that governs the penetrability. In addition, the geometry and transmissivity of rock fractures have been examined, producing a much better understanding of groundwater flow and seepage through rock masses. These studies will form a conceptual model of the sealing effect of different grout mixes, the spread of grout in fractures and the grout takes. Theses produced by the Academy in Sweden related to rock grouting are shown in the reference list.

Aim

The aim of this presentation is to present the theories behind grouting of fractured rock using cement-based grouts. The theories have been applied to both tunnel and dam grouting and have been tested for different types of geology. They have been found to be sufficiently accurate and practical.

Water ingress into tunnels

Tunnels excavated below groundwater level change the water pressure conditions. The tunnel acts as a well and the water flows towards the tunnel as long as the water pressure outside the tunnel is higher than inside the tunnel. The volume of water and the flow rate depend mainly on the depth below the groundwater level and the resistance to the flow is often described using the hydraulic conductivity of the rock mass.

Engineering problems related to tunnels and water ingress vary in nature. The volume of water flowing into the tunnel can give rise to problems with excavation. Almost every aspect of the excavation cycle, such as mucking, drilling, charging and rock support, would be affected negatively by large-scale water ingress. Tunnels have been delayed and even abandoned due to sudden and very high water ingress. Concrete lining work and shotcreting require dry conditions to achieve good results. Even low levels of water seepage may have a negative effect on the quality of the work.

Even a small ingress can produce a high level of humidity, which could give rise to functional problems due to corrosion of equipment in the tunnel. It could also result in negative environmental effects due to the lowering of the groundwater level following subsidence and with the drying up of wells as a result. It all depends on the hydrological balance between infiltration of rainfall and discharge of water.

Water flow may cause instability due to internal erosion of fracture filling and erodible rocks. Flowing water exerts shear stresses on fracture surfaces. When the shear stresses exceed the shear resistance of the fracture filling, the water will pick up particles and erosion starts. The shear stresses increase with the gradient and fracture aperture. Water pressure, built up close to the tunnel surface, can be dangerous.

In many cases highly complex aspects need to be taken into account. In urban areas where groundwater lowering is unacceptable, the ingress level is very low: in the order of a few litres (2-5 l) per minute per 100 m of tunnel. In more rural areas and with a surplus of water from heavy rainfall, much higher levels of water ingress can be accepted. Ingress higher than 50-100 l/min per 100 m of tunnel will normally lead to practical problems related to pumping and disposing of the water. The function of the tunnel will influence the acceptable level of ingress. Tunnels for conveying water, such as headrace and tailrace tunnels to hydropower plants, can tolerate quite high ingress. The acceptable level is of course much lower for traffic tunnels if negative effects on the function are to be avoided.

In many cases it is possible to drain the tunnel and pump out the water. However, this may not always be possible or even the most economical solution. In such cases the flow of water must be reduced or prevented, which involves injecting grout to fill and seal the rock fractures. Resistance to water flow increases and ingress is reduced. Experience shows that this injection work should be carried out before the water ingress towards the tunnel front has become too high. The procedure is known as pre-excavation grouting or front grouting or simply pre-grouting. However, this work delays tunnel excavation and becomes time-critical work for most tunnels.

Pre-grouting starts with drilling a number of boreholes into the rock ahead of the front. Packers are installed and connected to the grouting equipment. The grout mix is injected under pressure into the boreholes. The grouting pressure must exceed the groundwater pressure for the grout to spread. Grouting is terminated when the stop criterion is reached and tunnel excavation can commence. Normally, a new grout fan needs to be carried out a couple of metres before the previous fan ends. This will produce an overlap and a grouted front, which reduces water flow into the front to acceptable levels. The aim of the grouting is to create a grouted zone around the tunnel by sealing the rock fractures and by doing so reduce the water-bearing capacity of the rock mass to an acceptable level. The procedure is shown in Figure 1.

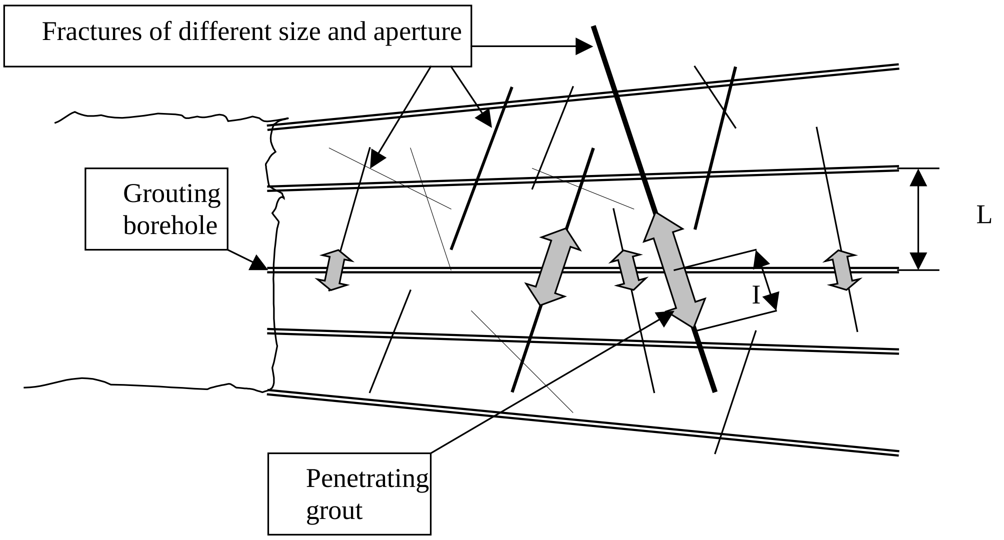

Figure 2. Outline of pregrouting ahead of the tunnel front. (L is the hole spacing and I is the grout spread), Gustafson and Stille (2005)

Water flow under dams

Dams are commonly built on rock. Water losses due to seepage may occur. Loads from the dam and the reservoir, including the effect of water pressure, may result in unacceptable settlement. Grouting is therefore used in conjunction with dam and foundation work to improve ground conditions. The primary aim is to reduce the hydraulic conductivity but also to improve the stiffness of the ground under the dam or foundation. These two specific features are called curtain grouting and consolidation grouting. The type of grouting used in both cases is permeation grouting, which means that the grout must penetrate the fractures and spread into the rock mass.

The primary aim of the grout curtain is to reduce water loss due to leakage under the dam to an acceptable level. The curtain also reduces the water velocity to reduce the risk of internal erosion of fracture filling of clay and silt and erodible rock to an acceptable level. The risk of adverse uplift from water pressure acting on the dam must be controlled. The drainage gallery and drainage boreholes need to be designed specifically to reduce the uplift.

The water loss depends mainly on the gradient over the curtain, the hydraulic conductivity and the depth of the curtain. In the case of lower dams, water loss through a curtain is normally acceptable when the hydraulic conductivity is less than 10-6m/s. In these cases there must be a balance between the economic loss and the cost of the grouting. For high dams and in areas where the water is more valuable or when there is a risk of hazardous groundwater flow, much lower hydraulic conductivity is required.

The risk of dam instability and clogging of drains due to internal erosion of clay and silt filling are related to the water velocity in the fractures of the rock mass. Local erosion may be regarded as acceptable as it will not affect dam stability. The water velocity depends on the gradient, fracture apertures and pathway geometry. If piping of foundation material needs to be prevented, prudent engineering (Houlsby 1990) recommends that the hydraulic conductivity should be less than 3·10-7m/s. The acceptable figure depends on the type of dam and curtain and the geological conditions.

There seems to be a tendency nowadays to use lower figures for acceptable hydraulic conductivity of the rock under dams. This is related to the need for a longer lifespan and the increasing cost of remedial work or the cost of shutting down the plant.

The curtain of grouted rock will reduce the groundwater flow and the risk of adverse uplift of the dam. Consequently, most of the pressure drop is over the curtain, given a substantially reduced uplift and hydraulic gradient downstream of the curtain, thus minimising the risk of erosion in the most sensitive area of the dam toe. However, the gradient through the curtain is increased significantly and consequently the risk of internal erosion.

The outline of a grouting curtain is shown in Figure 2.

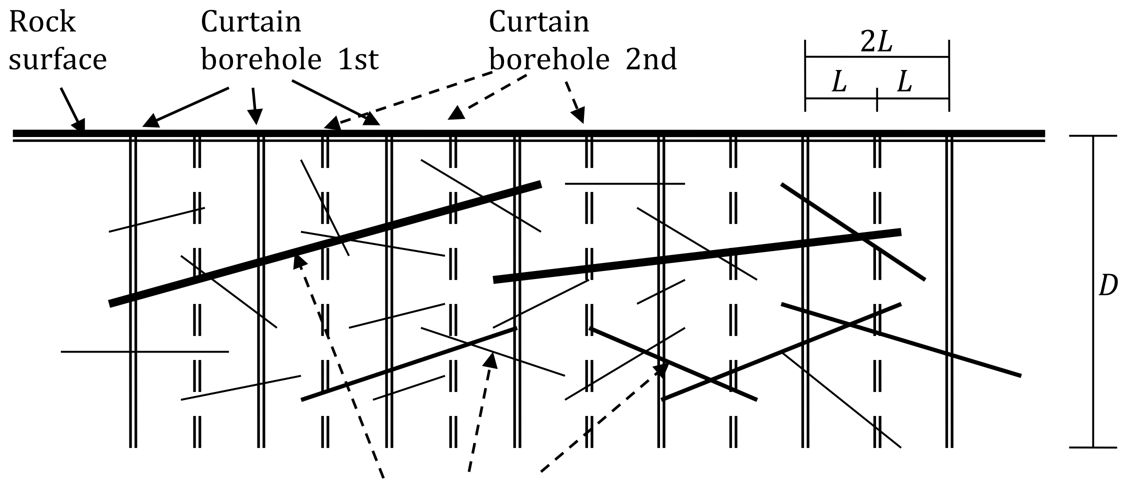

Figure 2 Outline of a grouting curtain, Stille et al. (2012)

A suite of boreholes is drilled along a line to depth D. After drilling, testing and grouting, a new series of boreholes is drilled, tested and grouted in a split-spacing configuration. Normally, at least three batches of holes are drilled and grouted (primary, secondary and tertiary holes). The advantage of this procedure is that the effect of the grouting of the previous batch can be controlled by the new boreholes, positioned among the new previous batch of boreholes. For higher dams the curtain will normally consist of several rows of boreholes, resulting in a wider curtain.

The aim is to inject grout into the fractures where the distance from the boreholes is such that the critical fractures in the gap between them are filled sufficiently with grout. This implies that the hydraulic conductivity of the rock in the grouted curtain is reduced significantly. This is achieved by having a spread in these fractures that is more than half the distance between the boreholes. This can be done based on knowledge of the hydraulic properties of the fractured rock, a correct choice of grout mix and a well-adapted grouting technique.

Dam grouting is carried out closer to the surface in comparison with tunnel grouting, which implies that the risk of the ground jacking as a result of the grouting pressure is much more prevalent. Dam grouting can be carried out by using parallel equipment. The grouting work is normally time critical, e.g. on the critical line of the dam construction work and thus directly affecting the time it will take to build the dam. This is pronounced for the lowest part, where no dam filling work can be carried out before the ground curtain is carried out.

Conclusion

Grouting of rock fractures to reduce the water-bearing capacity of the rock mass is important in many civil engineering projects. The aim is to fill the fractures by injecting grout and pressurising the mix. It has been found that theories describing the spread of the grout in fractures are applicable and can describe the process with sufficient accuracy. It has also been found that the application can reduce the grouting time substantially. However, grouting is a complex process and many different disciplines and subjects are involved.
The presentation discuss the theories and how they are connected in order to facilitate their application and provide a basis for further development of the art of grouting.

The theories will also enable the observational method to be applied. The experience-based stop criterion and completion criterion can be changed to more relevant grout spread criteria. The grouting process can be controlled and adjusted in real time by applying the theories to ongoing grouting operations.

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