# GROUTING ON THE KÁRAHNJÚKAR HYDROELECTRIC PROJECT'S TUNNELS

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## ABSTRACT

The Kárahnjúkar project in the eastern highlands of Iceland is a large hydro power project consisting of a big concrete face rock fill dam, 2 smaller saddle dams and some 72km of tunnels feeding a 690kW generating plant. The project is a vital element of establishing industry in this remote area of Iceland required to try and stop the population flow to Reykjavik, however it has attracted significant attention as an environmental catastrophe.

The dams and the tunnels both require considerable amounts of grouting work making this technology a significant portion of the project. Grouting on a hydro project includes mostly curtain grouting and some consolidation and contact grouting for the dams and while in the tunnels, a certain amount of curtain grouting is also required the contact and consolidation grouting is far more important. Most of the contact and general consolidation grouting is planned and included in the engineering drawings, whereas in the tunnels, the consolidation grouting consists of pre injection and post injection works which are required as a reaction to the prevailing ground conditions. The grouting also provides a ground support benefit, enhancing rock mass stability.

The traditional grouting where sub contract crews carry out the work according to well established industry practices without any real impact on the production aspects of the project are generally carried out effectively. However there is a significantly different attitude both from management and the labour force to the ad hoc grouting that is required to deal with the exceptional inflows of water and the work is generally carried out to sub standard level of quality and performance.

The reasons for these difficulties are examined and discussed with the conclusions being that a combination of incorrectly applied equipment and inappropriate labour skills contribute to the poor results. Cooperation and planning by all levels of management including the instructions being given also has a significant effect on the success or failure of the various elements of the water sealing efforts.

Major improvements were made through improved relations between the contractor and the representative where the systematic injection of the leaking areas under the valley floors is in critical financially and environmentally sensitive areas. However there are several major inflows where attempts have been made to seal off water flows up 250 l/s that were unsuccessful and these still require considerable cooperation and resources to mange effectively during the future finishing works.

# 1 Introduction

This paper discusses some of the problems encountered with water ingress on the 72km of tunnels on this project. Grouting is always a significant portion of dam projects and with the quantities of water expected in the tunnels, was also going to be an important element of the underground works as well. However it is unlikely that anyone could have foreseen the extent of the problems to be encountered with the water inflows and grouting requirements actually being experienced. Grouting to deal with water problems also contributes a ground support element, improving the stability of the rock mass.

Case studies are included for both pre grouting and post grouting, however only very limited examples are used that were actually experienced during the study period which extended from the end of April 2006 through to the beginning of September 2006.

# 2 Project arrangement

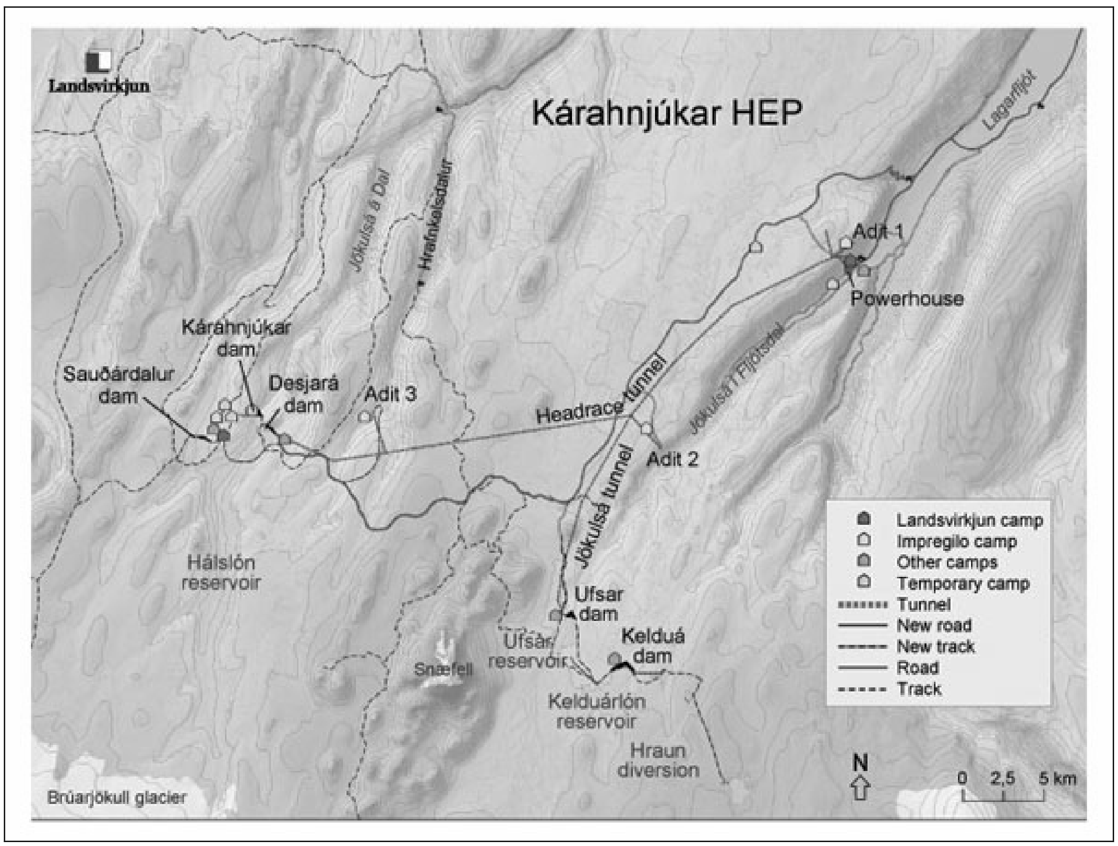


**Figure 1 Overall project layout**

The project is based on a head of about 600 metres. The installed power of the Kárahnjúkar project is 690 MW, produced in six generating units. Maximum flow is 144 $m^3$ per second and

the annual generating capacity is about 4,600 GWh. To generate this energy, the Jökulsá River is dammed by three dams, the largest, a concrete-faced rock fill dam (CFRD), is located at the southern (upper) end of the Hafrahvammar canyon and is about 730 metres long and 193 metres high. Completing the trio are two smaller earth core rock-fill dams and together the three combine to create the main 57km$^2$ Hálslón storage reservoir (
Figure 1). When full, the water level will reach a height of 625 metres above sea level, and its shores will reach the edge of the Brúarjökull glacier.

From the Hálslón reservoir, the water runs through a tunnel to a junction with another tunnel running from the Ufsarlón reservoir, and from there is carried north-east through a combined headrace tunnel to an intake at the Valþjófsstaðafjall escarpment a total length of 53 km varying in depth from 100-200 metres.

Two steel-lined vertical pressure shafts lead the water from the intake to the underground powerhouse. Each shaft is 420 metres high, and the total head of the project is 599 metres. The powerhouse houses six Francis turbines, each with a rated output of 115 MW.

The headrace tunnels and parts of the access adit tunnels will be drilled using three full-face (TBM) boring machines, while the remainder are excavated by drill and blast.

An extensive Environmental Impact Assessment (EIA) on the Kárahnjúkar hydropower project was completed in 2001. Following a final positive ruling by the Ministry for the Environment, legislation authorising the project was passed with a sizable majority by the Icelandic Parliament, the Althing, in 2002. Later the same year, the Ministry for Industry issued the necessary permit, and the local municipalities concerned then issued a construction permit in February 2003.

Electricity generated at the Kárahnjúkar power plant will be transmitted to the Fjarðaál aluminium smelter to be built in the port of Reyðarfjörður on Iceland's east coast and a 40-year contract to provide power for the plant was concluded with US multinational Alcoa in March, 2003.

# 3 Environmental Policy

An important aspect of the Kárahnjúkar HEP project is the environmental impact the project may have on an area of remote and almost untouched wilderness. During the preparations for the project it has been actively aimed at to show consideration for the environment. The project layout is the result of cooperation between the designers and the EIA scientists, as well as the conclusion of the Government in its ruling on the environmental impact of the project. All structures have been designed to appear neatly in their surroundings and to cause minimum impact to the environment. The Icelandic Minister for the Environment approved Kárahnjúkar Power Plant with a list of twenty conditions. Two of the most influential conditions were that:

- Several diversions will not be carried out, particularly in Phase 2 of the hydroelectric project, so as to lower its environmental impact. This means much less curtailment of the open expanses surrounding Snæfell Mountain.
- The design and arrangement of the largest dam holding Hálslón are modified so that overflow water will run into Hafrahvammagljúfur canyon. Not only will flow through the canyon during the late summer of most years remain similar after development, but damage is avoided that would stem from an overflow through Desjarárdalur valley.

# 4 Geology

The bedrock in the project area consists of an approximately 2700m thick sequence of basalt flows with intercalated sediments and moberg formation of various kinds. The basalt is classified into the three following petrographic types: tholeiite basalt, olivine basalt and porphyritic basalt.

The accumulation rate of lava and the average period between eruptions in the Fljótsdalur-Jökuldalur area have been determined to be about 500m/My and 20,000 to 30,000 years respectively.

Sediments in the area occur as intercalations between lava flows as well as thick accumulations filling depressions and old valleys. Moberg formations occur in the upstream part of the project as buried bodies of pillow lava, pillow breccias, tuff-breccias and tuffs.

# 5. Grouting for the tunnels of the Kárahnjúkar project

Jet, compaction, permeation, and hydrofracture grouting methods are frequently used in soft ground excavation whereas hard rock grouting generally require the application of consolidation grouting and contact grouting where secondary linings are placed. Curtain grouting is less routine in tunnels however is commonly used in hydraulic structures such as the head race tunnels of a hydropower project where high pressure water is present.

The characteristics that make hydropower projects particularly grouting intensive are the safety and water retaining capabilities of the dam itself. Combined with this is the requirement for considerable distances of underground construction where each different application has a different inflow regime. An underground powerhouse with critical equipment installed to high tolerances will require a dry environment. On the other hand a low pressure tailrace tunnel has no constraints on additional water entering the tunnel.

A high pressure headrace tunnel will have many different aspects regarding the inflow and outflow specifications including environmental and aesthetic elements involved with rising of the water table. Kárahnjúkar Hydroelectric Power Project is a typical large hydropower project with extremely complex grouting requirements. Applications of grouting required on the underground sections of the project include:

- Consolidation grouting
- Contact grouting
- Curtain grouting
- Tunnel Pre injection
- Tunnel Post injection

Concerted supervision of the tunnel pre and post grouting activities was only effectively begun upon the arrival of a senior grouting inspector in March 2006. By the end of May there was team of four grouting inspectors supervising the tunnel grouting as well as the consolidation, curtain and contact grouting in the tunnels during finishing works. With the arrival of a grouting team the whole process involved in the grouting on the project came under considerably more intense scrutiny.

One of the main reasons for this scrutiny was the fact that the owner's representative was not particularly happy with the end results being produced and felt at times that there was an excessive wastage of materials for which the contractor was being paid. This was compounded by the extremely high volumes of water flowing out of the tunnels, especially adits 2 and 3 where at times over 1000litres per second were being recorded. These high quantities of water were compensated to the contractor at an increasingly high rate leading to significant monthly payments for water control. Naturally there was the potential for the opinion that it was more advantageous for the contractor to allow the water to flow than plan and carry out an effective grouting programme to reduce these payments.

## *5.1 Tunnel Pre Injection*

In the specification documents the tunnel pre injection is referred to as consolidation in the machine/heading zone ahead of the face. The purpose of the pre injection is to consolidate and improve the stability of the heading face or seal off the inflow of groundwater.

- Tunnel pre injection is generally considered in drill and blast drives when one or a combination of the following is encountered:
  - a) Sudden inflow exceeding 40 l/s occurs at face;
  - b) Water inflow from a single pilot hole is larger than 10 l/s and from three pilot holes exceeds 25 l/s;
  - c) Water inflow under high pressure is observed from pilot holes;
  - d) Unstable saturated ground ahead of the face is indicated by pilot holes or by significant worsening of conditions at the face.
  - e) Fault, dyke or shear zone with an extensive area of severely disturbed ground is indicated by pilot/probe holes.
- Pre injection will generally only be considered in TBM drives in the event of large inflows from the face.

A key factor of pre injection for both TBM and drill and blast headings is that thorough critical zones grouting should be carried out systematically. This proved to be unrealistic due to production pressures and therefore water encountered was eventually left to be dealt with by post grouting.

## *5.2 Tunnel Post Injection*

For the Kárahnjúkar headrace tunnels the post grouting was required for three main reasons. The first of these was to reduce the high costs to the client of payments to the contractor for dealing with the high volumes of water. Secondly from an excavation point of view this volume of water was not a major problem although minor difficulties were encountered for the maintenance of the rail tracks due to the flow of water and debris around the sleeper blocks. The major challenge arises from the finishing works that are going to be needed with post injection to reduce the high level of water inflow from the relatively few major features that have been encountered.

The third and most politically significant reason was that in the areas of low overburden grouting was required to prevent the outflow of water from the tunnel. Any outflow of water will have two effects, one financial and the other environmental. Financially, any loss in volume will affect the power able to be produced at the turbines. An outflow of just 100 l/s will lead to lost power worth approximately €1million per year. Environmentally it is an important requirement in the design and construction of the tunnels that the hydro geological system is not unduly affected, especially on the surface.

There are 3 specific areas along the preliminary stretches of the tunnel where the overburden is such that the full head of water from the dam could cause leakage of water from the tunnels to leak out to the surface. These areas are Ch0 to Ch3+100, Ch4+500 to Ch6+400 and Ch7+500 to Ch10+100. In these areas systematic grouting is required and in general all leakages into the tunnel will indicate points where water may escape from the tunnel.

For the systematic injection, the methods revolved more around the materials used, which on this project was Degussa (now BASF) two component PU grout Meyco MP355 A3. For the major features the materials play a much smaller part in the process and the following is a general guideline on how to deal with major water inflows by post grouting.

One of the first technical situations to understand in performing effective post-grouting is that the proper preparation has to done at the tunnel surface around and in the point(s) of flow. The preparation phase requires an enormous amount of time as well as sound engineering, the proper equipment, tools and materials together with knowledgeable crews having a sufficient numbers with the appropriate skills.

To properly prepare the area of tunnel having the flowing water, one must adapt the following basic methods:

1. Clean out to the fissure of all loose, unsound material.
2. Set as large diameter (75 to 125-mm) pipe(s) into the fissure as appropriate
3. To force the flowing water into pipe(s), seal around the pipe(s) and as deep into the fissure as physically possible using a variety of materials such as bags of sand and/or cement, wood blocks and wedges, rags, fast setting mortars, and finally shotcrete. This step is very important and the one most neglected. It is unlikely that one can go overboard in performing this step.
4. Place valves and/or caps on the pipes, and shut all of the valves.
5. Watch for leakage in the vicinity. It is highly likely that there will be additional leakages commutating with major flow leakage points.
6. If the grout leakages are greater than the available grout injection rate, repeat steps 1 through 6 until all of the leaks are sufficiently sealed.
7. Now drill injection holes into feature, set the packers, and close all valves except an appropriately placed relief hole at the very highest point of the feature.
8. Once these steps have been successfully followed the grouting material may be injected into the feature.

Note: If steps 1 to 5 are followed effectively a 70 to 80% reduction of ground water flow from a large feature may be expected. The injection of the grout material is to make this temporary sealing arrangement permanent by sealing the water further into the solid rock.

## *5.3 Equipment*

As with pre injection the basic tools of post grouting are the drill, pump and packer system. The SK90 was the pump recommended by Degussa (BASF), the supplier of the PU grout being used. The key factor with the pumps was maintenance and the compressed air requirements, especially the high volume required by the SK90.

Drilling for the post injection was either using the production drill jumbo equipment in the drill and blast sections or hand held drill rigs and air legs in the previously excavated TBM tunnels. Neither method is ideal or recommended. By hand, the work was extremely slow and exceptionally heavy labour while using the drill jumbo interfered with the production in the drill and blast headings.

There was also limited access to a Tamrock Commando hydraulic drill rig mounted on flatbed rail car, but this was rarely used, and caused considerable congestion in the tunnel. This was not acceptable when the TBM was boring and required materials to be supplied to the face or muck transported from the drill and blast headings.

For the systematic post grouting a platform was constructed running on the rails. The drilling was performed by hand from this platform and was the most labour intensive and time consuming part of the process. The platform was towed to the required chainage using the locomotives servicing the drill and blast section of the drive. This initially led to some conflict with the drill and blast sub contractor regarding slowing the mucking cycle. However, this was later overcome and the moving of the platform was planned to coincide with the drilling when the locomotives were not required.

The pumps were all pneumatically driven and the air supply was provided by an Atlas Copco XAS186 compressor, installed in the side of the tunnel. The movement of this compressor required the use of the rail mounted crane and this often caused delays to the grouting process. This was because there were only two rail mounted cranes between the 3 tunnel drives and there were delays between ordering the machine and it being available on site due to the distance between adits. This was especially true for breakdowns when the compressor had to be brought out of the tunnel for repair.

The packers used for the post injection were the BVS38 /40 type automatic packers and they proved to be ideal for this application and generally worked very well.

Referring back to the steps required for the effective sealing of major features, additional equipment that would be needed could be:

- Dry shotcrete equipment with highly accelerated pre bagged drymix for spraying over flowing water and damp areas. The shotcrete will not seal high flows of water but can help to seal low pressure areas as well as around pipes and timber.
- Excavator for removal of debris and cleaning of loose material and broken ground.
- Electric saw for quickly cutting timber wedges of various sizes to the exact shape required.
- Mechanical lift for access to higher points on the feature.

## *5.4 Materials*

The material used for the post injection was Meyco MP355 A3 Polyurethane grout. In general PU grouts are useful in rock injection as a supplement to cement and other injection materials rather than as an injection material in its own right. This is because the viscosity is high giving poor permeation in comparison to many other products. It is a “dirty” material in the sense that PU sticks to anything it comes in contact with and re-use of pipes, packers and valves becomes a hassle. However, well trained and experienced staff will be able to handle PU without much difficulty.

The usefulness is primarily linked to the application of quick foaming products that can be used to block running water (typically when backflow into the tunnel is a problem), to locally fill larger openings and voids, and sometimes to limit and control spread of the primary injection materials.

This two-component product consists of the B component (isocyanate) which is combined with the A component (polyol) to produce a foam end product. The components are delivered ready to use and the two-component pump must be set at 1:1 by volume of A and B (this is 1:1.2 by weight). The components are conveyed from the pump to the injection packer in separate hoses. Mixing takes place through a static mixer and the mixed product goes through the packer into the ground.

The chemical reaction of MP355 does not depend on contact with water, since all the necessary elements are in the A and B components. The A-component mixed with B produce the following properties in the laboratory at 25 °C:

| **Properties** | **MP 355 A3** |
|---|---|
| Density (g/cm3) | 1.013±0.02 |
| Viscosity (mPas) | 220 ±20 |
| Potlife mixed (s) | N/A |
| Reaction time (s) | 42-48 |
| Foam factor | Variable |

In terms of ground water control and running water cut-off the two-component product is the first choice because of the large volumes and high water inflows.

For the systematic post injection, 39mm holes were drilled at about 50cm spacing either side of the fault or leaking joint. These holes should be about 1.5m to 2m deep to intersect the feature some way back in the rock, however this was rarely the case due to the difficulty of drilling in the confined space of the platform and often without an air leg.

The grout was injected through the BVS 38 packer and pumped until major returns were seen through the joints or leakage points in the rock. The static mixer was then cleared using a short burst of only Part B and the pump stopped. The leaking point was then temporarily sealed using rags and wooden wedges after which the grouting was continued.

This process was repeated until about an 80% reduction in the flow was achieved. Grouting was normally started from as close to the invert as possible and progressed up the feature to the crown. Nevertheless, acceptable sealing was often impossible from the platform due to the presence of the high volumes of water in the invert and the ventilation bagging in the crown. These areas will have to be grouted again during the finishing works.

## *5.5 Case Study Ch2+002*

The difficulty with making effective post grouting activities is illustrated by an example with which the author had direct personal experience during the study period. The feature intersected at Ch2+002 was totally unexpected even though continuous probing was being carried for about 12m in front of the face at the time. The probe holes for this section of the tunnel showed no inflow what so ever. The fault was not encountered at the time of the blast but when the face was being scaled prior to final cleaning and rock support. It was noticed that there were some minor leaks in the face and as these were being investigated regarding pre injection requirements, a portion of about $2m^2$ of the face gave way and a huge volume of water flowed into the tunnel bringing with it considerable quantities of fill material. The operator of the excavator and inspectors present at the face beat a hasty retreat and after some time returned to the face to examine the situation.

The geological description is of very strong dark grey basalt in the crown underlain by moderately strong red scoriae with a thin red siltstone layer. The fault intersects the tunnel almost perpendicular and has a minimum width of 30cm partially filled with fractured rock. There was a blocky fractured zone for some 2m before the fault.

The feature at Ch2+002 initially produced an estimated 350-450l/s of water. This was calculated from the flow through the tunnel and later born out by the peak flows at the flow meter at the portal. Having encountered this high volume of water the first decision was made to stop the excavation until the water had been contained to a certain extent and the area made safe. This had the added advantage that the sub contractor's crew wase available to carry out the initial remedial works together with the grout crew. The sub contractor's labour consisted of highly skilled and motivated miners. The same could not generally be said for the majority of the labour initially assigned to the grouting crews during the study period.

The first step in the containment of the water was to drill pressure relief holes in the feature some 5m+ back into the fault. The pressure relief holes were 75mm diameter and were drilled at $45^o$ to the tunnel axis. They were instructed at positions 5m, 7m and 9m back from the fault. On the right hand side the hole at 5m was dry so another hole was drilled at 8m.

The left hand side of the fault initially produced somewhat higher flows, however this decreased as the level of material on the right hand side was washed out and lowered as the muck pile was removed. The lower 2m of the fault fill remained solid and enabled a relatively quick fix to be carried out placing the pipe well back into the void and then packing around with bags and wedges. Shotcrete up to 500mm thick was then applied over this to seal around the pipe.

Because the initial sealing was not quite sufficient and the fast setting abilities of the shotcrete mix and accelerator were not fast enough there was still a flow of water out at the invert. However, in general the majority of the water had been contained in the pipe according to the recommended method. Prior to this the void in the crown was also filled with shotcrete. This also helped to create a solid limit to the void that had to be filled with the bags and wedges.

Once the water on the LHS had been contained and the muck pile in front of the right hand side had been removed the flow on this side was significantly higher than on the left. As the muck pile was removed, the wash out of fill material continued and, to find solid ground, the fault was eventually opened out to over 1m wide. The solution to achieve containment on this side was to construct a simple timber frame and then place the pipes as far back in the fault as possible, in this case up to 4m.

Once the pipes were in place, sand bags and rags soaked in PU were used to seal around the edges. However the learning curve on the sealing, while steep, was not quick enough to seal the left side of the timber effectively. This eventually became quite a troublesome area to seal.

This process of building up the dam around the pipes and sealing with bags, rags and wedges continued until eventually 5 pipes were installed. More effective sealing would have been achieved if more PU soaked rags had been inserted behind the timber right from the first layer so that as they expanded they were forced into the gaps with the pressure of the water behind. The cutting of the timber cross pieces was done by hand and could have been done more accurately and with several layers to achieve a closer fit against the solid rock. Finally some form of short steel lagging could have been driven into the invert to improve the seal at the bottom of the structure.

In reality, time was at a premium and this pressure led to the first pipe being installed in hurry before these elements could be properly thought through and accomplished. However, from the second pipe upwards the sealing was vastly improved.

Once all 5 pipes had been installed and the dam sealed as much as was now possible, the remainder of the void above was filled with shotcrete and as much of the area around the timber packing as was possible. At this point some lack of communication led to the area on the left hand side of the timber being ignored by the grouting crew who had been given the job of sealing with rags and wedges before the shotcrete. This was not done and as is often the case was much more difficult to achieve afterwards

Once the pipes were effectively installed the grouting process was started. Firstly a pattern of holes 3m back from the fault were drilled at 45$^{o}$ and 1m spacing into the feature over the crown of the tunnel. These were non standard 45mm holes to allow the use of the BVS38 packers that were available on site. With the help of the drill and blast crew and their equipment, this was achieved quickly and relatively effectively, with PU being injected to fill up the voids.

The second phase of the injection was to pump PU through a series of injection holes drilled at 5m back into the fault. The initial concept was to close the valves and leave the drainage pipes open, although controlled with packers, to allow easy closure. Then pump the PU grout into the static water closest to the dam while the flowing water is diverted through the drainage holes, thus allowing the PU sufficient time to react and expand before being washed out. As grout appears in the drainage pipes they can be shut and the void gradually filled.

However, at this stage there was a change in personnel from the OR and also the sub contractor was given the go ahead to continue excavation. This meant that the continuity in management and the motivation from the contractor was lost. This led to a number of problems occurring that eventually led to the situation where some 12 days were wasted with no results and the shotcrete was damaged with little benefit or reduction in water flows.

This specific situation was when the instruction was given to drill 9m long holes into the fault and then place packers at about 5m from the collar of the hole. The holes were drilled using the production jumbo, but because of the production schedule, these had to wait and were eventually only drilled just before the end of the day shift. The night shift grouting crew then had to place the packers with the 6m pipes and inject the grout. However, due to the broken ground through which the holes were drilled, it proved impossible to insert the packers to the correct depth. Instead of redrilling the holes and inserting the packers to the correct depth, they were placed as deep as possible and grout injected. Here, again because of the broken ground, the grout found it easier to flow directly into the tunnel about 0.5m away rather than down the 9m of hole. As the grout then expanded this pressure over a wide area debonded the shotcrete and made no effect on the water outflow at all. The reasons for this could perhaps lead to considerable finger pointing, but in general it comes down to correct instructions being issued and followed fully by knowledgeable, expert crews. The higher the level of expertise in the labour force, the less detail is required in the instructions.

# 6. Conclusion

The grouting activities in the tunnels on Kárahnjúkar have been a very challenging and interesting test during the study period. The contrast between the planned activities, where easily defined schedules and payments were possible, and the unscheduled activities of the pre and post grouting in the tunnels, is very clear and dramatic.

There are many possible reasons for these differences and problems that were observed, some of which could be related to the resources available, and others that related to the interest and effort of management and labour required to carry out the activities.

Without being too critical of the way these activities have been planned and executed, these conclusions will outline some of the industry best practices that may be applicable to the project.

It has to be born in mind that during excavation post grouting is difficult and time consuming and may become impossible. Pre grouting, on the other hand, is simple and efficient provided that a tight face area is maintained. A 5 to 10 m buffer is recommended. High static head or large volumes require care and special measures. It is important not to allow high pressure water too close to the face, particularly if in poor ground. To achieve this, correct drilling equipment needs to be installed and used correctly on the TBM, and purpose designed and fast setting cementitious materials used for the injection.

For the post grouting the key factor is having properly trained crews capable of carrying out all elements of the required activities. Relying on specific initial instructions is not practical and the ability to adapt to the specific conditions encountered is essential. Together with the crews the appropriate equipment and access needs to be available at all times. Payment again needs to be related not only to the quantity of materials injected, but also take into account the amount of preparation needed before any injection is started.

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