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Core drilling by reverse flushing - a new drilling concept for small diameter boreholes

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- A NEW DRILLING CONCEPT
FOR SMALL DIAMETER BOREHOLES

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ABSTRACT

In order to minimise the contamination of the groundwater and the preexisting fractures during drilling, SKB's first step in early 1980's was to use specific water wells to provide the water supply for the drilling operation. The next step toward cleaner boreholes was taken as the technique of telescope-type core drilling was introduced. The present report describes the latest improvement toward cleaner boreholes; the development of a core drilling technique using reverse flushing in small diameter boreholes. Reverse flushing is based on the principle of only using formation water, which flows into the borehole, as media to cool off the drill bit and transport the drill cuttings to the surface. The construction of the equipment is described, as well as performance results from a pilot drilling test. Furthermore, factors affecting the reverse flush drilling is discussed. It is concluded that reverse flushing works satisfactory, even under circumstances of only moderate water inflows to the borehole. For good drilling performance, comparable with conventional core drilling, it is required that the borehole penetrates water-bearing zones/fractures every 50-70 m. Due to initial pressure losses in the equipment system for reverse flushing, the technique is not recommended at depths less than 100 m.

ABSTRACT

För att minimera föroreningen av grundvattnet i och ikring undersökningsborrhål och de naturliga sprickorna i borrhålsväggen, var Svensk Kärnbränslehantering AB:s (SKB) första steg i början på åttiotalet att borra speciella vattenborrhål, för att därigenom erhålla spol- och kylvatten med en kemisk sammansättning liknande den för grundvattnet vid det planerade undersökningsborrhålet. Nästa steg mot renare borrhål togs då man introducerade tekniken med sk teleskopisk kärnborrning. Föreliggande rapport redogör för den senaste förbättringen i syfte att minimera kontamineringen av borrhål och dess geologiska omgivning; introduktionen av kärnborrning med omvänd spolning i borrhål med liten diameter (56 mm). Omvänd spolning är baserad på principen om att endast nyttja formationsvattnet, vilket rinner in i borrhålet, för att kyla borrkronan och transportera borrkaxet till markytan. Rapporten redogör för utrustningens konstruktion såväl som resultat från den pilotborrning som utförts. Vidare diskuteras de faktorer som påverkar borrresultatet då omvänd spolning nyttjas. Slutsatsen från den pilotborrning som utförts är att kärnborrning med omvänd spolning fungerar tillfredsställande, även under förhållanden då flödet av vatten till borrhålet från formationen endast är måttligt. För att erhålla borrprestanda jämförbart med konventionell kärnborrning krävs att borrhålet penetrerar vattenförande sprickor/zoner varje 50-70 m. På grund av initiella tryckförluster i utrustningen för omvänd spolning bör tekniken inte användas på djup grundare än 100 m.

PREFACE

This report constitutes an English description of the work conducted within the Reverse Flushing project from 1988 - 1992. The Reverse Flushing project was divided into two stages, with two phases comprising each stage, and each phase has been written up as a SKB progress report. The majority of the material presented here has been extracted from these reports.

During the different stages of the project the following persons have been in involved:

Torbjörn Hugo-Persson SGAB Borr	- Project management; all phases
Bengt Fridh SGAB Borr	- Project management; phase 1A, 1B, 2A
Christer Ljunggren Vattenfall Hydropower	- Project management; phase 2B
Roger Norman SGAB Borr	- Construction, drilling
Kent Hansson Geosigma AB	- Geohydrology
Karl-Erik Almén SKB	- Project representative at SKB

SUMMARY

For certain applications it is of special interest to reduce the contamination of the formation water in a borehole, and at the same time avoid introduction and clogging of drill cuttings in preexisting fractures. Examples of such applications could include geochemical investigations on the formation water or geohydrological tests in the borehole on the surrounding rock mass.

The present report describes a core drilling technique by reverse flushing in small diameter (56 mm) boreholes. Different from conventional core drilling, reverse flushing is based on the principle of only using formation water, which flows into the borehole, as media to cool off the drill bit and transport the drill cuttings to surface.

Compressed air is pressurized into the drill string and down the borehole via a double rod concept, which constitutes the section for air-lift pumping. At a certain depth, the compressed air is discharged into the column between the two rod strings in the double rod section, creating a lifting force. This force enables the mixture of air, water and drill cuttings to be transported through the column up to the surface. A pressure difference is then created, with a higher pressure on the outside of the drill string as compared to the inside, creating a water flow from the rock formation, into the borehole, downward to the drill bit, in through the bit and further up through the drill string. Thereby the principle of reverse flushing is created.

Core drilling by reverse flushing was performed in a borehole from 113.7 m depth to final hole bottom at 291.1 m depth. The borehole was drilled with a 56.5 mm drill bit and a 57.0 mm reaming shell. The results from the pilot drilling show that the method works satisfactory, even under circumstances of only moderate water inflows to the borehole. For good drilling

performance, in parity with conventional core drilling, it is required that the borehole penetrates water bearing zones/ fractures every 50-70 m. The pressure losses in the system will otherwise increase to a level where the effect of the air-lift pumping is insufficient.

If the upward water flow decreases under a critical lower limit (≈ < 10-11 l/min) the number of revolutions on the drilling machine must be decreased in order to reduce the pressure losses. This will, however, have a negative impact on the penetration rate.

Due to initial pressure losses in the system for reverse flushing, the technique is not recommended at depths above 100 m.

Core drilling by reverse flushing is not intended as an alternative for conventional applications, but instead as a complement in cases where a probably higher drilling cost can be accepted for the benefit of a cleaner borehole.

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1 INTRODUCTION

1.1 Background

Core drilling is the most common drilling technique used in site investigation projects under the direction of the Swedish Nuclear Fuel and Waste Management Company (SKB). The drilling depth is normally 500-1000 m, and the boreholes are typically 56 mm or 76 mm in diameter.

For conventional core drilling water is continuously pressurized down through the drill string to cool off the drill bit, and to transport the drill cuttings from the coring process up through the column between the drill string and the borehole wall to the surface. However, due to the overpressure of the flushing water in relation to the groundwater pressure, a significant portion of the flushing water (including the drill cuttings) will enter into fractures exposed in the borehole wall. In deeper holes, the amount of flushing water recovered to the surface very often will go down to zero. The water used in this process does not necessarily have the same chemical composition as that in the rock formation penetrated by the borehole. Consequently, the formation water may become contaminated. Furthermore, it may be safely assumed that the drill cuttings, on their way to the surface, can partly block preexisting fractures in the borehole wall. This may lead to a reduction in the hydraulic transmissivity and changes in the transportation network of the formation water.

Chemical composition of the groundwater and hydraulic characteristics of the formation fractures are important site specific parameters for the SKB site investigations. Consequently, an initial step taken by SKB in early 1980's to minimise contamination was to avoid the use of surface water in the drilling process. Instead, specific percussion drilled water wells in the same rock formation provide the water supply during drilling, see Figure 1-1. However, along a 500-1000 m deep borehole several different aquifers and groundwater compositions may exist, which may differ from that in the water supply well. Thus, in order to account for potential contamination of drilling water in the formation water, the drill water is always tagged using a suitable tracer.

A second step was to develop a modified core drilling technique, the telescope-type drilling technique /Almén and Zellman, 1991/. This modified technique was aimed at:

1) Reducing the contamination of drilling fluid and drill cuttings in the formation water and formation fractures.

2) Optimizing the borehole design for the post-completion testing programme.

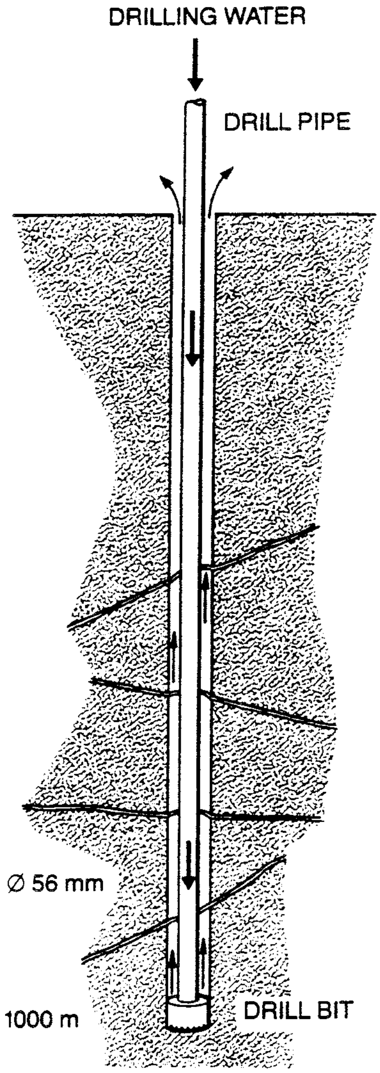

Figure 1-1 Principle of conventional core drilling equipment.

Reduced contamination of the drilling water and the effect of the cuttings is achieved by means of air-lift pumping from the uppermost reamed-up part of the borehole during core drilling, see Figure 1-2. The air-lift pumping creates a draw-down effect along the borehole, the effect being dependent on the distribution and capacity of the major groundwater conductors. Normally, however, at least some reduction of the water pressure occurs all the way down to the drill bit at the hole bottom. The technique of telescope-type core drilling, which was extensively used in the Äspö Hard Rock Laboratory project (HRL), has proved to be a major step forward in minimising contamination of the formation groundwater.

In some cases, however, when a large number of groundwater conductors are penetrated by the borehole (thereby reducing the air-lift draw-down effect to almost zero) the efficiency of the telescope-type core drilling technique, in reducing the contamination of the formation water, is very limited. Under such circumstances and, if very high quality water samples are needed, this method is unsuitable. Consequently, SKB initiated a study to develop a drilling technique using reverse flushing for the core drilling of slim boreholes.

In 1988 SGAB Borr (now Kärnborrning Norr AB) was contracted by SKB to study the possibilities of developing a core drilling technique based on reverse flushing that could reduce or eliminate the remaining contaminating effects around the borehole caused by conventional and telescope-type core drilling. The project was divided into two stages; stage 1 and stage 2. Each stage was furthermore divided into two sub-stages; A and B, respectively. The rationale for this was to allow the preceding stage, to a certain extent, provide the guide lines for the next stage.

This report aims at describing: a) the equipment for core drilling by reverse flushing, b) the drilling technique, c) the results from a pilot drilling test, and d) some factors affecting the result of core drilling by reverse flushing. The work conducted in the early stages of the reverse flushing project is briefly summarized below in section 1.2.

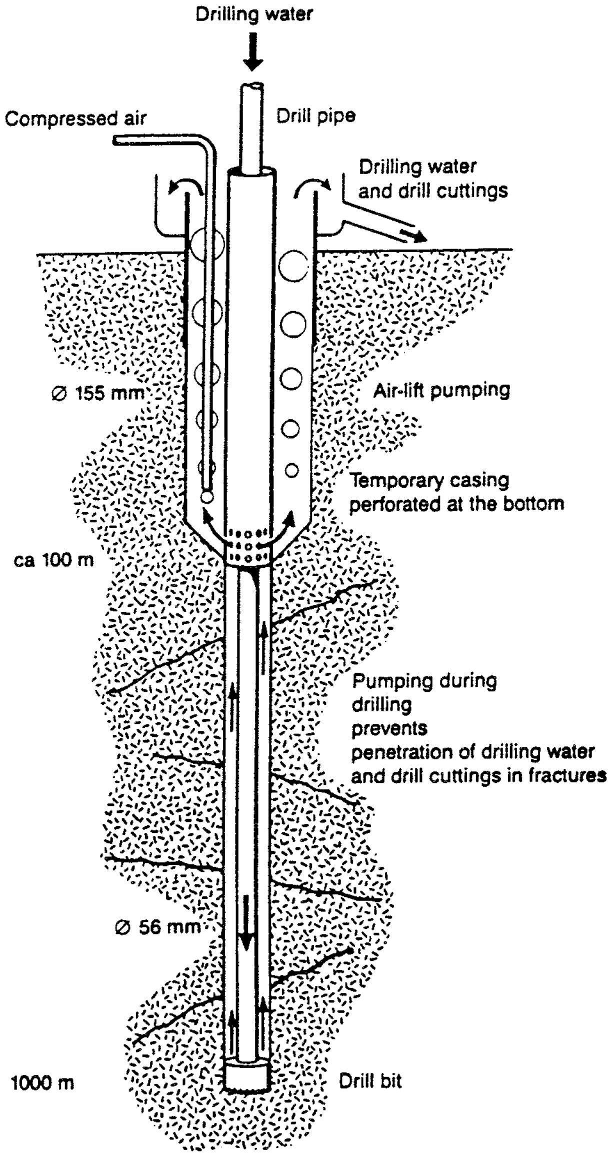

Figure 1-2 Principle of telescope-type core drilling using air-lift pumping for the retrieval of drilling water and cuttings. After Almén and Zellman, 1991.

1.2 Early stages of the project

The first project stage, stage 1A /Fridh and Norman, 1988a/, of the reverse flushing project aimed at investigating previous work in the field and searching for equipment already developed for reverse flushing in small diameter boreholes. A literature review on the subject revealed only limited and vague information. Stage 1A was subsequently completed with some initial theoretical calculations on pressure losses using a drilling system based on reverse flushing. The report formed the initial basis for designing and construction of the equipment.

In the second stage, stage 1B /Fridh and Norman, 1988b/, the theoretical calculations were further developed and refined. Practical tests were performed on certain sections of the equipment under consideration, either as a complement to the theoretical calculations (due to difficulties in calculating the pressure losses appropriately), or to verify the validity of the calculations. Special emphasis was put on: a) investigating pressure losses across the drill bit, b) losses as the water passes through the column between the inner and outer tube in the core barrel, c) the effect of varying the outer diameter of the inner core barrel, and d) the effect of rotation on the pressure losses. The report from stage 1B also included additional and improved designing of the equipment using the pressure loss calculations carried out. Consequently, certain critical sections and limitations of the system were discovered.

The stage 2A work included sensitivity analyses on reverse flushing with respect to varying potential water flow from the rock formation, in addition to the compilation of water capacity data on a number of well documented boreholes in Sweden, to obtain an indication of normal water inflow. It also included descriptions of alternative methods to reverse flushing, listing their respective advantages and drawbacks. The report from stage 2A, / Fridh and Norman, 1990/, formed the basis to decide on a full scale test using reverse flushing in the core drilling process.

2 THE PRINCIPLE OF CORE DRILLING BY REVERSE FLUSHING

As suggested by the name of the method, core drilling by reverse flushing is based on the principle of reversing the water flow for flushing and cooling in the drilling process. Hence, instead of pressurizing water from the surface through the drill string to depth, as in conventional core drilling, the water is transported the opposite way. The implication is that the removal and transportation of drill cuttings and the cooling of the drill bit is achieved only with the water obtained from the surrounding rock formation. That is, no external water is supplied for the drilling. The primary prerequisite, therefore, is that the surrounding rock formation is sufficiently conductive to supply the necessary water flow to the borehole.

The system of core drilling by reverse flushing developed within this project is based on a double rod system, Figure 2-1. Reverse flushing is generated by means of air-lift pumping in the 200 m - 300 m double rod part of the drill string. Drill rods, of a type normally used in wireline core drilling, constitute the outer rod of the double rod section, and a inner rod string, which is locked against the wireline rods, serves as a transport channel for the pressurized air.

In cross-section, the double rod system consists of a inner air rod, a column and an outer drill rod. Compressed air at a predetermined flow and pressure is transported through a swivel at the top of the rod system and into the inner rod string. The compressed air is pressurized down the inner rod and is discharged at a certain depth out into the column between the outer and inner rods through a nozzle. The nozzle is placed at the end of the inner rod string.

The total length of the double rod section varies depending on the drilling depth, but should never, according to both pressure loss calculations and experience from drilling, exceed 300 m in length. Hence, if drilling extends below 300 m depth, a drill rod with a reduced inner diameter is attached between the double rod and the core barrel, Figure 2-1.

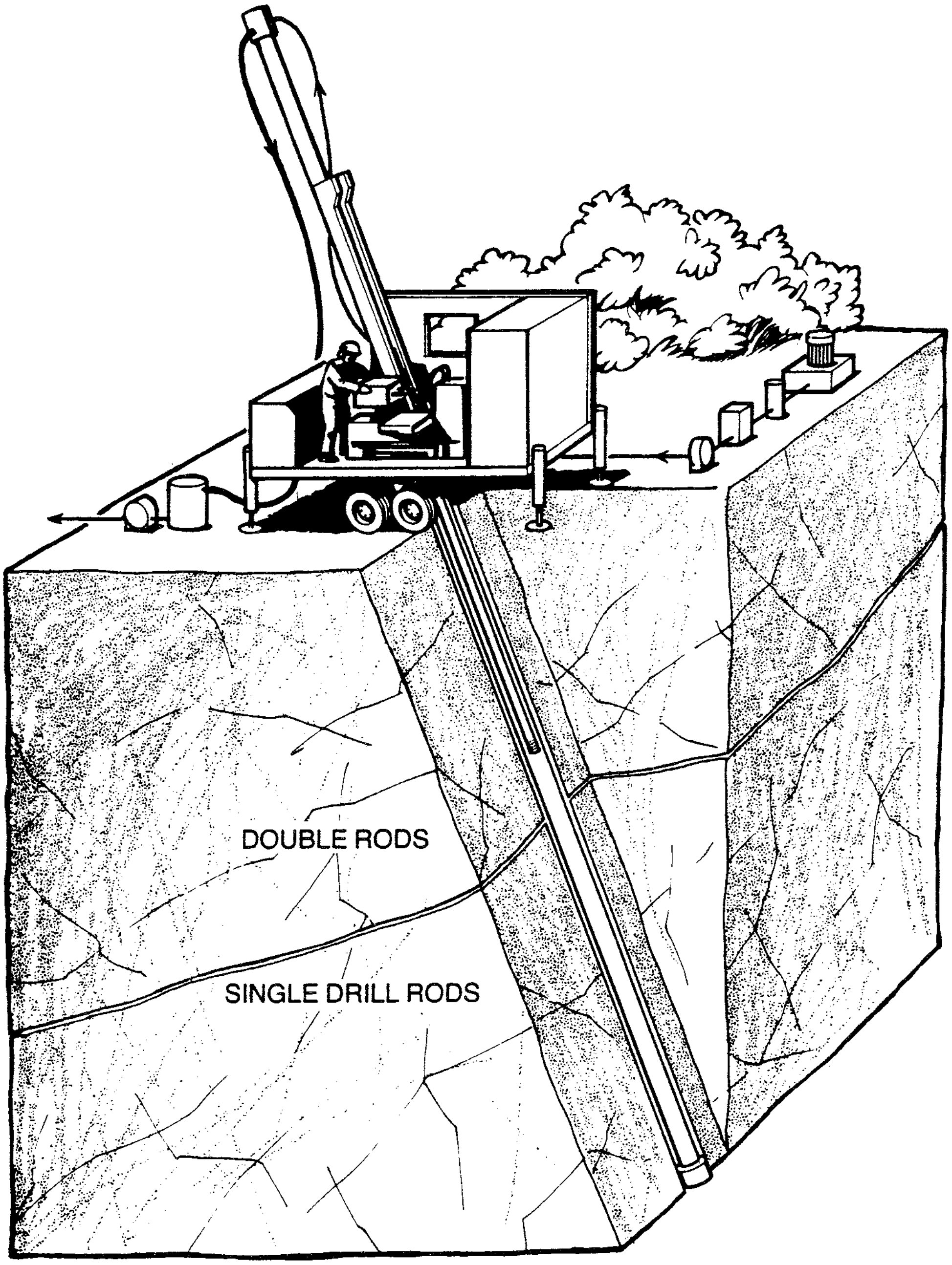

Figure 2-1 Illustration of core drilling by reverse flushing.

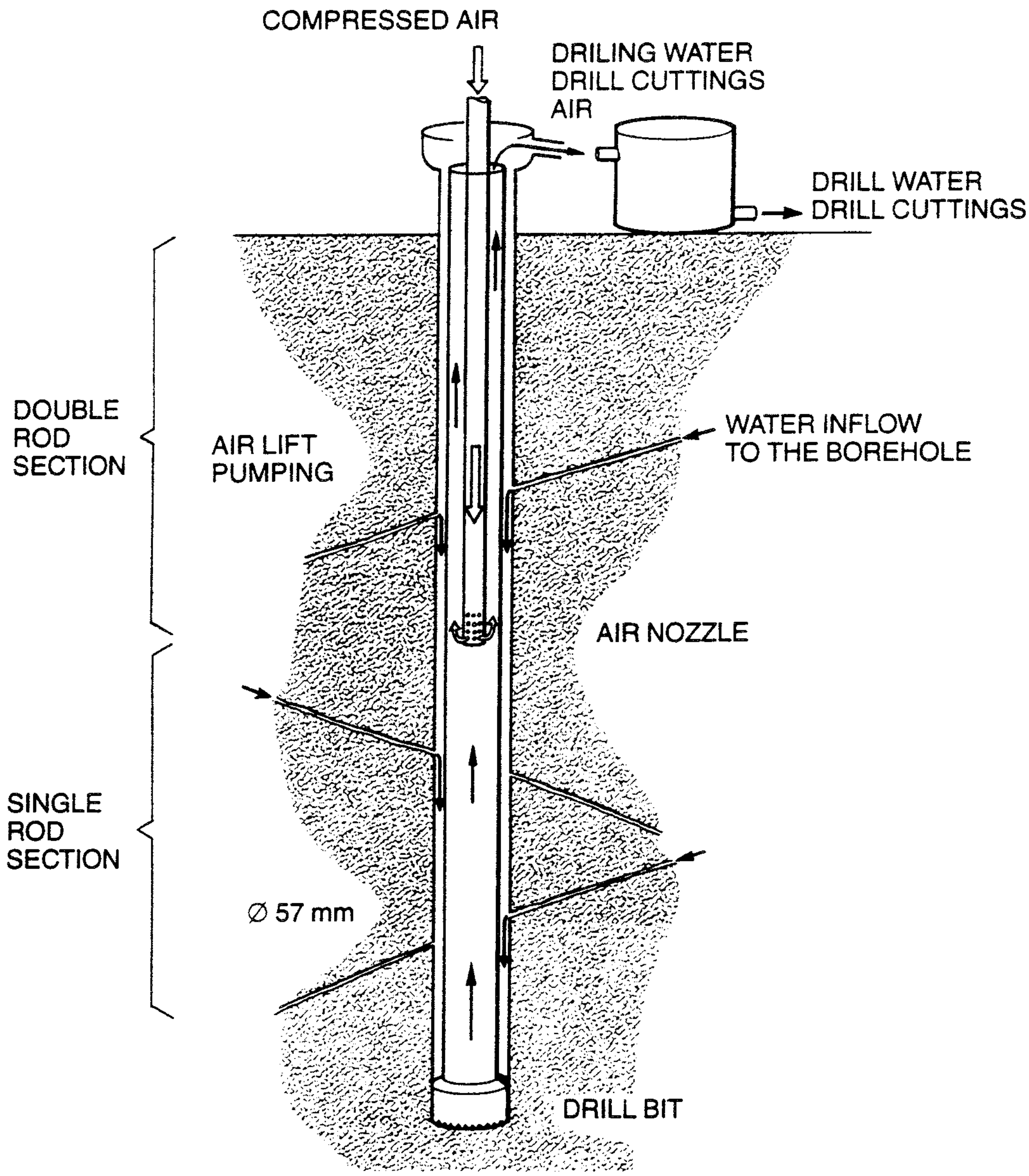

Figure 2-2 Flow chart of the air, water and drill cuttings in core drilling by reverse flushing.

The compressed air, which is pressurized down through the inner rod and out to the column between the rods, creates a lifting force which, in turn, causes the water and drill cuttings to be transported together with the compressed air towards the surface. A pressure draw-down is created in the drill string thereby inducing water transport from the rock formation into the borehole toward and across the drill bit. The water then continues up and into the column between the inner and outer tube in the core barrel and further upwards towards the ground surface in the column between the air rod (inner tube) and the drill string (outer rod). At the surface, the mixture of air, water and drill cuttings passes out from the column in the double rod section through the same swivel as used for the downward compressed air.

This drilling technique is, in principle, no different from conventional core drilling and does not put any special requirements on the drill rig. However, since drilling using reverse flushing requires a continuous and even water flow from the rock formation, it is vital to register and measure the upward water flow. In the following chapter the equipment required is described and discussed.

3 EQUIPMENT

During the development process a number of modifications were carried out mainly to reduce pressure losses and to improve the transportation of drill cuttings. Most of the equipment changes and the impact on the drilling results during a pilot drilling test are fully discussed in chapter 4. The final lay-out of the equipment is described below.

3.1 In-the-hole equipment

The equipment which is lowered into the borehole during drilling can be divided into three sections: (i) the double rod section, (ii) the single rod section, and (iii) the core barrel and drill bit.

The double rod section, Figure 3-1, constitutes the pump part of the system where compressed air is transported in the inner rod. The outer rod consists of a wireline drill rod made of steel. The advantage of the wireline rod as compared to a conventional aluminum drill rod is firstly the larger inner diameter of the rod. This is of great importance since the inside space shall include an air rod with a sufficiently large diameter, and the column for the upward transportation of air, water and drill cuttings. Secondly, the wireline rod has a smooth inner surface without any sharp edges or diameter reduced sections (like the couplings of the conventional aluminium drill rods) that can disturb the transport of the upward flow in the column between the outer and inner rod.

The inner rods are used as a transport channel for the compressed air, and are clamped against the outer rods via centering devices, Figure 3-1. A nozzle is attached at the lower end of the inner rod string where the air is discharged into the column between the rod strings. The nozzle is constructed such that the air stream is turned upward before it is discharged in order to obtain the same direction as the water.

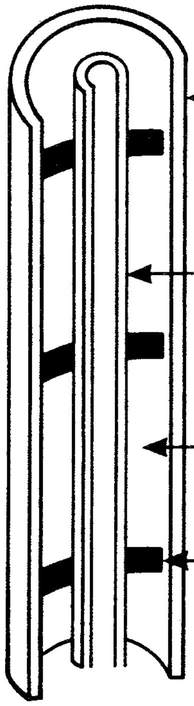

Figure 3.1 The double rod section of the equipment for core drilling by reverse flushing.

The second part of the drill string is the single rod section, Figure 3-2, which is connected through the nozzle to the double rod section. The single rod is a conventional aluminium rod with steel end couplings for thread connections. Inside, the aluminium rod is equipped with a plastic liner to reduce the inner diameter and to obtain a smooth inner surface. The reduction in inner diameter increases the water velocity and hence improves the capability of lifting the drill cuttings to the ground surface even at relatively low water flow rates (≈ 10 l/min). Equally important as the reduced inner diameter is the smooth inner surface which reduces the risk of any accumulations of drill cuttings along the rod surfaces.

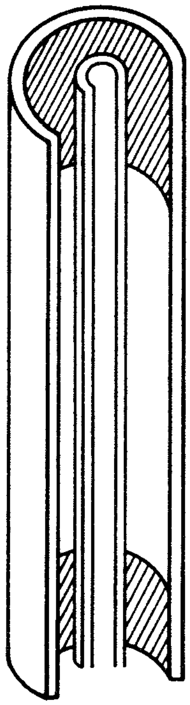

Figure 3.2 The single rod section of the equipment for core drilling using reverse flushing.

The third and last part of the drill string is the core barrel and the drill bit. In the development phase a core barrel 3 m in length was used although a longer length would have been preferred to reduce total drilling time. The main reason for using a short barrel was to reduce the pressure losses in the system, as much as possible, since the passage through the barrel is one of the most critical sections due to the very narrow column between the outer and inner tube in the barrel. There is nothing, however, in the layout of the drill string that prevents changing to a longer core barrel as long as the flushing water flow does not decrease under the critical limit (< 10 l/min).

It should be pointed out that the core barrel has been modified substantially for reverse flushing. Some of the most important modifications are:

- A reduction of the outer diameter of the outer tube to enlarge the column between the borehole wall and the core barrel.

- A reduction of the outer diameter of the inner tube to increase the column between the outer and inner tube.

- An increase and modification of flushing holes in the head of the core barrel to improve the passage of the water/ drill cuttings mixture.

The drill bit and the reaming shell have also undergone a number of modifications. In order to reduce the pressure losses between the borehole wall and the drill string, the diameter of the drill bit has been increased from normally 56.0 mm to 56.5 mm. Consequently, the outer diameter of the reaming shell has been increased from 56.5 mm to 57.0 mm. The channels between the diamond segments have been ground on both the drill bit and the reaming shell to facilitate the water passage. Finally, the inner diameter of the reaming shell has been increased from 46 mm to 47.5 mm.

3.2 Surface equipment

In addition to the drill rig, which can be any conventional design, the surface equipment includes the following components:

- An air compressor with pressure and flow regulation possibilities. The compressor should be rated for a 30 bar pressure and a flow rate of approximately 80 m^3/h (free emitted air quantity).

- Instrumentation to register drilling parameters.

- Equipment for treatment of the upward flushing -and cooling water.

- A double-swivel for the compressed air transport and for the upward water/air/drill cuttings mixture.

The equipment and connections is shown in Figure 3-3.

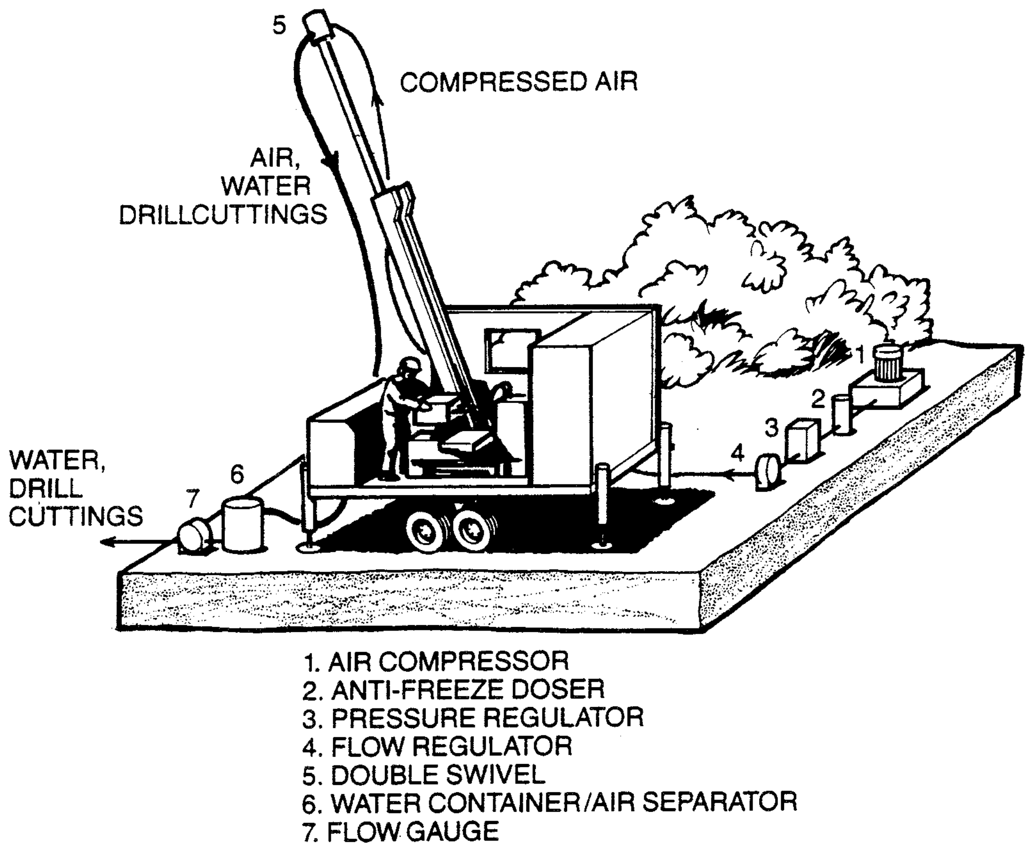

Figure 3.3 The surface equipment for core drilling using reverse flushing.

The compressed air (delivered by the compressor) passes through a pressure reducing valve and a constant flow regulator, then further via the double swivel into the inner rod of the drill string. The optimum pressure and flow rate of the air to be used depends on the actual drilling depth.

During core drilling with reverse flushing the most critical parameter is the flow of the upward water. If the flow rate is too low it may, for one thing, result in a poor penetration rate and the transport of drill cuttings will be insufficient. Furthermore, the penetration rate, number of revolutions of the drilling machine and the flow of the upward water are closely dependent on each other. In order achieve optimum drilling performance the equipment should therefore include an instrument that continuously logs these parameters. Other parameters of interest to log may be the thrust force and rotational resistance. In the pilot drilling test a Dia-printer, manufactured by ENVI, was used to register the drilling parameters. This instrument has the capacity of registering up to six channels simultaneously. Moreover, besides the logging and presentation unit, the instrument includes gauges to register different parameters including the upward water flow.

In order to register the upward water flow properly, the air has to be separated from the mixture of water, air and drill cuttings. This is handled by passing the mixture through an inlet placed high up in a container and then removing the water/drill cuttings through a low placed outlet. Besides separating the air, this treatment also reduces the otherwise pronounced pulsations of the water.

If drilling is conducted at low temperatures, around zero ± a few degrees, an anti-freeze doser must be added to the air system to avoid the build up of ice in hoses and connections.

4 CORE DRILLING BY REVERSE FLUSHING - A PILOT TEST

The pilot drilling project commenced in the autumn of 1990 at Malå in the county of Västerbotten. This was partly based on an inventory of water capacity data from existing boreholes in the area. The final borehole depth at 291.1 m depth was achieved in the spring 1992. The drilling had then, however, been disrupted a number of times either because of extensive modifications to the equipment or because of different bore-hole tests related to the project.

4.1 Drilling technique

A limitation of reverse flushing is that it cannot be applied immediately from surface. Hence, the pilot borehole had to be drilled using conventional core drilling technique down to approximately 114 m depth.

The pressure losses in the system for reverse flushing can in simplified terms be described by fixed (or initial) and movable pressure losses. In order to overcome the fixed pressure losses and to achieve a net uplift of the water column, the drilling has to reach approximately 100 m depth before applying reverse flushing. Then, provided adequate water from the surrounding rock formation into the borehole is obtained, the effect from the air-lift pumping should be sufficient for reverse flush drilling.

To achieve maximum effect from the air-lift pumping, the drill string from the onset should consist of double rods from the surface down to the core barrel at approximately 100 m depth. Even so, the total pressure losses at this depth will be so high, compared to the effect from the air-lift pumping, that the net uplift effect will only result in a reduced upward water flow. To increase the water flow to an acceptable level it might then be necessary to reduce the number of drilling revolutions. Based on the experience gained from the pilot borehole, this procedure may have to be continued down to approximately 200 m depth.

As the drilling advances below 100 m depth there are two alternatives each time a new drill rod has to be added to extend the drill string. If the upward water flow is unsatisfactory (less than 14-15 l/min) then another double rod should be added; if the flow is sufficient and the drilling machine is run at approximately 1500 rpm, a conventional drill rod could be added. If the latter is the case, the rod should be placed below the double rod section. As discussed above, the drill string will most probably have to consist of double rods down to at least 150 m depth and possibly even down to 200 m depth, before the single rods become a viable alternative. However, it should be pointed out very clearly that the final effect of the air-lift pumping, and hence the drilling performance, depends on the water flow from the rock formation into the borehole, and at what distance from the drill bit the majority of the water enters the borehole.

Based on the limited information obtained from the pilot drilling test, 150 m - 200 m of double rods should be sufficient for reverse flush drilling down to 400 m - 500 m depth. Based on theoretical calculations on the pressure losses in the system, the length of the double rods should not have to exceed 300 m even if the drilling continues down to 1000 m depth. This assumes, however, that normal circumstances exist with regard to the water inflow from the rock formation into the borehole, and the regular penetration of water-bearing zones/fractures at least every 50 - 70 m.

To summarize the drilling technique, or rather the procedure during drilling, the following can be concluded. Since some of the pressure losses in the system are dependent on the number of revolutions, an upward water flow which is too low implies that the number of drilling revolutions should be decreased from 1500 rpm to 1100 rpm (lower limit). This will increase the upward water flow, but at the same time decrease the penetration rate. The latter could, however, be compensated to some extent by increasing the thrust force.

4.2 Results and experience from the pilot drilling

Core drilling using reverse flushing started at 113.7 m depth. At commencement the drill string consisted of 102 m double rods, 9 m of single rods and a 3 m core barrel. At this stage, however, the outer rods of the double rod system did not consist of wireline rods but instead conventional aluminium core drill rods.

Initially the water flow was very low (6-7 l/min) which resulted in drilling problems such as insufficient transport of drill cuttings. A large quantity of drill cuttings accumulated in the core barrel, eventually totally blocking the water flow. By modifying the core barrel and reducing the number of revolutions to approximately 1100 rpm, an increase of flow to approximately 10 l/min was obtained. The penetration rate at this stage was around 10 cm/min. Table 4-1 summarizes the major modifications to the equipment during the drilling test, and the results from the changes.

The number of double rods in the system was continuously increased as drilling progressed down to 160 m depth. By then, when all manufactured double rods where included in the drill string, the water flow had increased to 11 l/min. Due to this very limited increase in the upward water flow, further modifications to the equipment where conducted, see Table 4-1.

The aluminium drill rods were used in the double rod section down to 203 m drilling depth, whereupon they were replaced by wireline drill rods. The main reason for this replacement was the discovery of drill cutting accumulations at the diameter changes over the threaded connections of the rods, Figure 4-1. This was also believed to have a negative effect on the water flow. At the same time as the rods where changed the length of the double rod part was reduced from 150 m to 100 m. The change of rod type resulted in an unchanged water flow even though the double rod section had been reduced by 50 m. The average penetration rate in the interval 150 m to 203 m was between 7 - 8 cm/min.

Table 4-1 Summary of major equipment modifications conducted during the pilot drilling test.

Depth (m)	Action	Result
113.7	Commencement of reverse flushing	
114.5	Modification to the top of the core barrel	Increased water flow $Q_w \approx 7$ l/min
125	Reduction of the rpm on the drilling machine to approx. 1100 rpm	Increased water flow $Q_w \approx 10$ l/min
160	Reduction of the outer diameter of the drill string to approx. 52 mm	Unchanged water flow
190	Change to an air compressor with larger flow capacity	Unchanged water flow
203	Change of the outer rods in the double rod system to wireline rods	Unchanged water flow, but now with only 100 m double rods
220	Adjustment of flushing channels on the drill bit and the reaming shell	Increased water flow $Q_w \approx 12 - 13$ l/min
247	Mounting of plastic tubes into the drill rods below the double rod section	Improved transportation of drill cuttings

The last major modification to the equipment was undertaken when the drilling had reached 247 m depth. By then, a constant problem had been the transportation of drill cuttings. Although a number of modifications had been made at earlier stages, significant amounts of drill cuttings were still accumulating at the bottom of the borehole. To reduce this problem plastic tubes were inserted and fixed into the drill rods positioned below the double rod section, c.f. Figure 3-2. This was carried out to gain two improvements; firstly, the insertion of plastic tubes resulted in a smooth surface thus minimising the accumulation of drill cuttings. Secondly, and equally important, the plastic tubes resulted in a smaller inner diameter for water transportation. Hence, the water velocity increases and the capacity of transporting drill cuttings also increased.

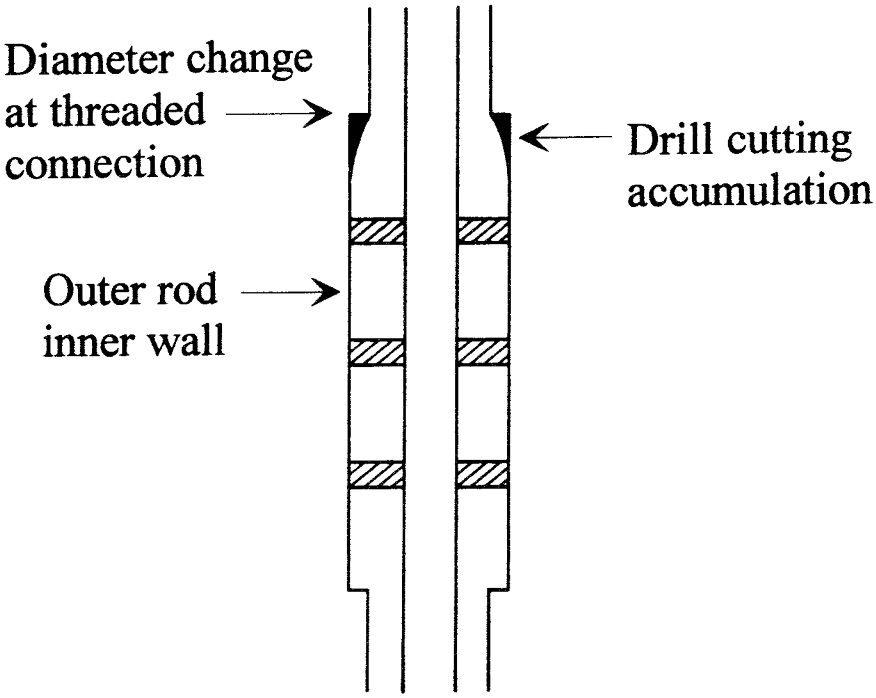

Figure 4-1 Drill cutting accumulations at the diameter changes over the threaded connections of the aluminium drill rods.

Drilling subsequent to the above modification clearly indicated an improved result as regards the transportation of drill cuttings. For example, drilling water reaching the surface had a markedly larger content of cuttings. Furthermore, the time spent to clean the borehole after the core barrel had been filled up, was reduced from approximately 15 minutes to only 5 minutes.

At 284.5 m depth the borehole penetrated a water-bearing zone and the upward water flow increased dramatically to approximately 30 l/min, Figure 4-2.

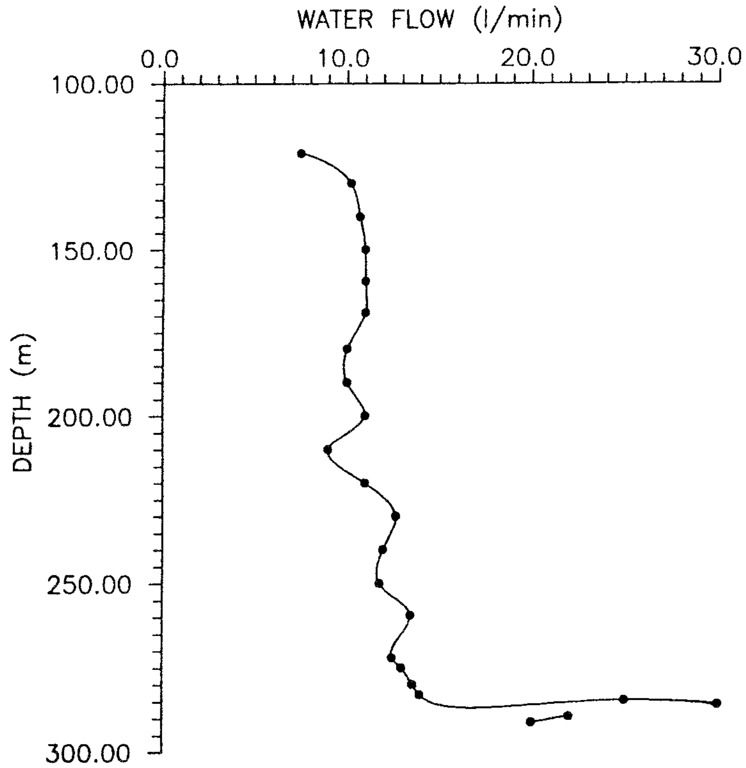

Figure 4-2 The resulting upward water flow as function of drilling depth during drilling using reverse flushing. (Conventional core drilling was used between 286 m - 289 m).

When the water flow is less than approximately 15 l/min the penetration rate very much depends on the upward flow rate. This occurs because a reduced water flow normally involves a reduced number of revolutions on the drilling machine, which in turn has a negative effect on the penetration rate. Figure 4-3 presents the penetration rate obtained during drilling of the pilot borehole.

Results from the final drilling (between 289m - 291 m) resulted in a marked increase in the penetration rate, Figure 4-3. This is solely a result of the increase in the upward water flow which allowed the number of revolutions on the drilling machine to be increased from 1100 rpm to around 1500 rpm. The conventional core drilling carried out between 286-289 m depth, aimed at obtaining a comparison of penetration rate with that of reverse flushing.

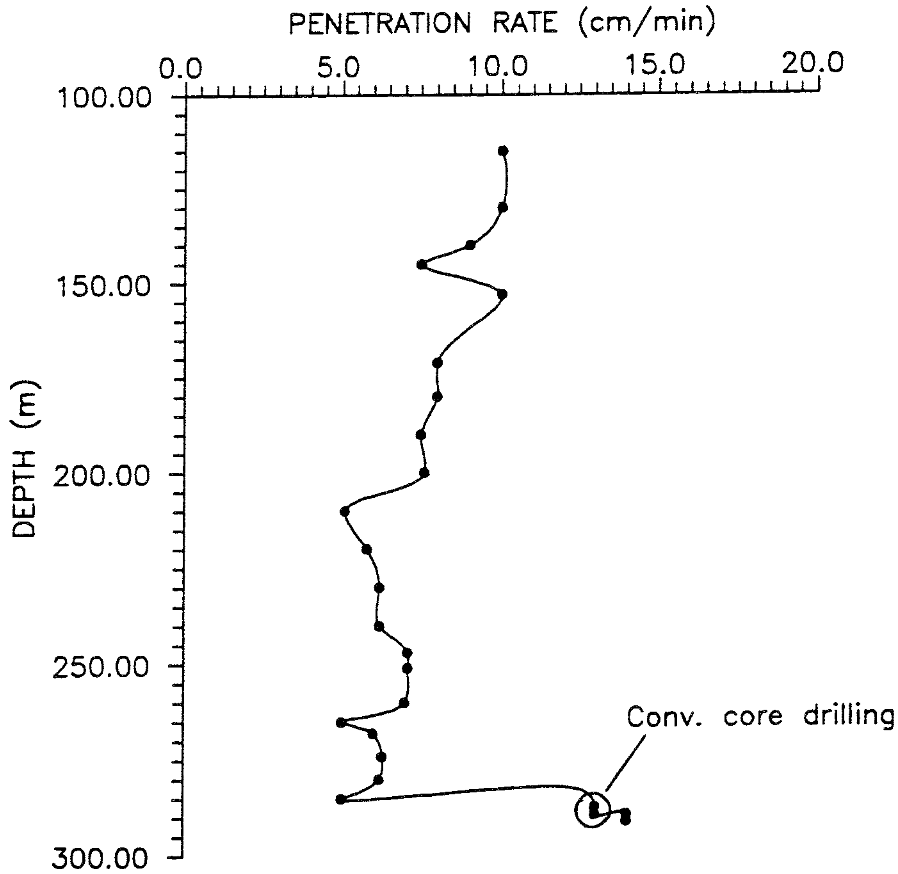

Figure 4-3 Obtained penetration rates during core drilling of the pilot borehole. (Conventional core drilling was used between 286-289 m depth).

5 FACTORS INFLUENCING THE RESULT OF CORE DRILLING BY REVERSE FLUSHING

A prerequisite for core drilling using reverse flushing is equipment specially constructed for this purpose. As described above, this includes, besides replacing some of the conventional equipment, to a considerable amount optimization of different sections of conventional core drilling equipment. In this case optimization means reducing the pressure losses in the system at the same time as the water velocity should be high enough to provide sufficient capacity to transport the drill cuttings.

Besides problems arising from modifying the drilling equipment, the drilling performance is also affected by a number of other factors and circumstances. Some of the most important factors and their influence on the drilling performance are discussed below.

5.1 Air compressor requirements and its importance for the water flow

In the case of reverse flushing an air compressor is needed for the air-lift pumping. This requires a high continuous air pressure while the air flow only needs to be moderate (≈ 15 m^3/h at 6-8 bar pressure down to 300 m depth). The maximum pressure required for drilling down to 1 km depth is estimated to 30 bar.

Since the pressure losses in the equipment increase with increasing drilling depth, the air pressure, and eventually the flow rate, has to be adjusted accordingly to achieve optimum upward water flow. Figure 5-1 presents the relationship between air flow and the upward water flow at 190 m and 260 m depth for the pilot borehole. Results at 190 m depth were obtained at 1100 rpm, without any thrust force on the drill bit, whereas the results at 260 m depth were recorded during ongoing drilling at 1100 rpm. In the latter case the system had underwent two major modifications; (i) the outer rods in the double rod system had been replaced by wireline rods, and (ii) the drill rods below the double rod section had been completed with inner plastic tubes.

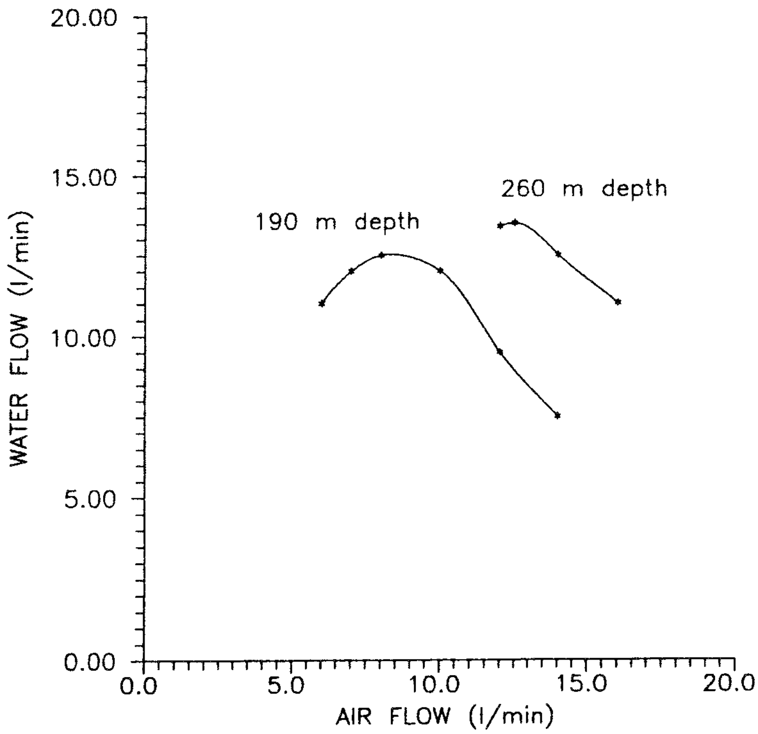

Figure 5-1 The relationship between air flow and upward water flow when core drilling by reverse flushing.

The experience from the pilot drilling demonstrates that the water flow is less sensitive to changes in the air flow above the optimum, in contrast to changes towards a level of air flow below the optimum which results in a more critical effect on the water flow.

5.2 Number of drilling machine revolutions

For conventional core drilling the number of revolutions normally lies between 1500 - 1600 rpm. As a general rule, the higher the number of revolutions the better the penetration rate obtained. Although this rule still applies also for reverse flushing, the situation is somewhat more complicated. Even though a high number of revolutions is beneficial for the penetration rate, the rotation also has a negative effect on the upward water flow. When the water flow decreases, the risk of drill cutting accumulations in the drill string increases. Hence, in the case of reverse flushing, selecting the number of revolutions has to be a compromise in order to achieve both a satisfactory penetration rate and suitable water flow. Drilling of the pilot borehole showed that 1100-1200 rpm is an optimum, balanced against a water flow of 10-12 l/min. Thus, if the water flow increases, the number of revolutions may also be increased.

Figure 5-2, illustrating the rotational effect on the upward water flow, shows that the upward water flow at 1000 rpm is some 60% of the flow at zero rotation, and at 1500 rpm only 45% of the water flow remains.

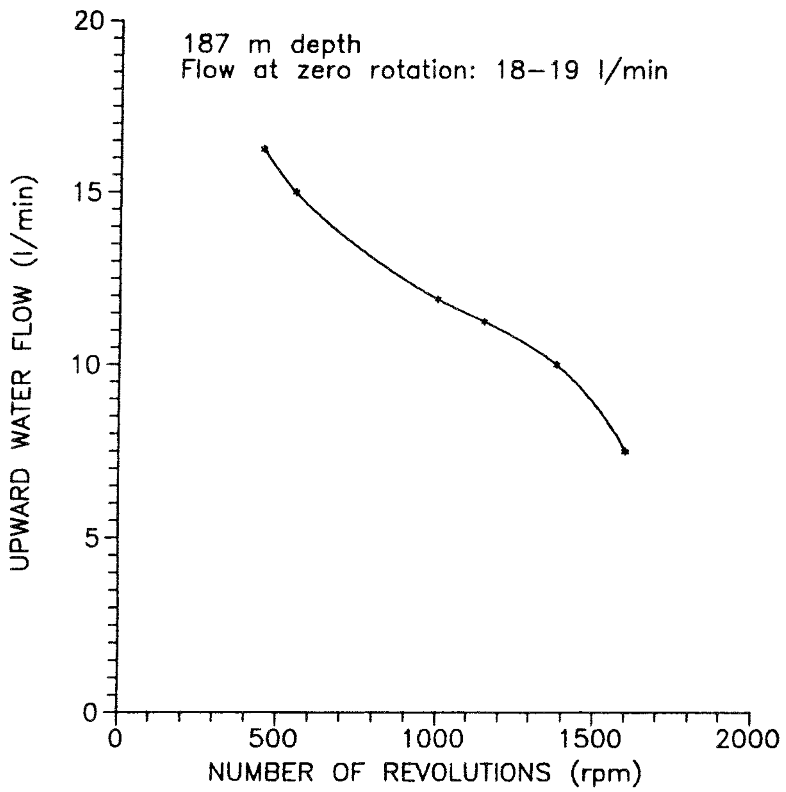

Figure 5-2 The effect of rotation on the upward water flow using reverse flushing core drilling.

5.3 Water inflow to the borehole

Besides availability of the necessary equipment, another prerequisite for reverse flushing is a sufficient water inflow from the surrounding rock mass to the borehole. The inflow must at least correspond to the minimum water flow requirements for flushing and cooling (≈ 10 l/min). Basically, this can only be assessed after drilling has been attempted. However, some general indications can be gained from complimentary boreholes within the same area. Before the exact location of the pilot borehole was decided, two investigations were performed to obtain information on the predicted water inflow.

In phase 2A of the reverse flushing project /Fridh and Norman, 1990/ water capacity data on a number of core drilled boreholes were compiled to get an initial understanding of the amount of formation water that could be expected. The results from this study showed that the majority of the investigated boreholes had a suitable capacity. Another conclusion from this study was that the water inflow to a borehole mainly comes from a limited number of fractures, with a mean distance between the water-bearing fractures of approximately 60 m.

Prior to drilling, water capacity data were also compiled from existing boreholes within the local area. This information, although limited, indicated large enough water capacities for drilling by reverse flushing.

After the borehole had been drilled to 113.7 m depth, air-lift pumping was carried out to evaluate the initial water capacity of the actual borehole. The results from the rise in groundwater level conducted after the air-lift pumping are shown in Figure 5-3. The water withdrawal during pumping was approximately 47 l/min; this was continued until an acceptable balance between withdrawal and inflow had been obtained, i.e. after approximately 40 minutes of pumping.

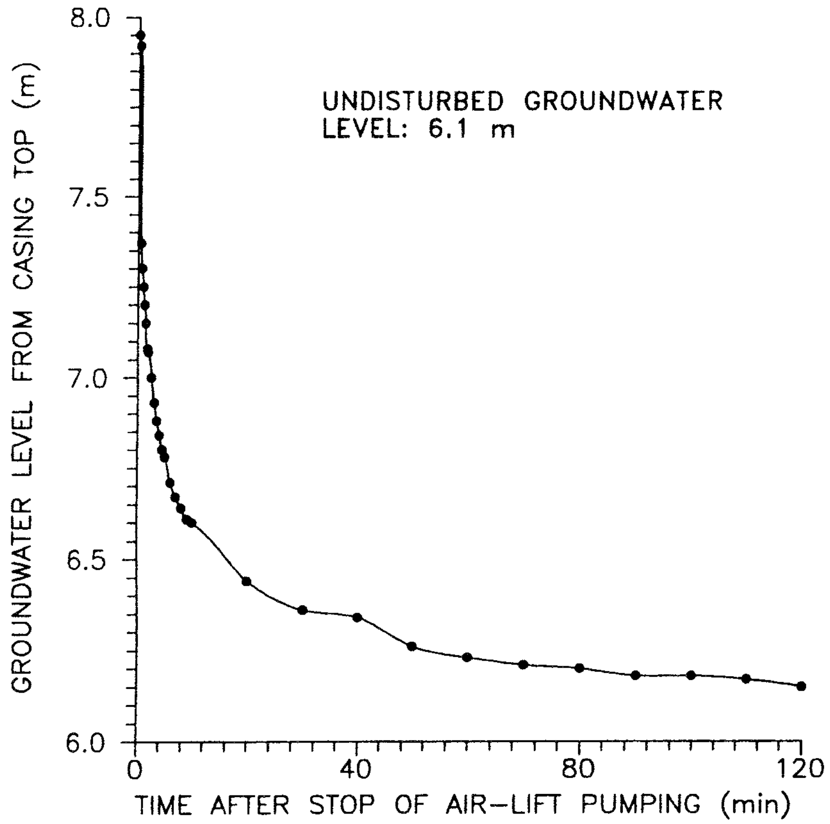

Figure 5-3 Results from the groundwater level recovery measurements in the pilot borehole.

When drilling had reached 200 m it was decided to conduct a packer measurement in the borehole, Figure 5-4. This decision was mainly taken due to the poor increase in upward water flow between 150 m and 200 m, c.f. Figure 4-1. The measurement was conducted in 10 m sections using a 0.1 MPa over pressure. As shown in Figure 5-4 most of the water inflow to the borehole occurs within the interval 30 - 80 m, and to a minor extent in the interval 120 - 150 m. The results show that most of the water inflow comes from the upper part of the borehole, which could explain the very poor water flow encountered during the drilling.

The packer measurement results, together with the drilling results, reflect how critical it is to penetrate water-bearing zones/fractures at fairly regular intervals to obtain a satisfactory result.

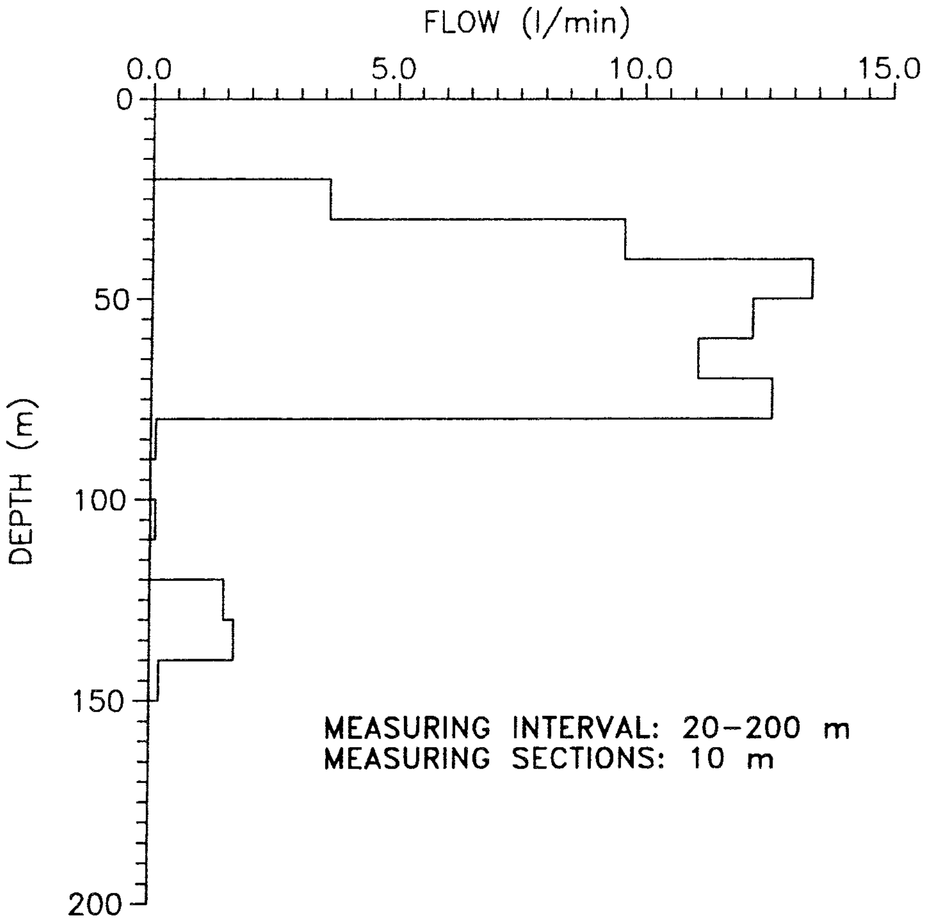

Figure 5-4 Packer measurement in the pilot borehole. Each test section was 10 m in length with an over pressure of 0.1 MPa.

The indications from the packer measurements that the inflow of water is mainly from the upper part of the borehole, was later verified by flowmeter logging after the borehole had been completed. A UCM flowmeter probe /Almén and Zellman, 1992/ registered the upward water flow simultaneously as air-lift pumping was carried out at 30 m depth. The measurement was conducted as discrete recordings every tenth metre, from 40 m depth down to the hole bottom at 290 m. At points where large anomalies were observed the intervals were reduced to one metre. The results, given in Figure 5-5, show that the borehole does not produce any water inflow between 100 m to 284.5 m, at which a water bearing zone was passed. The only exception is a minor anomaly found at 135 m depth.

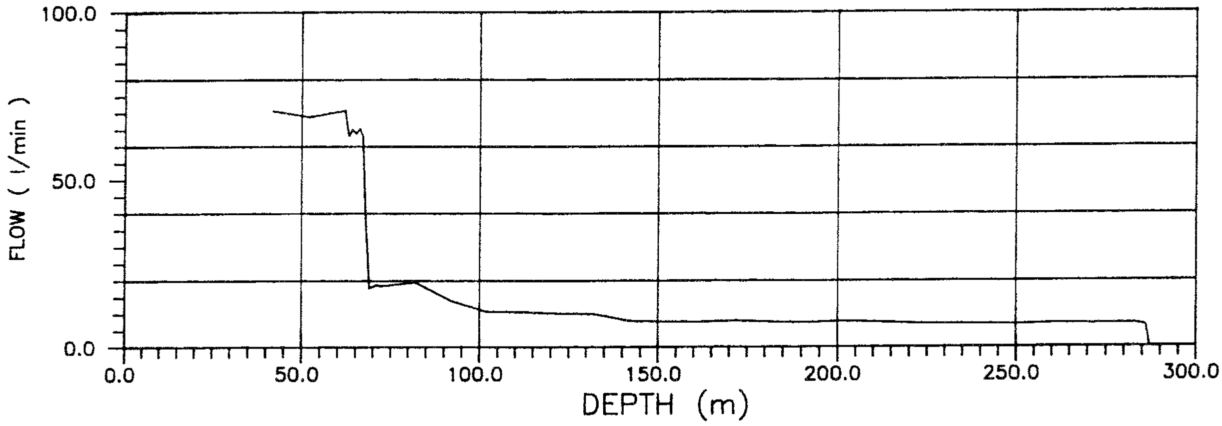

Figure 5-5 Results from the flow meter measurements during air-lift pumping in the pilot borehole. Measuring section 40 m - 290 m.

6 CONCLUSIONS AND RECOMMENDATIONS

This pilot study has shown that core drilling by reverse flushing can be applied with satisfactory results using mainly conventional core drilling equipment, but with modifications and special arrangements on vital parts of the equipment, such as drill rods (design and optimum dimensioning) and drill bit.

Core drilling using reverse flushing is not intended as an alternative to core drilling for conventional purposes, but rather as a complement to be used in situations when higher drilling costs can be accepted for the benefit of cleaner boreholes. A cleaner borehole means in this context, a borehole which has not been contaminated with flushing -and cooling water, and where, to a large extent, the accumulations of drill cuttings along the borehole wall and in fractures has been reduced.

There is a high probability that the drilling costs of reverse flushing will exceed that of conventional core drilling, since the technique is dependent of a natural water inflow to the borehole. The pilot drilling test has also shown that it is vital to pass water-bearing zones/fractures every 50-70 m to achieve a drilling performance comparable with that of conventional core drilling. The passage through the water-bearing zone at 284.5 m was very important in that aspect, as it indicated penetration rates in parity with conventional drilling. It also gave a very clear indication that the transport of the water in the column between the borehole wall and the drill string is a critical factor for the drilling performance.

One can conclude, however, that the method works even in a situation when the water inflow to the borehole is proportionately poor, or, in the case when the distance between water-bearing zones/fractures is too great.

The construction of the equipment also offers the possibility to restrict reverse flushing for only drilling selected sections of a borehole. If a section at depth is of special interest, demanding high requirements on clean drilling techniques, conventional or telescope-type core drilling may be used for the upper limit of the section to reduce drilling time, and further drilling of the section can then be continued using reverse flushing.

It should be noted that if a situation of unsatisfactory upward water flow should arise, the equipment can be switched quickly from reverse flushing to drilling based on air-lift pumping in through the inner rod in the double rod system and out via a nozzle to the column between the drill string and the borehole wall, Figure 6-1. At the same time water is pressurized down through the drill string to the drill bit. The switch is done by a replacement of the deepest rod in the double rod section. In principle, this technique is very similar to that of the telescope-type core drilling method. It should be noted that the change will lead to a less clean drilling technique as compared to reverse flushing, but in parity with the technique of telescope-type core drilling.

By being able to switch to the drilling alternative mentioned above, and also to conventional or telescope-type core drilling, the eventual economic risks of using reverse flushing are reduced.

The main part of the pilot borehole was drilled using an upward water flow between 10-12 l/min and a reduced number of drilling machine revolutions. To reduce the number of revolutions is to reduce the penetration rate. To drill by reverse flushing using an upward water flow of less than 10 l/min is not recommended, since it results in an inadequate transportation of drill cuttings, and insufficient cooling of the drill bit. At this low flow rate, drill cuttings accumulate at the drill bit which drastically increases the jamming risk. Experience from the pilot borehole demonstrates that drilling using an upward water flow around 10 l/min lies just at the lower limit.

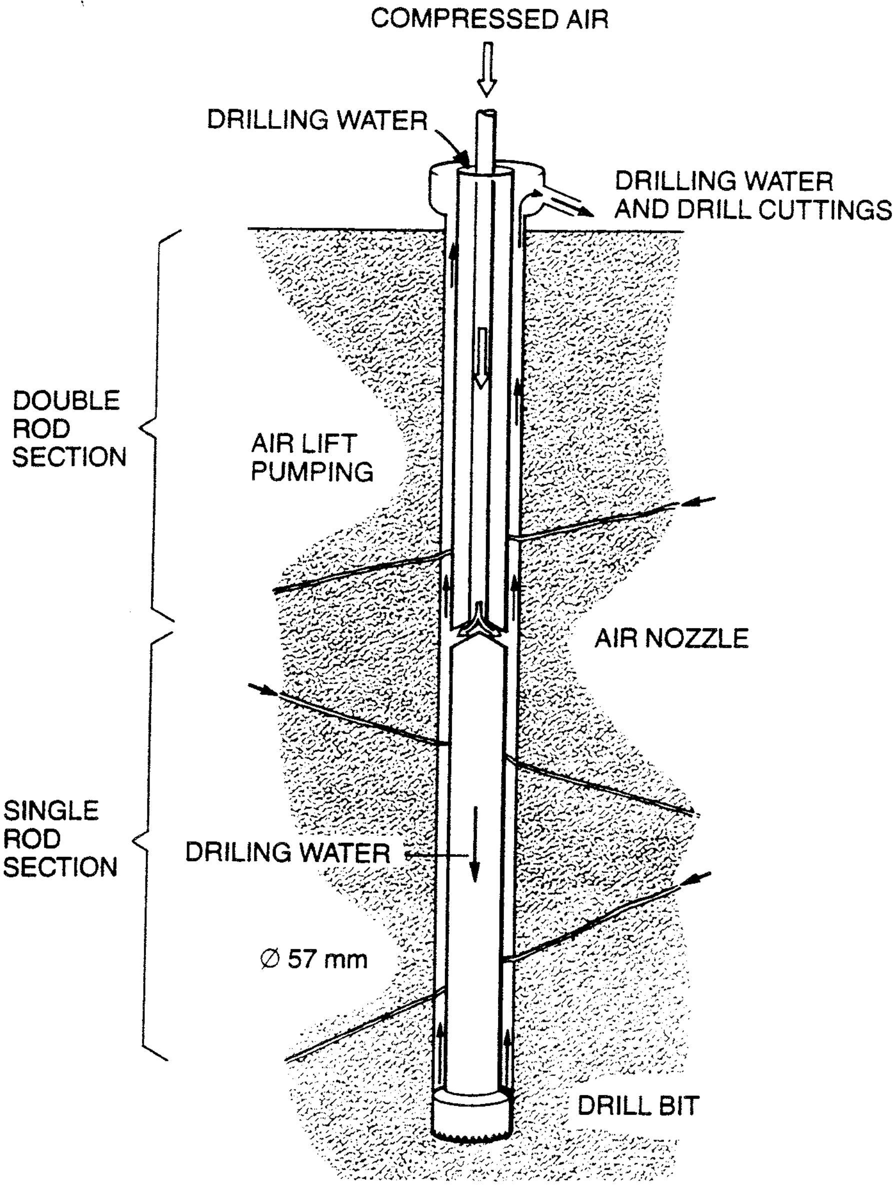

Figure 6-1 Alternative drilling technique which may be used when an unsatisfactory drilling performance is obtained with core drilling using reverse flushing.

It should also be advised against decreasing the number of revolutions below approximately 1100 rpm, since the risk of jamming increases with a decreasing number of revolutions. Drilling by reverse flushing when the upward water flow is between 10-15 l/min is therefore a balance between the number of drilling machine revolutions and the upward water flow.

Due to the lower water pressure at the hole bottom, and that the water flow is upward through the drill string, core drilling by reverse flushing is potentially superior in comparison to conventional core drilling when penetrating weak zones. In those cases when drilling of the pilot borehole was conducted without any disruptions for testing etc., the results show that the filling of the core barrel had been very good. Only in one case, at 284.5 m depth, had drilling to be disrupted due to a stop in the core barrel. This was later confirmed to have been caused by subaxial splitting of the core causing wedges in the barrel. In one case, a sand/gravel zone was penetrated without any problems in the core barrel.

The pilot drilling was performed using a 3 m core barrel; this could be increased to 4.5 m or 6 m in length if there is an excess water flow to allow for an increase in pressure losses.

It is not possible to give any precise recommendations as regards the flow and pressure of the compressed air, due to the variation in conditions that effect these parameters. During drilling using reverse flushing a lowering of the water table in the borehole takes place, which influences the air pressure. Furthermore, the water in the column between the inner and outer rod mixes with air when the air lift pumping starts which after a short pumping period reduces the required air pressure. Tests indicate an optimum drilling performance at an air flow of 10-15 m^3/h at 6-8 bar air pressure.

It is recommended that the development of this equipment and technique is now applied without any major modifications to the system. The test should preferably be conducted at an occasion when another borehole in the same area is drilled using the telescope-type core drilling technique. Subsequent hydrogeological and geochemical test in both boreholes may then indicate if reverse flushing produces cleaner boreholes.

Apart from the potential of cleaner boreholes, it is possible to identify two other positive effects by using reverse flushing:

- The water capacity of the borehole may be estimated during drilling.

- Test pumping can be conducted using existing equipment, and samples of the formation water taken during drilling.

Although the concept of using reverse flushing has proven to give satisfactory drilling performance, there should be further possibilities to improve the equipment. Such efforts should concentrate on the column between the borehole wall and the drill rods. Examples worth studying include whether a screw-shaped jacket on the drill rods can contribute to a reduction in pressure losses in the column, and the possibility to further reduce the outer diameter on the drill rods which are positioned below the double rod system.

It should finally be noted since the equipment for reverse flushing has initial or fixed pressure losses, regardless of drilling depth, the drilling technique is not recommended at depths above 100 m. Even if the complete drill string consists of double rods the air-lift pumping will not be large enough to generate a sufficient net uplift force. The uplift force should not only compensate for the pressure losses, but also generate a surplus to obtain a satisfactory upward water flow.

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