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KBS-3H – DETUM

Steered core drilling of boreholes K03009F01 and K08028F01 at the Äspö HRL

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This report concerns a study which was conducted for Svensk Kärnbränslehantering AB (SKB). The conclusions and viewpoints presented in the report are those of the author. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

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Abstract

The drilling of the cored boreholes K03009F01 and K08028F01 was carried out in the Äspö HRL during 2013–2014 under the auspices of the DETUM Large fractures and the KBS-3H projects. DETUM was run by Swedish Nuclear Fuel and Waste Management Co (SKB) of Sweden while KBS-3H was run jointly by SKB and Posiva Oy of Finland.

The boreholes are located at a depth of 400 m and are both in the order of 100 m long with a c. 20–30 m separation, being closest at the end of the boreholes.

The main focus of the DETUM project was testing of techniques and methodologies to identify and quantify fractures/structures, including their size characteristics while the KBS-3H project's focus was on investigating pilot borehole drilling techniques, in particular achieving the desired straightness of the pilot hole required by KBS-3H.

The report covers the procedures, including site preparations, steering strategy for drilling, results and experiences gained during drilling of the boreholes. It also details the comprehensive effort of assessing the performance of various deviation measurement tools, including their testing in the Äspö borehole deviation control facility at the Äspö HRL, prior to the boreholes being drilled.

Work carried out in K03009F01 included tests of various steering measures, whereas drilling of K08028F01 included systematic deviation measurements with continuous assessment of the outcome and corrective actions when required. The outcome of the latter drilling demonstrated that ± 10 mm/6m (vertical) and ± 20 mm/6m (horizontal) could be established for the full extent of the borehole.

The work reported constitutes the first in a series of steps aiming at demonstrating that the KBS-3H geometrical requirements imposed on the pilot borehole can be fulfilled over a 300 m length scale. A significant result is thus the recommendations on how to proceed and implement the developed strategies and methodologies for future drilling operations over a 300 m length scale.

Large Underground Concept Experiments

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Contents

1 Introduction

SKB and Posiva are planning for disposal of spent nuclear fuel from Swedish and Finnish nuclear power plants at depth in crystalline bedrock. This to ensure the safety of human beings and the environment for long periods of time. The method selected for the final repository is the KBS-3 concept, Figure 1-1. The reference design is KBS-3V employing vertical disposal of the waste canisters, where horizontal disposal of the canisters, KBS-3H, is a possible alternative which is being explored by the two organisations. SKB's and Posiva's current programmes for KBS-3 are detailed in SKB's RD&D Programme 2013 (SKB 2013) and in Posiva's TKS-2009 (Posiva 2010).

Drilling of two boreholes (K03009F01 and K08028F01) aim at: investigating pilot borehole drilling techniques (KBS-3H) and; testing of techniques and methodologies to identify and quantify fractures/structures and their size characteristics (DETUM – Large fractures and KBS-3H).

KBS-3V is based on 300 m long deposition tunnels located at 400–500 m below ground from which vertical deposition holes are drilled and fuel canisters placed. The deposition tunnels are planned to be preceded by core drilled pilot holes, 76 mm (N-size), in order to characterise the rock volume in detail before drill and blast excavation. For long term safety reasons, it is important that the pilot holes keep within the tunnel periphery, i.e. they are removed during excavation. This defines the geometrical requirements on the pilot holes in the KBS-3V design.

The KBS-3H design is based on deposition of Supercontainers, which are made up of fuel canisters surrounded by bentonite blocks inside metallic shells. The Supercontainers are placed horizontally in 300 m long, slightly upward inclined deposition drifts with diameters of 1.85 m and located at similar depth underground as in the KBS-3V design. To achieve the required bentonite density the void between the Supercontainers and the drift wall is small, thus requiring a straight drift so the Supercontainers don't get stuck during deposition. The suggested technique for constructing the disposal drifts is to drill a 76 mm (N-size) core drilled pilot hole, followed by stepwise reaming of the hole to the full size of the drift, i.e. Ø 1.85 m.

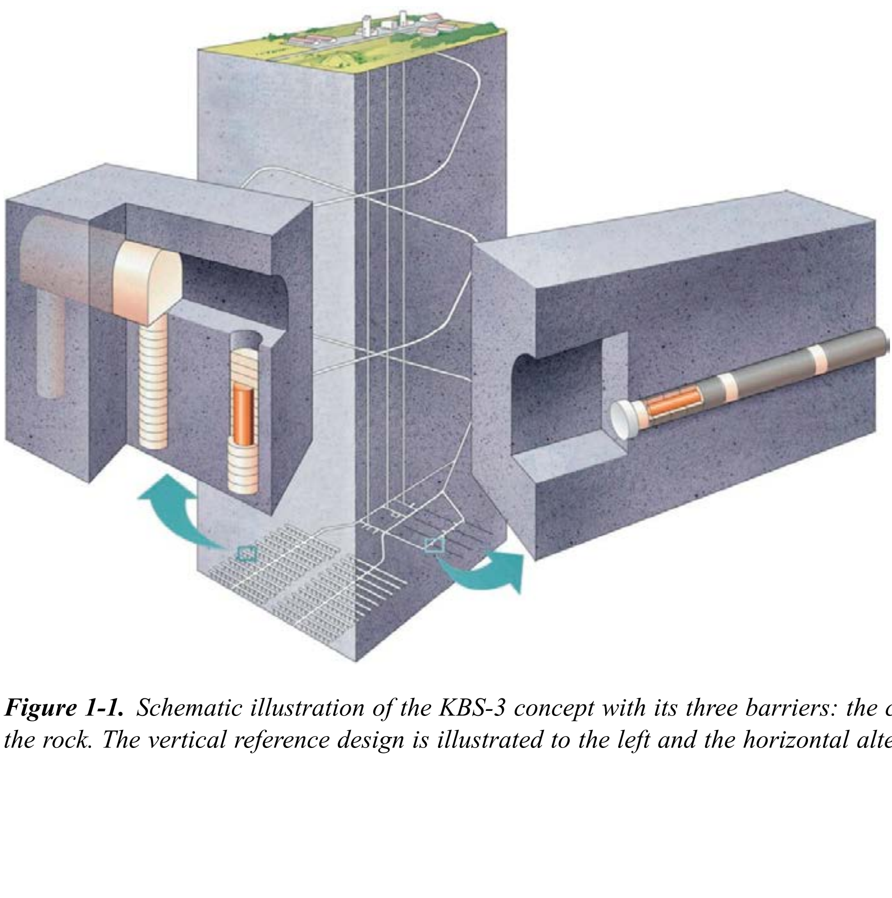


Figure 1-1. *Schematic illustration of the KBS-3 concept with its three barriers: the canister, the buffer and the rock. The vertical reference design is illustrated to the left and the horizontal alternative to the right.*

Both KBS-3V and KBS-3H thus have high demands on drilling accuracy and will most likely have to rely on steered drilling in order to fulfill pilot hole requirements. Steered drilling relies on accurate deviation measurements. There are multiple suppliers of tools available for surveying boreholes, however, they have the inherent problem that the quality in the data produced is difficult to verify simply due to the fact that the holes are not available for independent geodetic control. SKB has previously addressed this by the use of different measuring methods for measuring each hole. This improves the situation but doesn't address it fully. In order to further assess the quality of the data, SKB has therefore developed a 300 m long calibration facility. It basically constitutes a pipe on the surface that can be geodetically surveyed from the outside to ensure the true location prior to measurement with the deviation tools inside. The calibration facility was in operation and utilized at the time of the second of the two drilling operations covered in this report.

The KBS-3H project has a test site available at the −200 m level at the Äspö HRL, where two deposition drifts have been excavated (15 and 95 m long) (Bäckblom and Lindgren 2005). A new test site, in the TAS08 tunnel, is being developed at the −400 m level, see Figure 1-2. The main objectives of the new test site are to demonstrate and verify performance of pilot borehole drilling techniques with subsequent reaming to 1.85 m diameter, including verification of fulfilment of set up geometrical requirements. Afterwards, post grouting using the Mega Packer technique will also be tested (Eriksson and Lindström 2008).

The objective of the DETUM (Development of methodologies for detailed site investigations) project is to further develop and adapt available methodologies and strategies for detailed site investigations applicable to the construction and operational phases of a repository. The collected data and information and associated site-descriptive modelling should enable a design adapted to site conditions and to answer up to design premises applicable to the various repository underground openings and associated engineered barriers.

One of the design premises is associated with the need to avoid large fractures/structures when siting deposition holes, which could be subjected to shear in case of an earthquake event in a neighbouring major deformation zones. Such fractures are currently screened by application of so-called Full Perimeter Intersection (FPI) related criteria (Munier 2010). However, given that these criteria also are likely to screen out fractures below the stipulated size criterion, there exists a need to enable siting of deposition holes based on direct or indirect inference of fracture size. One of DETUM's subprojects is devoted to testing of techniques and methodologies to identify and quantify fractures/structures and their size characteristics. This comprises characterisation and modelling data from the Äspö Expansion project and information from the two boreholes which are in focus in this report.

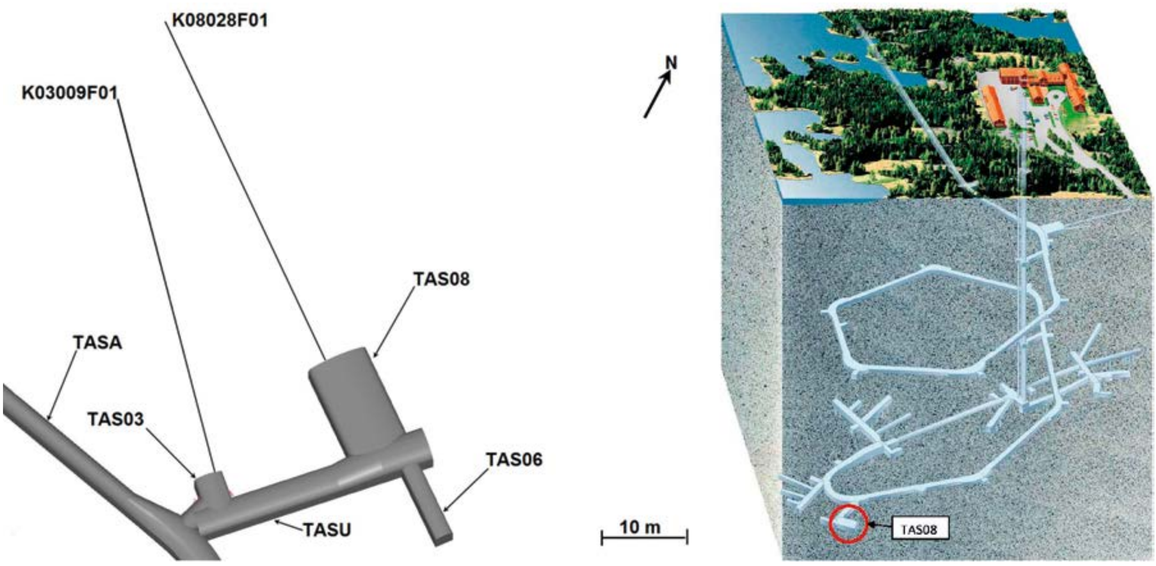


Figure 1-2. *Left, schematic view showing the service tunnel TASU with the connected KBS-3H experimental drift TAS08 and the DETUM niche TAS03, right, TAS08 location at Äspö.*

In this context the drilling of the two 76 mm (N-size) boreholes K03009F01 in tunnel TAS03 in December 2013 and K08028F01 in TAS08 in June 2014 can be regarded as a successive evolution, where steered drilling with associated deviation measurements initially were tested out in conjunction with drilling of K03009F01 and subsequently fully implemented in conjunction with drilling of K08028F01, including full application of the KBS-3H geometrical requirements.

All activities at the new test area covered by the two boreholes were carried out in close collaboration between the KBS-3H and the DETUM-1 project. The drilling of K08028F01 is also part of the EC Project Large Underground Concept Experiments (LucoeX) which focuses on the technical feasibility in situ for safe and reliable construction, manufacturing, disposal and sealing of repositories for long-lived high-level nuclear waste. Borehole K0802F01 was thus also partly funded by the European Commission.

The KBS-3H design has been developed jointly by SKB and Posiva since 2002. This report has been prepared within the project phase "KBS-3H – System Design 2011–2016".

1.1 Purpose of this report

This report documents the procedures, steering strategy for drilling, results and experiences gained during drilling of boreholes K03009F01 and K08028F01 at the Äspö HRL. It also reports preparations prior to drilling of the boreholes involving a comprehensive effort to assess the performance of various deviation measuring tools, e.g. by testing them out in Äspö deviation control facility at the Äspö HRL.

Figure 1-3 illustrates the activities reported.

For KBS-3H the work reported constitutes the first steps, in a series of steps, aiming at demonstrating that the KBS-3H requirements can be fulfilled over a 300 m length scale. The report also presents recommendations on how to implement the developed strategies and methodologies for future drilling operations over a 300 m length scale.

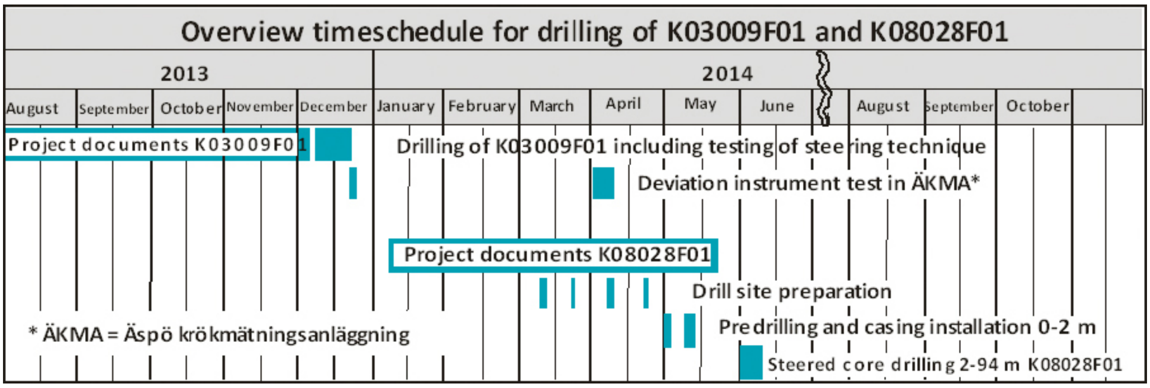


Figure 1-3. Overview time schedule of the preparations and drilling performance of borehole K03009F01 and K08028F01.

2 Geometrical requirements

2.1 Detum

K03009F01 was drilled with DETUM's large fracture studies in mind and the following geometrical requirement was implemented for the borehole:

- Drilling shall be carried out so that the borehole does not deviate outside a cylinder of 0.7 m in radius. The borehole should be directed exactly to the endpoint if drilled perfectly straight.
- So-called "careful steered drilling" should be applied so that the radius of curvature does not exceed 0.1°/m, to ensure that different probes and borehole instruments are able to pass every section of the borehole without obstruction.
- The inclination should ideally be −1°, i.e downward, and on no occasion should the inclination be positive (i.e. upward).

2.2 KBS-3H

K08028F01 was drilled with the objective to fulfil the KBS-3H geometrical requirements (SKB 2012). In addition it provides an important second borehole for the DETUM-project. The requirements which are defined for the deposition drift also apply to the geometry of the pilot borehole:

- The upward inclination should be 2° ± 1°. On no occasion should the inclination be negative (i.e. downward). Using the criteria 2° ± 1° result in Z displacement 10.5 ± 5.2 m for a 300 m borehole and 3.5 ± 1.7 m for a 100 m borehole.
- The maximum horizontal deviation (azimuth) from the nominal position over a 300 m borehole length is ± 2 m (which gives ± 0.67 m for 100 m).
- The maximum vertical offset in the pilot borehole should not exceed 10 mm from the straight line between any points of 6 m distance.
- The maximum horizontal offset in the pilot borehole should not exceed 50 mm from the straight line between any points of 6 m distance.

3 Geological and hydrogeological premises

3.1 Borehole K03009F01

Various alternative geometries for borehole K03009F01 were reviewed by the DETUM Large fractures subproject, finally adopting a geometry with a bearing of 319° (RT90) and a downward inclination of −1°, whereby two interpreted deformation zones (DZ1 and DZ4) were projected to be intercepted in the first c. 10–15 m of the borehole, c.f. Figure 3-1. The two deformation zones were labelled as being of high confidence given that they were observed in both borehole and tunnel. They were projected to be hydraulically conductive with transmissivities in the order of 8×10^{-6} m^2/s. The projected high transmissivity together with projected poor rock quality in connection with the two deformation zones were expected to affect drilling in the section including the zones. In this section drilling would also be conducted in partly grouted rock (associated both with borehole KA3007A01 and pre-grouting whilst excavating tunnel TASU). However, the rock volume between deformation zone DZ4 and the future KBS-3H borehole (i.e. K08028F01), presumed to be of geometrical, geophysical and hydrogeological interest to the Large fractures subproject, was projected to be of high quality. Table 3-1 summarises the hydrogeological prognosis prior to drilling.

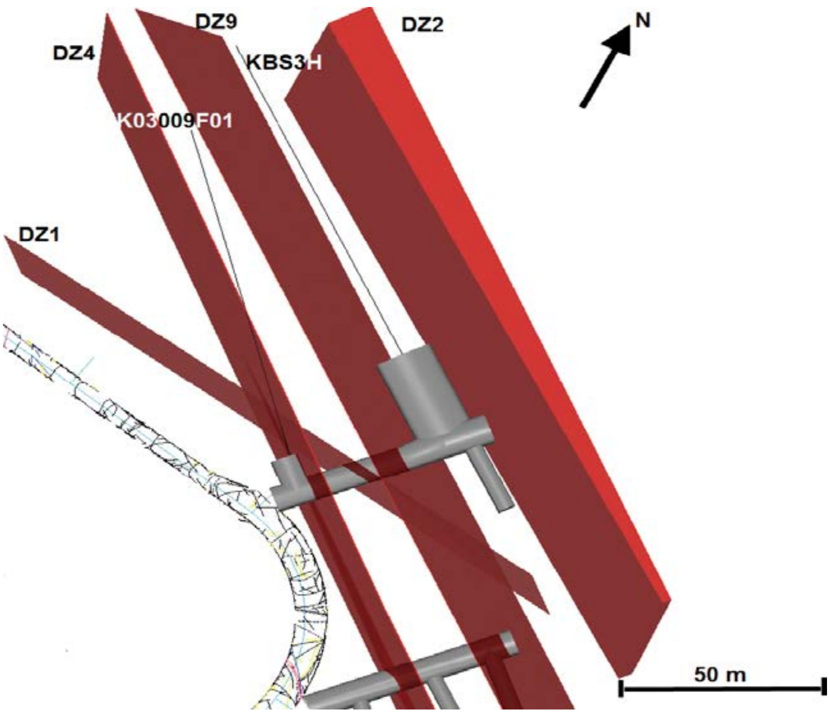


Figure 3-1. *Descriptive model of deformation zones in conjunction with the Äspö Expansion area. The TASP and TASU service tunnels with borehole K03009F01 and K08028F01 ("KBS-3H"). Notable is the lack of projected intercepts of interpreted deformation zones along K08028F01.*

Table 3-1. Prognosis for borehole K03009F01.

Borehole length (m)	Rock quality, deformation zone and hydraulic conductive feature (HCF)	Flow (L/min)	Sections where pressure responses are expected
0–15	Bad quality rock	1–5 if previous grouting (TASU) is ok 200–300 if not ok.	KA2050A KA3010A KA3065A02 KA3065A03 KA3067A KA3068A SA3045A minor
10	DZ1 HCF KA3007A01_2	1–5 if previous grouting (TASU) is ok 100–200 if not ok.	KA2050A KA2051A KA3005A KA3010A KA3065A02 KA3065A03 KA3067A KA3068A KA3105A minor KXTT1 KXTT2 KXTT5 SA3045A
10	DZ4 HCF KA2051A01_4	1–5 if previous grouting (TASU) is ok 100–200 if not ok.	KA2050A KA3010A KA3065A02 KA3065A03 KA3067A KA3068A SA3045A lite
Intercept not expected	DZ9 HCF KA3011A01_4	5 (if intercepted)	If intercepted KA2050A KA3010A
First section Second section The complete borehole	Ävrögranodiorite Äspödiorite Subordinate rock types Fine grained diorite-gabbro	17 (for 15–100 m borehole length)	

3.2 Borehole K08028F01

3.2.1 Geometry and structural descriptive model

Detailed geoscientific data collected within the Äspö Expansion project complemented with data from the drilling of borehole K03009F01, provided basic knowledge about the geological and hydrogeological conditions in conjunction with the test site where K08028F01 was to be drilled. No deformation zones were projected to be intercepted by borehole K08028F01, cf. Figure 3-1. However, correlation of mapped foliation of the bedrock as seen in borehole KA2598A, KA3007A01 and in the DETUM borehole (K03009F01) suggested the presence of an increased intensity of foliation (possibly increased fracturing) at the bottom of K03009F01, see Figure 3-2.

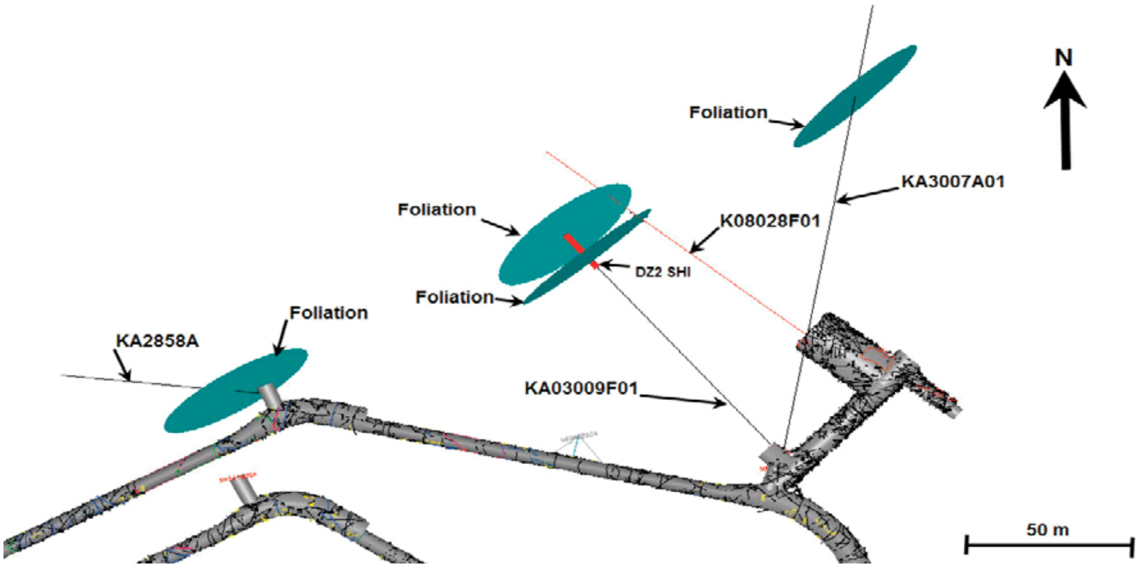


Figure 3-2. *Schematic figure of the rock volume which the planned pilot borehole K08028F01 will sample. Foliated sections earlier encountered in surrounding boreholes, that possibly may be intercepted by K08028F01, are also shown in the figure.*

3.2.2 Expected geological and hydrogeological conditions

Generally, the bedrock in the rock volume in which the Äspö HRL is constructed has a mainly granitic composition consisting of several varieties of granitoids and some accessory rock types, e.g. Äspödiorite, fine-grained granite, Ävrö granodiorite and fine-grained diorite-gabbro. The fracture frequency is generally low. In borehole K03009F01 it is approximately 3.6 fractures/metre. Similar lithological and structural conditions were also expected to be found in borehole K08028F01. The specific geological prediction made before drilling included a deformation zone (DZ 2SHI) that might manifest itself as increased foliation and red staining of the rock from c. 64 m borehole length, cf. Figure 3-2.

The hydrogeological prognosis prior to drilling predicted low water inflow in the "good", non-deformed rock and even less inflow in the altered rock towards the borehole end, see Table 3-2 and Figure 3-2.

Table 3-2. Summary of the prognosis from geology and hydrogeology in K08028F01.

Borehole length or interval (m)	Geological structure, DZ, fractures, HCF, rock type boundary etc.	Groundwater flow (L/min)	Neighbouring boreholes where pressure responses are expected (HMS) during drilling of sections 0–64 m and 64–100 m, respectively
0–64	Good rock to be expected without any specific structures. Dominated by Äspödiorite with subordinate rock types; Fine-grained granite, Ävrö granodiorite. Fine-grained diorite-gabbro	~4.2	K03009F01 KA2050A KA2051A01 KXTT1 KXTT2 KXTT5
64–100	Possible DZ from SHI of K03009F01. Rock types: Äspödiorite and fine-grained granite.	~2.3	K03009F01 KA2050A

3.2.3 Handling of effects of foliation

From earlier geological mapping it is concluded that the rock volume penetrated by borehole K08028F01 is characterized by variable degrees of foliation, which may exert an influence on the drilling of the hole, mainly by forcing the borehole

- slightly down,
- slightly to the right (east).

The activity leader must take this into account in decisions on steering.

4 Deviation measurements

4.1 General

Within the framework of SKB's geoscientific research and development program, drilling and borehole surveys are important and vital parts of the characterisation of the rock mass. This entails high demands on the data set delivered to be accurate and traceable according to SKB's approved quality control system. Presentation and modelling of data in 3D-models requires reliable deviation measurements, meaning that high precision coordinates in 3D space can be calculated along the entire length of a borehole. In some cases, SKB also has specific requirements on the borehole direction and straightness, and in these boreholes deviation measurements are part of the steered drilling technique employed.

There exist a number of commercially available deviation measuring instruments based on different physical principles. Some instruments are based on magnetometer-accelerometer technology, whereas others follow the principles of angular momentum (gyro instruments). Also optical systems have been frequently used. A well-known weakness of all deviation measurement systems, irrespective of measurement principle, is that performance and accuracy are difficult to control, since it is difficult to test the instruments properly. This is due to the simple fact that boreholes seldom are accessible for successive direct independent geodetic control measurements in the absolute sense (not even at their endpoints, unless drilled into or intercepted by an underground opening, which is rarely the case).

SKB's strategy to overcome this quality problem and to develop methods to quantify uncertainties of borehole deviation data has previously been to use multiple tools (mag/acc tools and optical tools) for multiple measurements, however, there is still a potential to improve the technique for borehole deviation measurements in order to increase the reliability of deviation data.

For this purpose, and to ensure that accurate instrument and modern measurement technique is to be used in the future, SKB has recently completed the construction of a deviation calibration facility for instruments aimed for deviation measurements at the Äspö HRL. This facility is described in Section 4.2.

4.2 Äspö deviation control facility

The Äspö surface-based deviation calibration facility (from here on abbreviated as "Äspö deviation facility") was constructed by SKB in 2013 (Figure 4-1, 4-2, 4-3). A 300 m long PVC pipe (simulating a borehole trajectory) is fastened to the ground with 151 non-magnetic pipe holders bolted to the ground whereof a third are reinforced with concrete pillars when the distance between the pipe and ground exceed 1 m. The location of the pipe is surveyed using a total station at fixed positions (reflectors) at its starting and end points, and on the pipe holder every second metre.

4.2.1 Technical specifications

The Äspö deviation control facility has been constructed to meet the requirements set up by the disposal concepts KBS-3H and 3V, e.g. when drilling pilot holes for the deposition tunnels in the planned repository for spent nuclear fuel. All materials used in the deviation facility are non-magnetic (mainly plastics and aluminum). The third of the pipe holders that are reinforced (see above) are therefore casted solely with concrete, i.e. without iron reinforcement bars.

- The pipe making up the simulated borehole is 300 m long and has a nominal inner diameter of Ø = 75 ± 0.2 mm.
- The pipe follows the topography of the ground but is basically horizontal. The elevation of the array varies between +6.75 and +3.2 m relative to sea level, cf. Figure 4-3.
- The pipe is supported by plastic pipe holders bolted to the ground with aluminum threaded rods every second meter.

- The first 6 meters are straight (section 0/0.0 to 0/6.0), made up of a rigid aluminum pipe.
- From section 0/6.0 to 0/62.0 the pipe is constructed as a sinusoidal wave with a wavelength of 8 m and surveyed amplitude of c. 13 mm with accuracy and a standard deviation of ± 1 mm as surveyed by a Total station. This to meet the strict KBS-3H requirement, implying that the vertical difference shall not exceed ± 10 mm over a borehole length of 6 m.
- The remaining section, from 0/62.0 m to 0/300.0 m, follows the topography, undulating both vertically and laterally with a surveyed accuracy of ± 2 mm.

Figure 4-1. *Äspö deviation control facility is a 300 m long plastic tube (Ø75 mm) secured firmly to the ground with 151 fastening devices. All material used in the construction is non-magnetic such as plastic and aluminum.*

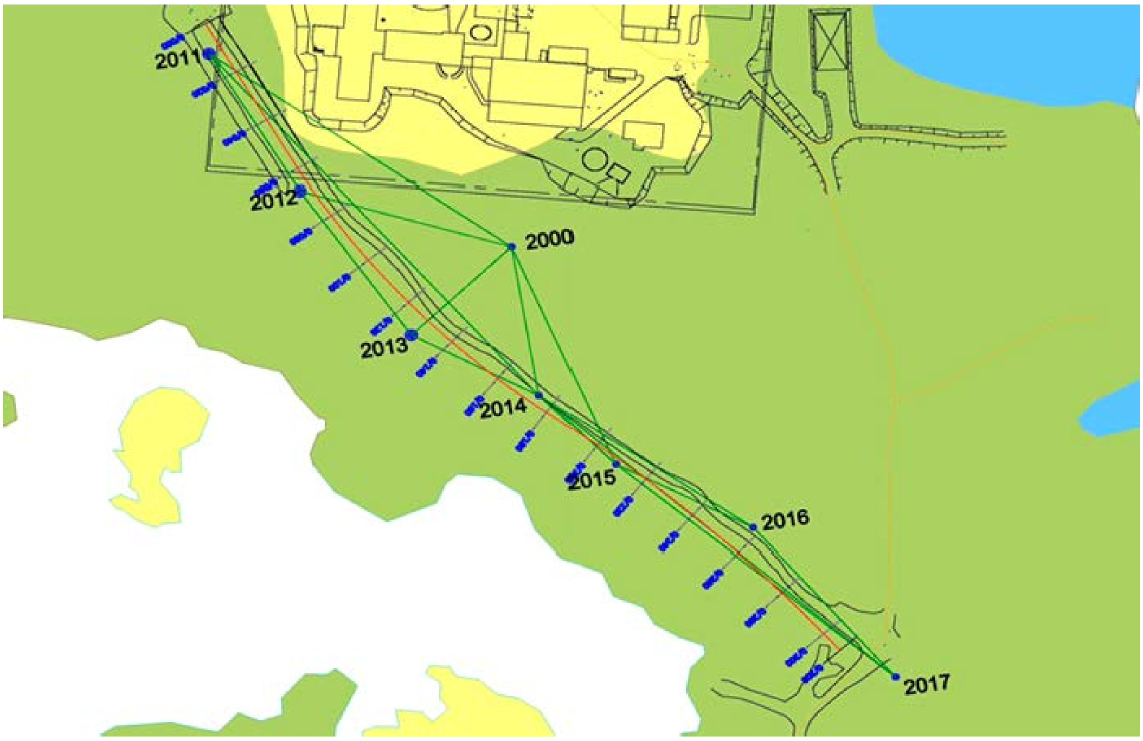


Figure 4-2. *Plan view of the Äspö deviation control facility (red line), also named KAS99, located close to the Äspö head office (top side of the figure). The geodetic fixpoints are also illustrated.*

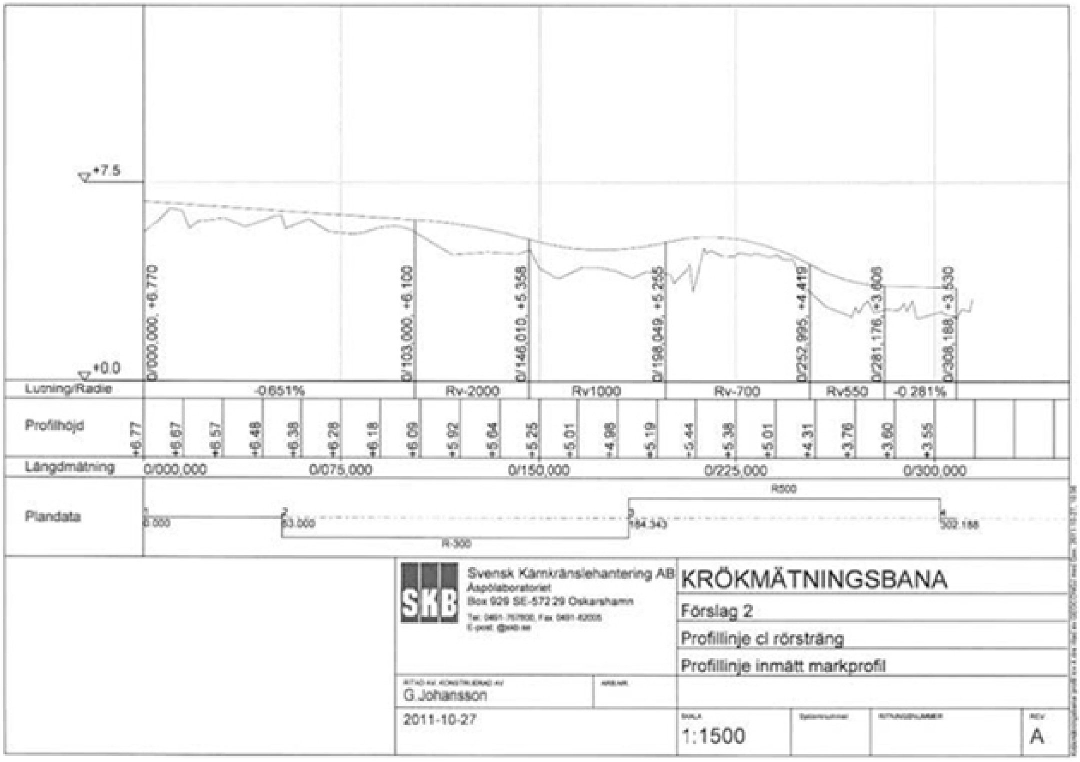


Figure 4-3. Vertical section of the Äspö deviation control facility. The difference in elevation between the end points is about 3.25 m. At the start and end points the tube is approximately 0.8–1 m above the ground in order to provide a convenient working height when the deviation equipment is pushed or pulled into or out from the tube.

4.2.2 Measurements

One of the most critical components in the KBS-3H-project is to demonstrate that the practical use of commercially available deviation instruments could fulfil the strict KBS-3H geometrical requirements.

Most of the deviation tools deliver data with high precision, i.e. several decimals, and in laboratory environment many tools are calibrated to 0.01° accuracy. However, operation of the instrument, length accuracy when pulling/pushing the tool, centralizing of the instrument in borehole, borehole conditions etc, will for certain reduce the accuracy.

Immediately, after finishing the steering tests, Devico AS carried out calibration measurements at the Äspö deviation facility in December 2013, with the DeviShot instrument used in borehole K03009F01, see Table 4-1.

The supplier of deviation measurement systems of the brand Reflex carried out calibration measurements at the Äspö deviation facility in April 2014 with the instrument Reflex Gyro, see Table 4-1. Measurements were carried out in both directions, measuring into the pipe, followed by repeated measurements out of the pipe. Between 0–62 m, measurements were made every metre, whereas between 62–300 m, measurements were made at every 2nd metre.

Figure 4-4. To the left, an electrically powered insertion rig is used for in and out transportation of the deviation tools in the 300 m long plastic tube. To the right Devico technicians prepare some of their instruments before measurement.

Table 4-1. The table presents the absolute differences at the end point for X,Y,Z and the absolute difference Δr from ReflexGyro, and Devishot (magnetic tool) that have been tested at the facility. A special measurement program has been utilized for the section 0–62 m to match the KBS-3H requirements. Data extracted from SKB's site investigation database (Sicada).

Name	Method	BH length (m)	Δr (m)	Absolute Δx (m)	Absolute Δy (m)	Absolute Δz (m)
Gyro_298_in	Gyro	298	3.183	2.377	2.109	0.173
Gyro_298_out	Gyro	298	0.764	0.588	0.359	0.332
Gyro_62_in	Gyro	62	0.133	0.038	0.128	0.009
Gyro_62_out	Gyro	62	0.183	0.003	0.182	0.022
Devishot_62_in	Magnetic	62	0.43	0.420	0.061	0.0
Devishot_62_out	Magnetic	62	1.076	1.030	0.301	0.079
Devishot_300_in	Magnetic	300	6.453	5.268	3.716	0.292
Devishot_300_out	Magnetic	300	8.496	6.978	4.836	0.322

4.3 Evaluation of deviation measurement tools

All deviation measurements are affected by uncertainties deriving from a variety of sources. Commonly, they involve uncertainties in the (individual) tool, external disturbances and human factors. The use of the Äspö deviation facility should contribute to decrease these uncertainties. Frequent measurements in the Äspö deviation facility will provide a better understanding of uncertainties associated with the tools and will at the same time inform technicians about which factors that is of most crucial importance in order to achieve high-quality measurement results.

The resulting difference calculation show that the Reflex tool is capable of achieving results within the stipulated accuracy as claimed by KBS-3H, see Table 4-1, Figure 4-5 and Figure 4-6. Vertical accuracy is very good, however, magnetic disturbances does as expected lower the accuracy of the magnetic tools.

According to Section 2.2 the deviation should be maximum 2 m for a 300 m long borehole and 0.67 m for a 100 m long borehole. In Figure 4-5 it is demonstrated that one measurement with the gyro (red open circle) gives results within the limits while the second measurement (red filled circle) is outside. However, for that second gyro measurement, one 2-m station was not registered (due to a human mistake) and consequently caused an absolute difference of 3.2 m that is outside the limit. The conclusion is that the gyro generates data with high precision if the instrument is used correctly. Minor mistakes performed during the measuring procedure cannot later be edited and the only option is to make a new measurement.

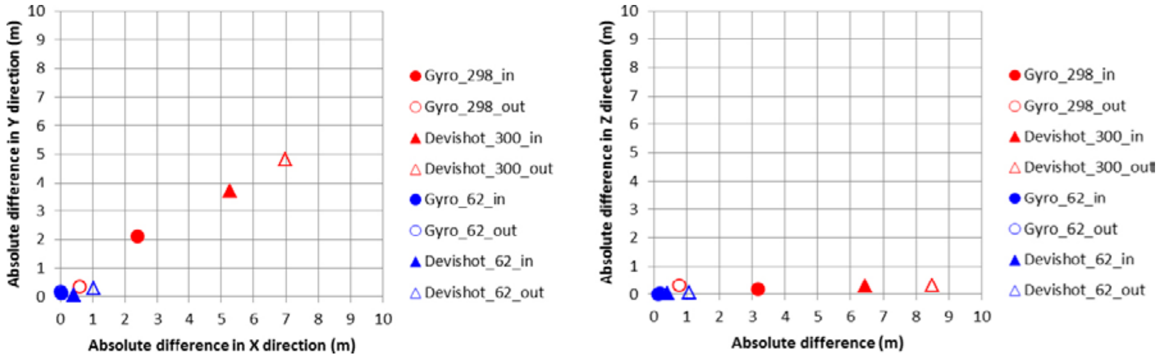


Figure 4-5. *The figure is based on data from Table 4-1***.** *To the left the absolute differences in Y versus X are presented. To the right the absolute difference (Δz) in Z direction versus the absolute difference Δr is presented. Comparison with the KBS-3H requirements given in Chapter 2 indicates that Reflex Gyro used are capable of measuring within the accuracies stipulated by KBS-3H.*

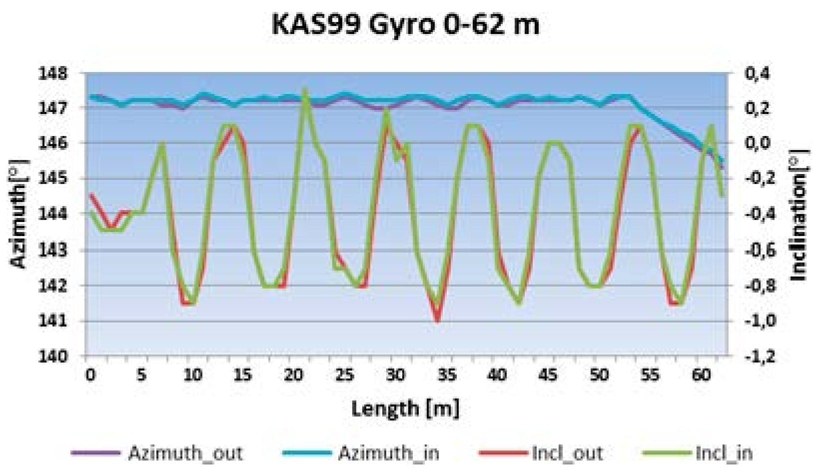


Figure 4-6. *Presentation of gyro measurements (both azimuth and inclination) in section 0–62 m in the Äspö deviation facility. The results of the in and out measurements are very similar.*

For the Devishot tool no measurement managed to be below the limits, probably caused by magnetic disturbances affecting azimuth, while the vertical distance, that is influenced of the inclination values are in the same range as the gyro values, see Table 4-1.

4.4 Selection of deviation measurement tools

The standard deviation logging tool adapted in the Devico steered drilling system (DEVIDRILL) is the magnetic based Pee-Wee tool (basically same as the tested Devishot tools). The system is designed for rapid measurement performance combined with high-speed transfer of data that can be analysed directly on site. The inclination data delivered from the instrument are comparable with all other tools, but the azimuth data can easily be disturbed, especially as magnetic minerals in the Äspö bedrock sometimes occur. Due to magnetic disturbances in the Äspö bedrock, the tool is not fully reliable for azimuth measurements.

The ReflexGyro is a complete down hole surveying kit for measuring in both magnetic an non-magnetic rock. The ReflexGyro is available in a complete or basic kit and contains its own internal quality checks. The initial azimuth reference at the collar is obtained by optical alignment. The instrument can be used to survey inside metal drill pipes, cased boreholes and at any borehole inclination. Surveyed data are transferred from the instrument to a field PC via high-speed Bluetooth. Surveyed data are then processed using the advanced GMIT5 navigation software. Operators can also tabulate, plot and export the data with GMIT5, which also contains its own internal quality assurance system.

The KBS-3H Project opted to use these two tools, the Devishot (Pee-Wee) and the Reflex Gyro. The Pee-Wee tool is primarily used for orientation of the DeviDrill system (toolface) but may of course also be used for complementary deviation measurements when so is needed. The Reflex Gyro is not affected by magnetic disturbances and therefore give more trustable values especially in azimuth.

5 Drilling of K03009F01

This chapter presents a detailed description of all activities carried out when drilling borehole K03009F01 included in the Detum-1 project (Development of methodologies for detailed site investigations). A close collaboration with the KBS-3H project enabled testingcareful steered drilling measures in selected sections of this borehole. The activities drill site preparations, core drilling, measurements and sampling during drilling were conducted in compliance with different steering documents prepared in advance. Results from these activities are presented more in detail in Sections 5.1–5.5.

5.1 General

Necessary guiding documents were developed and the purchasing procedure resulted in engaging the Swedish contractor Drillcon Core AB to drill borehole K03009F01with Devico Sweden AB (branch office Devico AS) providing the equipment for steered drilling and expertise. According to the safety regulations, the access to Äspö HRL was denied during the last week before Christmas as the elevator underwent a comprehensive service (exchange of the electrical transform). To optimize the budget and keep the time schedule it was important that the drilling activities should be completed before the year end. Therefore a local company, MiRo AB was engaged to perform pre-drilling for casing in mid-November, after which casing installation and drill site preparation were carried out. From late November to mid-December 2013 Detum was able to drill borehole K03009F01, collared in the TAS03 tunnel, see Figure 5-1.

Detums requirements for the steered drilling are presented in Section 2.1. Additionally an objective was the testing of the technology available for steered drilling on behalf of KBS-3H.

5.2 Results

5.2.1 Pre-drilling and mounting of casing in K03009F01

Pre-drilling and installation of a casing followed the standard procedures for implementation of core drilling underground at the Äspö HRL. As mentioned above, in November 11, 2013, a small drill rig was used for pre-drilling for the casing. This was carried out with 116 mm diameter to 2.55 m length. The tunnel front in TAS03 is altered and fractured, combined with a groundwater inflow. Consequently also the core displays highly fractured rock, and the discharge of groundwater from the borehole (0–2.55 m) amounted to 1 L/min, see Figures 5-2 and 5-3. Water inflow together with a hydraulic overpressure of c. 30 bars rendered subsequent grouting of the gap between the casing and the borehole wall unfeasible, meaning that the water jet will flush out the grout before hardening. Therefore it was necessary to seal the borehole by grouting, see Section 5.2.2.

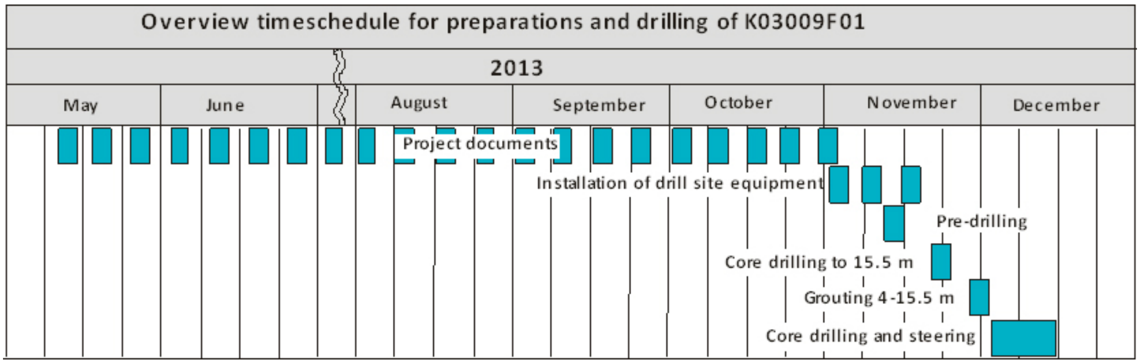


Figure 5-1. *Overview time schedule of the preparations and drilling performance of borehole K03009F01. The initial work started almost half a year before commencement of drilling in November 2013.*

Figure 5-2. *Pre-drilling of K03009F01 in TAS03. The tunnel wall is fractured and wet.*

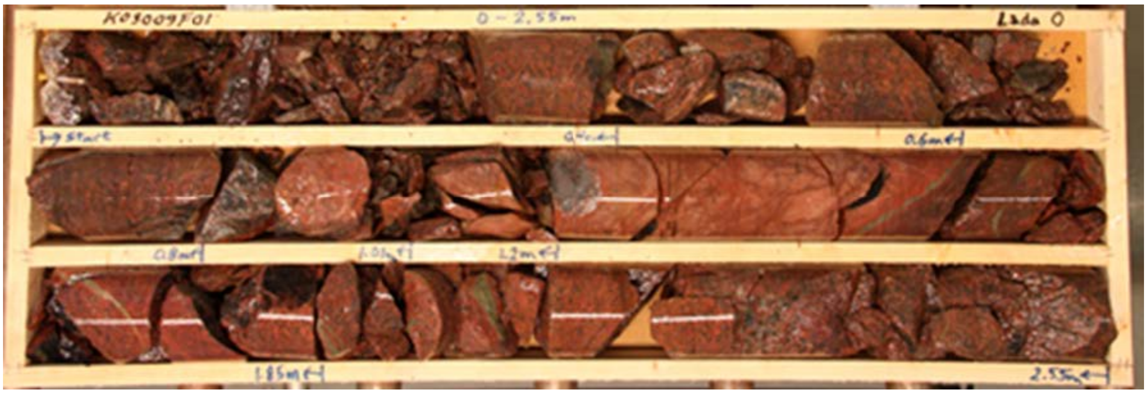


Figure 5-3. *The core in section 0–2.55 m is altered and highly fractured.*

5.2.2 Grouting of the pre-drilled borehole to 2.55 m

In November 13, 2013, an injection packer was mounted at a location in the borehole that permitted the section 0.335–2.55 m to be injected. The first batch with a grout volume of 108 L was mixed with Injektering 30 to VCT 0.8 and then pumped into the borehole. No stop pressure was achieved, and instead the grout was discharged out of fractures at the tunnel face. Therefore, a stiffer batch was mixed (VCT 0.5) and pumped into the borehole so that the flow in the tunnel face ceased and that a stop pressure of 30 bars was obtained. When shutting off the injection pump, the pressure decreased to 20 bars. By repeating the same procedure for additional 3 times, the flow of grout stalled and the pressure raised to 30 bars and was kept stable for 5 minutes before the valve was closed, see Figure 5-4. It must be mentioned, that the injection pump used had a maximum capacity of 30 bars (this was the only available pump at that time).

20 hours later the packer was released. It was noticed that the grout had hardened, but a small water flow at 0.25 m length in the borehole was observed, exactly where the packer had been expanded.

In November 18 the grouted borehole was re-drilled and after that the casing was installed.

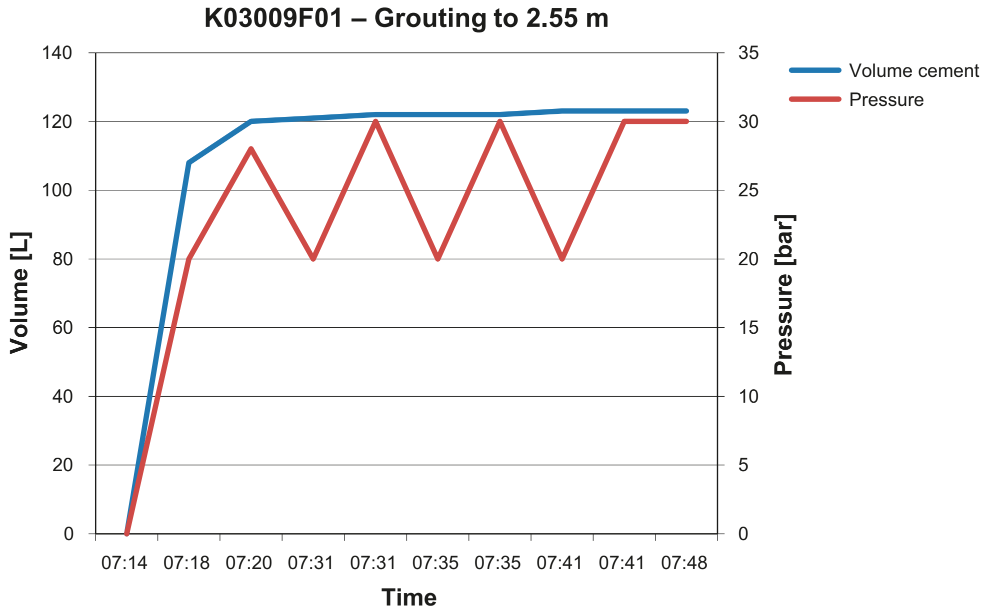


Figure 5-4. *Grouting performed in the pre-drilled borehole to 2.55 m. The injection pump capacity is maximum 30 bars, almost the same as the hydraulic groundwater pressure in TAS03.*

5.2.3 Drilling and grouting to 15.5 m

Due to expected large groundwater inflows along the first part of the borehole, grouting was prepared for and steered drilling was planned to be employed first at c. 40 m borehole length. The hydrogeological prediction turned out to be accurate, and at about 10 m borehole length the water inflow was found to be c. 250 L/min. The borehole was subsequently extended to 15.5 m, after which the entire borehole was grouted. Usually, the grouting activity is included in the drilling contract, but because the contractor had no high pressure injection rig available, it was decided that the project management would procure the grouting activity separately.

In order to obtain accurate hydrogeological data of the fracture zone, a 6-hours long flow test was carried out. Combined with pressure build-up data collected when the valve was closed, an injection strategy including a suitable grouting recipe was designed, see Table 5-1. BESAB was employed for the field work supervised by an activity leader from Chalmers University of Technology.

Table 5-1. Materials and weight ratio (W/DM = 1.4) based on INJ30 and GroutAid.

Material	Type	Weight Ratio
Water	Fresh water	1.68
Cement	INJ30	1.00
Silica fume	Grout Aid	1.37
Superplasticizer	Setcontrol II	0.07
Provides W/DM		1.4

For two sacks of cement à 20 kg, the mixture will be as follows:

Material	Type	Weight Ratio/ Volume
Water	Fresh water	67.2 kg/ 67.2 L
Cement	INJ30	40 kg
Silica fume	Grout Aid	54.8 kg/ 39.1 L
Superplasticerare	Setcontrol II	2.8 kg/1.9 L
Provides W/DM		1.4

Desirable properties of the grout to be used is:

Field Method	Unit	Value	Acceptable limits
Mudbalance	Kg/m^3	1520	±20
Marshkon	seconds	50	±5
Yield stick	Pa	14	>13 Pa

BESAB established their grouting equipment at December 03. The injection packer was installed 4.5 m from TOC (top of casing) into the borehole, see Figure 5-5. Following the recipe in Table 5-2 almost 800 L cement/silica mixture was pumped into the section 4–15.5 m with a stop pressure of c. 80 bars.

After hardening for 18 hours the borehole was re-drilled and the grouted section turned out to be completely sealed in terms of groundwater. Thereafter the core drilling continued to 40.05 m where steered drilling was initiated. A decrease in flow from over 200 L/min to less than 1 L/min was achieved.

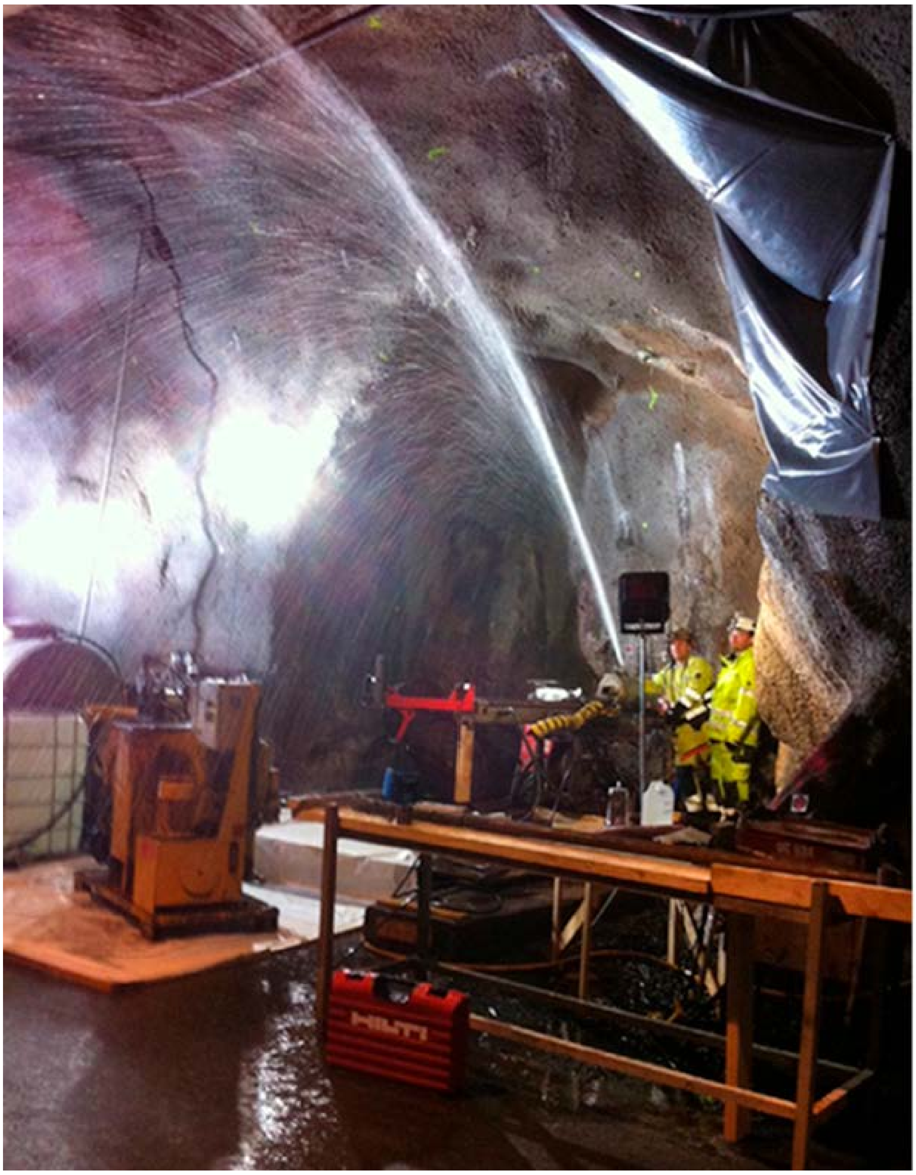


Figure 5-5. *Grouting of K03009F01. To be able to insert the grouting packer by hand into the borehole at the length of 4.5 m, the valve must be open. When the packer is expanded, the groundwater inflow of 250 L/min with c. 30 bars overpressure creates an impressive outflow through the valve.*

5.3 Measurements of water inflow

Flushing water used for drilling of K03009F01 was delivered from the Äspö fresh water supply. During the drilling period, sampling and analysis of flushing water for analysis of the contents of the added fluorescent tracer (uranine) was carried out systematically for at least every second water tank filled, see Figure 5-6. As borehole K03009F01 was drilled below the groundwater table, all added flushing water, as well as the accumulated inflow of groundwater to the borehole were recovered as a return water outflow at TOC (top of casing). According to notations in the drillers log and a rough calculation of the accumulated return water volume from opening time of the borehole gives a water balance of 1.19 calculated for the interval 15.5–100.92 m drilling length. The relatively low quotient is mostly due to extraordinary long drilling periods caused by the steered drilling when the amount of flushing water used (30 L/min) exceeded the water-yielding capacity of the borehole (11 L/min), see Figure 5-7.

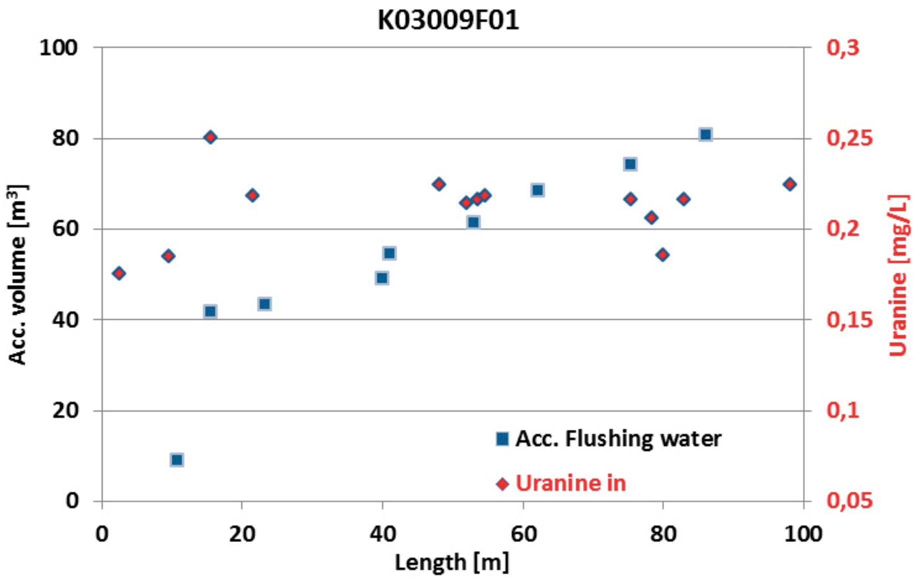


Figure 5-6. Uranine contents in the flushing water consumed (red squares) and accumulated flushing water volume (blue squares) versus drilling length during drilling of K03009F01.

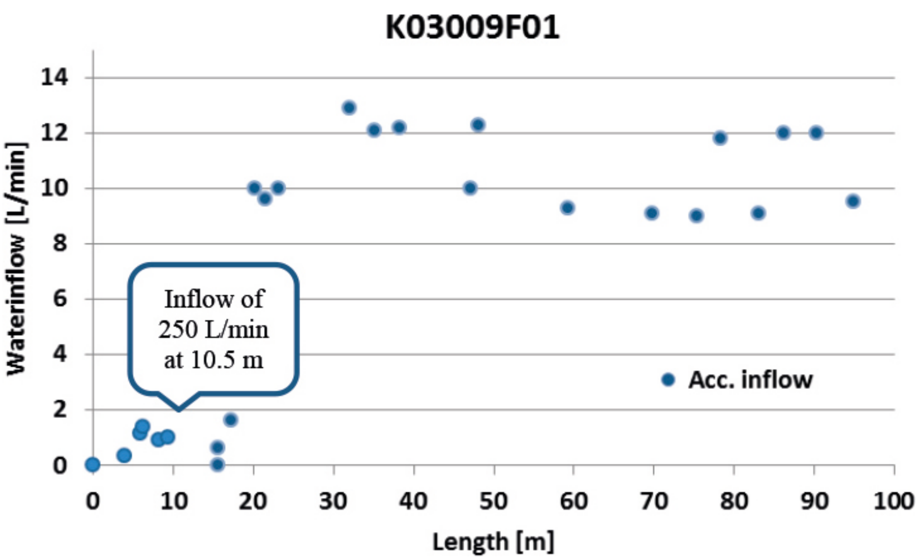


Figure 5-7. Accumulated inflow to the borehole measured after finished drilling but with the drill string still left in the borehole. The section with a water inflow as large as c. 250 L/min at 10.5 m length was grouted, which resulted in that the section was completely sealed.

5.4 Steering tools

The DeviDrill™ WL design is a directional wireline core barrel with an adjustable eccentric housing that allows for various dogleg (DLS)[1] settings[2]. The eccentric housing is kept at a fixed orientation by expanding pads pressed out to the borehole wall operated by circulating fluid pressure, see figure 5-8. With the DeviDrill™ system the borehole is steered to the selected target. By surveying with DeviTool™ (Pee-Wee) the borehole trajectory is controlled. The DeviDrill system for steered drilling is applicable only to boreholes with a diameter of 76 mm (N-size).

By using wire-line technique the DeviDrill is quickly activated to correct the steering direction, see figure 5-9. The Pee-Wee tool is mounted within an inner tube placed inside the DeviDrill at the borehole bottom. A protractor (360°) is attached to the drill pipe, and after winching up the inner tube with the Pee-Wee instrument, a toolface[3] reading is used for calculating how much the drill string needs to be rotated (with a pipe wrench) to obtain the correct steering direction.

Figure 5-8. *DeviDrill core barrel. Left: When water pressure increases (about 20 bars), the sliding packer expands and locks the barrel in its position. Right: The end of the DeviDrill. The drill bit gives a 31.5 mm core in sections where steering is applied.*

Figure 5-9. *Orientation of the DeviDrill tool. The Pee-Wee instrument is mounted inside the DeviDrill when brought into to the bottom of the borehole. A reading is taken and the instrument is winched up and based on the reading may the drill string be rotated to the correct position. Then the inner tube with the Pee-Wee instrument is pumped back into the DeviDrill to check the setting before the steered drilling starts.*

[1] Dogleg: The measure of the curvature of the borehole trajectory (given as angular degrees/30 m. The maximum curvature stipulated for K03009F01 was 0.1°/m which can be expressed as 3/30 m, i.e. Dogleg = 3.

[2] Setting of the DeviDrill regulates the strength of the imposed steering on a scale from 0 to 8 (where 0 is "no steering" and 8 implies a strong imposed curvature (dog leg). The scale is not linear and the setting is therefore not directly correlated to the dogleg curve. The setting and the effect of the steering is dependent on a number of variables. In K03009F01 "High" implies a setting = 2.4.

[3] The parameter TF (toolface) provides (over 360 degrees) the orientation towards which the DeviDrill steers. "Zero" is oriented up along the drill stem; TF 270 implies active steering "to the left" etc.

Finally, to safeguard that the accurate orientation is achieved, the Pee-Wee tool is pumped back into the drill string to the DeviDrill, a reading is taken, and the instrument is winched back out of the drill string for data check. A tolerance of ±3° is regarded as acceptable by Devico.

5.5 Steering tests in K03009F01

When the borehole reached 40 m length, the steering test began. Initially, in order to obtain the borehole start orientation, the magnetometer Pee-Wee tool was used for measurements, into and out of the borehole using a 1 m point distance to 39 m length. With this instrument the inclination was measured with a high accuracy. Small deviations and effects of careful steered drilling are easier to detect if the deviation measurements are carried out in conjunction with, or directly after completed steered drilling. Measurements with the Pee-Wee tool are carried out in open borehole, indicating that the rods and the core barrel are frequently transported into and out of the borehole. This entails that subsequent measurements are levelled out, because the borehole is equalized and made smoother by reamers.

Instruments based on magnetometer technology like Pee-Wee measure azimuth in relation to magnetic north. Changes in the magnetic field intensity and magnetic interference may introduce false deviation values for azimuth. Some of the rock types prevailing in the Äspö HRL contain magnetite, which periodically affects the ability of the instrument to accurately measure magnetic north. This is a factor that may deteriorate the quality of the data surveyed.

Already the initial measurement showed that the start inclination value differs from the one determined by geodetic technique by approximately 0.23°. Possible causes to this discrepancy are:

1. If the drill rig is not properly lined up, the gap between the borehole equipment diameter (75.8 mm) and the inner casing diameter (80 mm) could depart c. 0.1°.
2. If the casing is not perfectly centralized, the gravity would strive the inner end of the casing upwards, due to much heavier weight at TOC (top of casing), where the flange and crossbeam are mounted.
3. Uncertain values if the deviation measuring tool is not resting closely towards the lower side of the borehole at the first measuring point.

In Table 5-2 various data for the start orientation of borehole K03009F01 are shown. The discrepancy in inclination between the setting out values and the final orientation of the casing is probably caused when mounting the casing. For precise drilling and measurements, a new casing with tighter tolerances should therefore be developed, combined with better possibilities to centralize the casing in the pre-drilled borehole.

Nine steered "drilling sessions" were carried out in borehole K03009F01, see Table 5-3. The results of the final deviation measurement (inclination and azimuth) are presented in Figure 5-10, together with information about the nine corrections made. The main purpose of the tests was to gain experience of careful drilling and to test different low settings to see which one gives rise to measurable changes with the Pee-Wee instrument. Because the inclination at 40 m is about −0.5°, to be compared with the ideal inclination of −1.0°, it was decided to conduct a careful steered drilling straight down (correction no. 1), see Table 5-3 and Figure 5-10. This was done in order to counteract the natural tendency of upward deviation, and in order to prevent that the borehole should cross the horizontal line. A low setting (DLS 0.9), a toolface of 180° and a steered drilling length of 1 m resulted in a change of inclination of approximately −0.15° over a distance of 5 m. The result was successful, well within the Detum project requirements and had the correct direction. The result of the controlling deviation measurements is visible on the surveyed data, see Figure 5-10.

Table 5-2. Presentation of different types of start orientation data for K03009F01 (Sicada).

ID	Azimuth	Inclination	Coord.system	Comments
K03009F01	330.82	−1	Äspö 96	Setting out
K03009F01	330.81	−0.98	Äspö 96	Measured on the drilling rig
K03009F01	331.00	−0.37	Äspö 96	Final measurement in casing ($Ø_i$ 80 mm)

Table 5-3. Nine steered drillings were carried out and the results are commented on in the right column.

Steering nr	Section (m)	Goal	Toolface	Setting	Comments on the results
1	40.02–41.02	Inclination −0.46° at 39 m. Borehole should not exceed the horizontal plane and therefore the first steered drilling is directed downwards.	180°	Low	Correction of the inclination with 0.15° over 5 m length.
2	47.08–48.16	First steering shows a small but clear direction downwards but the natural tendency goes upwards. Continue with further steering downwards to avoid that the borehole does not exceed the horizontal plane at the drilling end.	0	Low	Steering direction turned 180° due to human failure.
3	48.16–49.14	As steering no. 2 failed, another attempt directed downwards was carried out. Keeps the same setting as in no 1 and 2.	180°	Low	Corrections according to the KBS-3H requirements.
4	53.11–54.53	Although previous steered drillings were directed downwards, the natural tendency will still continue upwards. Resolving to make a longer steering downwards to gain experience of how much it violates the borehole and then immediately make control no. 5 to the right.	180°	Low	Corrections with 0.34° over 6 m.
5	54.53–56.12	The azimuth is affected of magnetic disturbances and is difficult to evaluate. After steering 4 downwards it was decided to continue directly with steering no. 5 directed to the right to get the first opportunity to evaluate a steering sideways.	90°	Low	Corrections in azimuth to the right. Magnetic disturbances!
6	62.24–63.71	Steering no. 6 is a continuation of steering no. 5, i.e. to the right, although the results of the evaluation of steering no. 5 were uncertain. The decision is justified because of need of getting more experience on how much we can bend the borehole in that scenario. As the drilling contractor had brought the Maxibor II, it was decided to supplement the measurement with this instrument after next steering.	90°	Low	Final measurement shows corrections to the right. Magnetic disturbances!
7	69.86–72.55	After the two steerings to the right, the outcome of the Maxibor measurement is uncertain, it was decide to increase the curvature of the core pipe, and choose a longer drill bit. To ensure that the hole does not strives upwards, the Devicore was directed slightly downwards as well.	100°	Low	Correction to the right but strong magnetic disturbances. Also a significant impact on the inclination that changed from −0.8° to −1°.
8	75.44–78.37	After three steerings to the right, not entirely sure of the outcome because of magnetic disturbances , it was decide to increase the curvature of the Devidrill core barrel even more, and drill a full uptake (3 m). Continue drilling with a soft bit.	90°	High	Continued correction to the right but still magnetic disturbances. Perhaps 3 m steered drilling is too much!
9	86.13–87.70	Last steering, no. 9 in the borehole. From the eighth steered drillings the effect of steering vertically is known and the project has gained experience to steer to the right, although there are uncertainties about the outcome of these steerings due to magnetic disturbances. Therefore, steering no. 9 is aimed to the left in a moderate bend to evaluate the effects of steering to the left. The rock type is basically Äspö diorite that is relatively easily to drill with a soft Devico drill bit.	270°	Medium	Good quality of the steering.

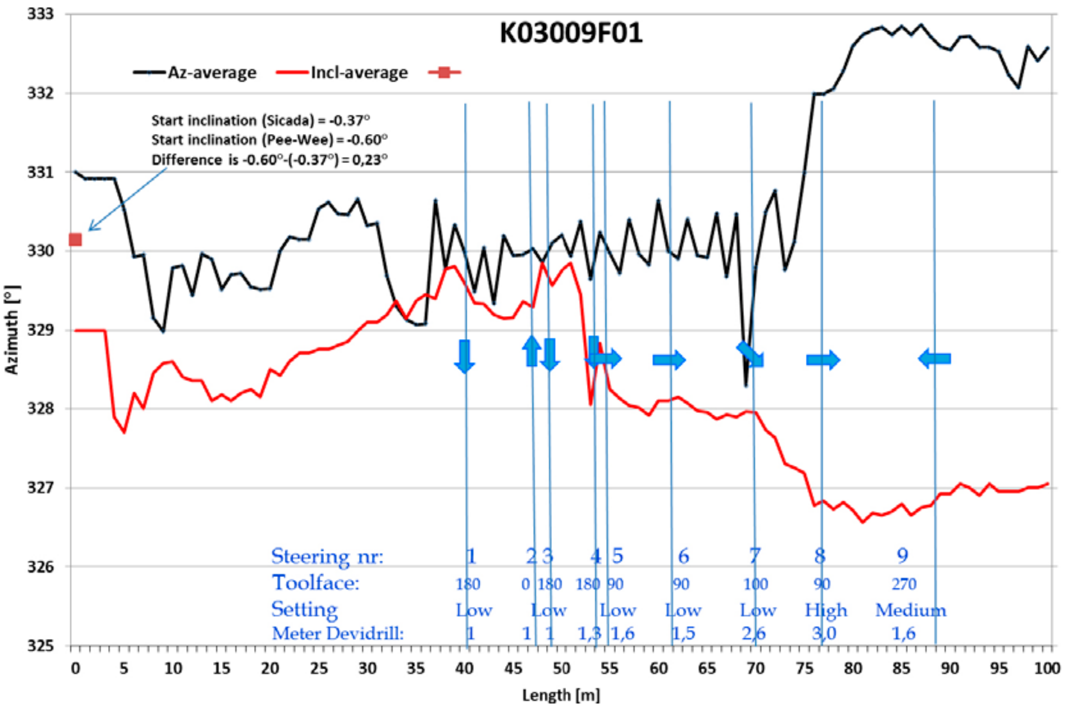


Figure 5-10. The result shown in the figure is an average calculation of all deviation measurements in borehole K03009F01 presented with azimuth, (black) and inclination (red). Nine steered drillings were carried out, where the fat blue arrows show the position as well as the direction of the DeviDrill barrel.

During correction no. 2 an operator error occurred when the drill string was inadvertently rotated reversely, whereby a screw was threaded off within the DeviDrill, with the consequence that the steering went 1 m in a wrong direction (180°) with an angle change of approximately 0.12° over 2 m. The error was quickly discovered and was compensated for with correction no 3. Here a drilling length of 1 m, a toolface of 180° (straight down) and the setting 0.9 was applied. The effect of the Devi drilling manifests itself as counteracting the rising trend after correction no. 2 in Figure 5-10. The result was successful within the project requirements and the correct direction was achieved.

For correction no. 4 it was decided to continue steering the borehole to reach an inclination of −1.0° and increase efficacy by extended the drilling length to 1.3 m but with the same setting (0.9) and toolface (180°, i.e. straight down) as previously. The effect was well documented as a change of 0.34° spread over 1.6 m (see Figure 5-10). The result of this steering was thus outside the DETUM requirement of 0.1°/m and such strong steering actions should be avoided.

The vertical direction of the so far conducted steered drilling was deemed as sufficiently good, but the borehole length imposes a restriction regarding how many steered drillings that can be carried out. Therefore, correction no. 5 is a direct continuation from no. 4 in direction to the right (tool face 90°), setting 0.9 and 1.9 m drilling length. The interpretation of surveyed data had to consider variations of the magnetic field intensity for calculating the effect of the steering. After several measurements including the final one, a slight effect to the right can be seen, see Figure 5-12. Steering was successful, however somewhat weak and within the project limits.

Correction no. 6 entailed continued steering to the right with a drilling length of 1.5 m, the setting 0.9 and the toolface 90°. Due to increased magnetic disturbances it is associated with some uncertainty to evaluate the effect of the steering, but both the final measurement and Maxibor II show that the borehole is bent to the right. The steering is regarded as successful and within the project limits.

After two careful steered drillings without results immediately indicating any significant effect, it was decided to steer harder to the right (correction no. 7). The setting of the DeviDrill was adjusted up to 1.2 and with a toolface of 100°. The drilling length was increased to 2.6 m. Magnetic disturbances from the bedrock made it difficult to identify any specific effect. Again, the final measurement still showed a successful steering and also a small but demonstrable effect on the inclination of the toolface 100° is observed.

Since the extent of the steering in the lateral direction was still uncertain, it was decided for correction no. 8 to further increase the DeviDrill setting to 2.4, to extend the drilling length to 3 m, but put the toolface to 90 (right), as the inclination has changed from −0.8° to −1°. As a result of the strong steering, a right curve most probably exceeded the Detum project constraints of 0.1°/m. The effect of the steering was larger than before, probably due to changes in geologic conditions, and the results are biased due to variations in the magnetic field. The Pee-Wee magnetic measurements indicate a bend of 0.2°/m, but data security is low at the borehole length between 70–80 m.

After borehole length 75 m the bedrock is more homogenous and with less magnetic disturbances. Since testing of corrections to the left were missing, a careful steered drilling with toolface 270°, setting 1.8 and drilling length 1.6 m was conducted (correction No. 9). The steering was successful and fell within the project limitations with an output of about 0.05°/m. This control was also immediately documented on the first survey since there are less magnetic disturbances. In Figure 5-10 this measurement at 85 m borehole length shows a reduced inclination whereas the azimuth graph is pointing weakly to the left.

Magnetic disturbances from the bedrock in combination with the strict tolerances of the KBS-3H project do not provide adequate data quality and accuracy in azimuth with a magnetic survey tool. Disturbances and associated deviations in azimuth at the first 10 metres of the borehole were probably caused by the casing, the drilling rig and other magnetically active materials at the drill site.

5.6 Assessing the steering tools capability

5.6.1 General

Initially, a deviation measurement with the Pee-Wee tool to 39 m length was performed and a file consisting of inclination and azimuth data was created. All subsequent measurements are imported into this file that continuously upgrades the average calculation. All decisions of the steering progress are based on the result from this file. In Figure 5-11 the number of measurements performed at each point of the borehole is presented. Maximum four measurements of the same length coordinate have been carried out. The shorter deviation measurements performed, that mainly covered the steered drilled sections, was added to the first single measurement performed to 39 m.

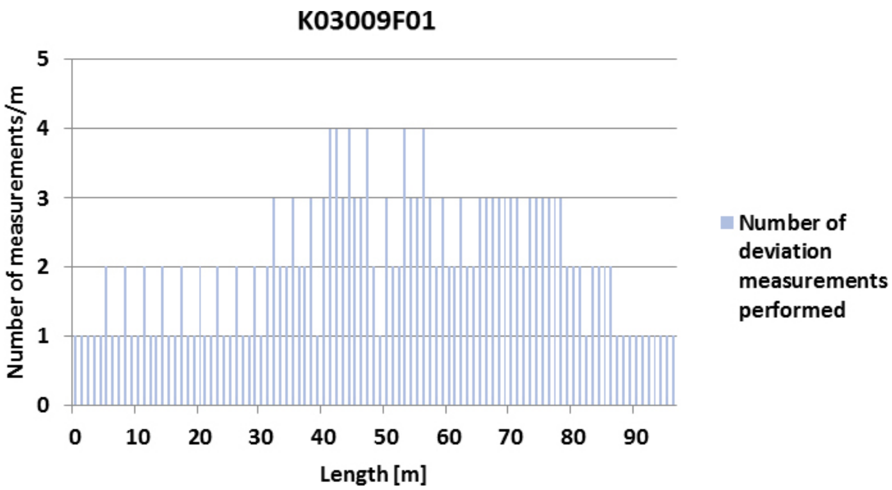


Figure 5-11. The figure shows the number of deviation measurements performed at each length coordinate in borehole K03009F01. Every new measurement is added for average calculation of the working file.

In Figures 5-12 and 5-13, the average values calculated from the "working file" for azimuth and inclination are presented together with the final measurement (Sicada) and one Maxibor II measurement to 82 m borehole length. In this case, Sicada data are based on two measurements with the magnetic instrument Reflex Multishot, with 3 m point distance. Unfortunately, the two Maxibor II measurements performed after drilling failed, and data could not be used. The Maxibor II measurement presented was performed just after the last steering in order to check if the azimuth data produced from the Pee-Wee tool were acceptable.

For azimuth the final measurement results are levelled out, to some extent depending on that a point distance of 3 m was used, but also because the borehole is equalized and made smoother by reamers on the core barrel. Also the Maxibor II results are levelled out, because the measurements with the 6 m long instrument are performed inside the drill string.

All three instruments used measure the inclination with magnetic accelerators. An uncertainty for inclination measurements of c. 0.1° is often given by the manufactures.

The "absolute deviation" is defined as the shortest distance between the real borehole bottom and an imaginary borehole bottom calculated following a straight line with the same inclination and bearing as that of the borehole collaring to full drilling length. For K03009F01 the "absolute deviation" is 0.82 m which is somewhat larger than the requirement of 0.7 m given in Section 2-1. The project will accept this given the importance of testing the steered drilling in different directions.

5.6.2 Conclusions

Devico's equipment with the Pee-Wee tool provides reliable results for inclination measurements, see Figure 5-13 but magnetic bedrock in combination with the strict tolerances of the KBS-3H project did not provide adequate accuracy in azimuth determinations with this magnetic survey tool, see Figure 5-12.

The tests in K03009F01 provided detailed knowledge and experience of how to carry out careful steered drilling in the bedrock at the level −400 m in Äspö HRL. Based on the survey results and lessons learned, it was concluded that careful steered drilling aiming at the KBS-3H requirements is feasible with Devico's directional drilling technology, however, improved measurement data is needed for the azimuth direction.

Therefore, measurements must be supplemented by an instrument, like the gyro, non-sensitive to magnetically disturbed environments to safeguard outcomes of steering horizontally. Non-magnetic tools that measure inside of the drill string (Deviflex or Maxibor II) may be helpful, but can only document changes in azimuth some metres after steering (earliest 6 m above the bottom of the borehole by normal drilling equipment). The fact that these instruments are 4 m and 6 m in length, respectively, also reduces their usefulness for point distance measurements.

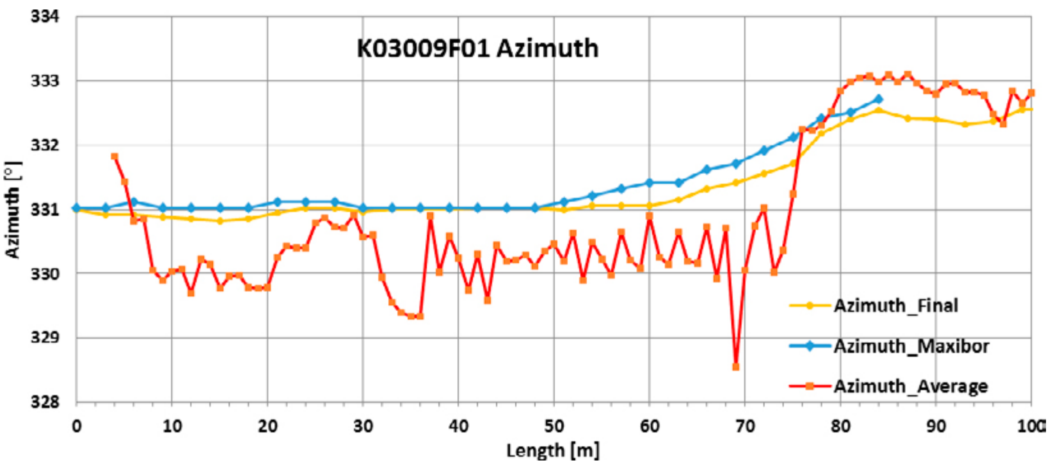


Figure 5-12. *The results from different azimuth measurements in K03009F01. The average calculated measurements are given in red, the Maxibor II measurements in blue, and the final measurements with Reflex Multishot from Sicada in yellow.*

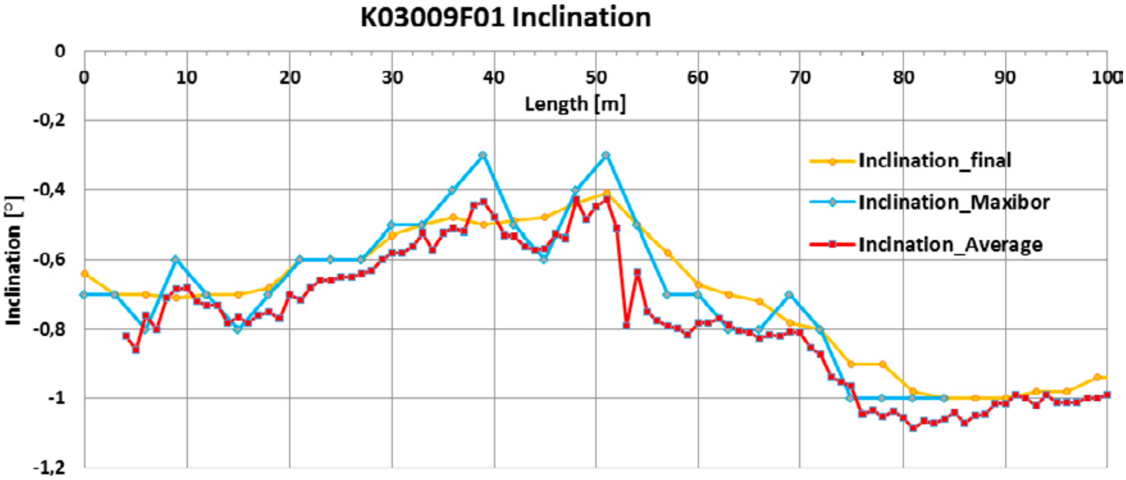


Figure 5-13. *The results from different inclination measurements in K03009F01are presented. The average calculated measurement (red), the Maxibor II measurement (blue) and the final measurement with Reflex Multishot from Sicada (yellow).*

Within this project, where the quality requirements and strict tolerances are of highest priority, the user must have full knowledge of the deviation tools and their behaviour during different measuring conditions. It is necessary to measure frequently to the bottom of the borehole in order to detect natural deviations at an early stage, and later on to control the effects of the steered drilling with as low setting so that the curve does not exceed 0.1° per metre.

5.7 Summary of important pre-conditioning measures

To meet the KBS-3H requirements, it is important that also other preparations are made in order to integrate the different working sub-operations in an optimum manner. For example, it is essential that the stipulated starting direction of the borehole is spot-on and that the casing is correctly dimensioned and has an inner diameter suitable for the drill pipes used. With a more powerful drilling rig the possibility to influence the drilling execution increases. To reduce the risk of an operator error when the DeviDrill is oriented, a reducer valve should be installed that prevents the flush water pressure to fall below 30 bars. At that pressure the DeviDrill is kept in correct orientation during the steered drilling period.

The DeviDrill barrel must be well serviced and carefully prepared so that repeatedly careful steered drilling operations can be carried out. Both the DeviDrill and standard wire-line drilling must be provided with drill bits of different hardness to meet various rock conditions found in the Äspö HRL.

It is essential that the drilling rig has a stable frame that is carefully anchored to the ground. If the borehole collaring is located higher up from the tunnel floor, a reinforced scaffold prevents the platform from swaying, which would obstruct accurate drilling and measuring activities.

6 Steering strategy for K08028F01

The chapter is divided into two sections, 6.1, “Premises” and 6.2, “Strategy”, which gives a more detailed description of how to address the KBS-3H requirements and of the stepwise decision-making process involved for the specific implementation of drilling and measurements of pilot borehole K08028F01 in order to meet the requirements.

6.1 Premises

6.1.1 Answering up to KBS-3H requirements

A recap of the KBS-3H requirements for borehole K08028F01 as presented in Chapter 2 is provided below:

Borehole inclination: 2° ± 1°

Maximum continuous vertical undulation: ± 10 mm over 6 m

Maximum continuous horizontal undulation: ± 50 mm over 6 m

Maximum deviation, sideways for a 300 m borehole ± 2 m

Maximum deviation, sideways for a 100 m drill hole: ± 0.67 m.

Requirements over the entire borehole

The allowed inclination, 2° ± 1°, together with the horizontal requirement, maximum sideways displacement of ± 0.67 m (at 100 m), results in a “target rectangle” centered on the theoretical end point (at 100 m) within which the borehole is permitted to end up, as shown in Figure 6-1 and 6-2 (minor simplification when changing to 2D). The reason why the hole is not centered vertically is that the actual start inclination was 2.18° (as built) instead of stipulated 2°. Note that the requirement of a maximum vertical undulation of ± 10 mm over 6 m has not yet been considered in this reasoning.

Length [m]	a [m]*	b [m]**	c [m]***
0	0.000	0.000	0.000
2	0.000	0.000	0.000
8	0.107	0.165	0.114
14	0.188	0.288	0.200
20	0.268	0.412	0.286
26	0.348	0.535	0.372
32	0.429	0.659	0.458
38	0.509	0.782	0.543
44	0.590	0.906	0.629
50	0.670	1.029	0.715
56	0.750	1.153	0.801
62	0.831	1.276	0.886
68	0.911	1.400	0.972
74	0.992	1.523	1.058
80	1.072	1.647	1.144
86	1.152	1.770	1.230
92	1.233	1.894	1.315
98	1.313	2.017	1.401
100	1.340	2.059	1.430

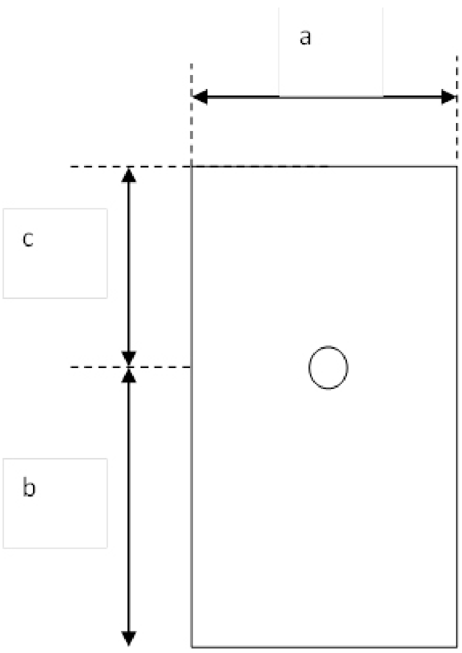


Figure 6-1. *Maximum tolerances at different lengths according to the requirement of inclination, 2 ± 1°, together with the requirement sideways, ± 0.67 m (at 100 m).*

Calculations of values a, b and c in the table.

* $a_L = \text{L} = \frac{L}{300} \times 4$ *(Maximum deviation, horizontally for a 300 m borehole ± 2 m ($a_{300} = \pm 2$ m)*

** $b_L = \sin 1.18 \times L$ *(2.18° − 1° = 1.18° Maximum deviation vertical ($b_{300} + c_{300}$)) = ± 5.2 m)*

*** $c_L = 0.82 \times L$ *(3° − 2.18° = 0.82)*

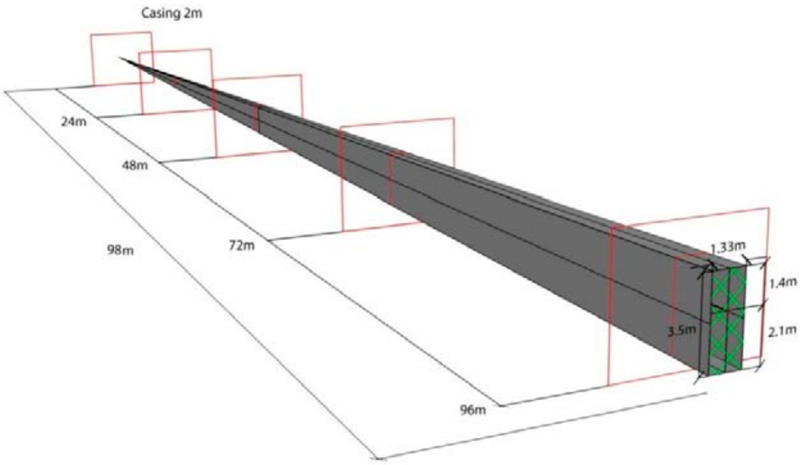


Figure 6-2. The schematic figure shows the maximum acceptable tolerances of the borehole geometry versus borehole length. The start inclination of 2.18° instead of 2.00° gives a discrepancy upwards.

Requirements linked to the insertion of the 6 m Supercontainer

At first sight and as interpreted at the time of the drilling operations presented in this report, the allowed maximum vertical undulation of ± 10 mm over 6 m (previously interpreted as 0.1°/6 m) is considered extremely difficult to achieve. The deviation of the borehole is measured with 1 m point spacing, and for most deviation instruments the inclination can be established with high resolution and accuracy. Devico AS reports that their deviation tools can be calibrated to 0.01° of accuracy in inclination. Although the instruments for deviation measurements have slightly lower resolution for azimuth than for inclination, it is still rather the length-wise position of the instrument in the borehole that may introduce the largest source of error.

In order to clarify the requirement about the maximum vertical and horizontal undulation, a fictive borehole where inclination values increase with 0.1°/m and azimuth values increase with 0.5°/m over a 6 m long reference length is applied. The coordinates for the fictive borehole is compared with coordinates from the straight borehole resulting in that the distances in mm from the target line in vertical and horizontal direction is calculated and presented in Figure 6-3 and 6-4.

In Figure 6-3 it is demonstrated that this vertical change versus borehole length corresponds to a distance to the target line of 37 mm upwards for the entire drilled section of 6 m length. However, if a 6 m long reference line, corresponding to the Supercontainer, is inserted in the borehole, we see that the maximum distance is only 8 mm.

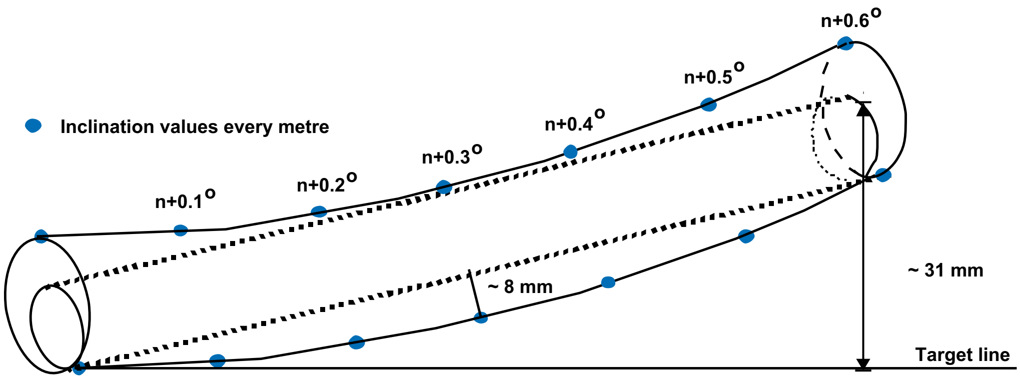


Figure 6-3. Figure showing when inclination continuously increases with 0.1°/m over a 6 m length gives an upward distance of 31 mm off from the target line, but only 8 mm distance (i.e. well within the 10 mm requirement) to the 6 m reference line (corresponding to the Supercontainer). This clarification implies a considerably easier target than the previous incorrect interpretation that 10 mm/6 m equal 0.1° for 6 m.

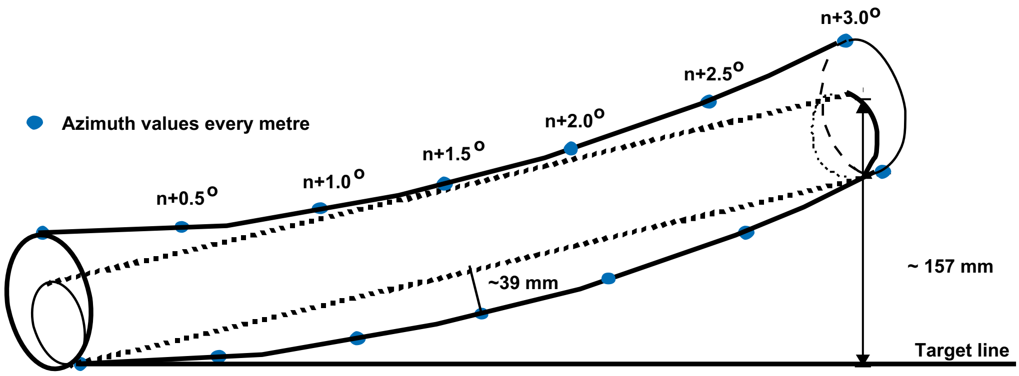


Figure 6-4. Figure showing when azimuth continuously increases with 0.5°/m over a 6 m length gives an upward distance of 157 mm off from the target line but only 39 mm distance (i.e. well within the 50 mm requirement) to the 6 m reference line (corresponding to the Supercontainer). This clarification implies a considerably easier target than the previous incorrect interpretation that 50 mm/6 m equal 0.5° for 6 m.

The same reasoning applies to the lateral requirement (azimuth), and in Figure 6-4 it is demonstrated that this horizontal change versus borehole length corresponds of distance to the target line with 157 mm sideways for the entire drilled section of 6 m length. However if a 6 m long reference line, corresponding to the Supercontainer, is inserted in the borehole, we see that the maximum distance is 39 mm.

The conclusion is that over a shorter section, a rise in inclination and azimuth slightly above 0.1°/m and 0.5°/m respectively can be allowed and still the requirements could be fulfilled. However, at the beginning of the borehole it is the rectangular area, see Figure 6-1 that is the strictest requirement to be followed. Also a straight start direction facilitates the possibility to keep the borehole close to the target line.

Following this review of the requirements it is concluded that carrying out careful steered drilling has changed from earlier being almost impossible to be feasible.

6.2 Strategy

This section describes the strategy for performance of drilling borehole K08028F01. The experience of the tests in K03009F01 pointed out some important preparations and measures that must be taken in order to succeed with drilling a straight borehole within the stipulated requirements. Practical measures are described in detail in Chapter 7, but are also mentioned briefly below.

- A stable platform to prevent dislodging of the drill rig during drilling. This is essential because the borehole is applied 3.5 m above the tunnel floor.
- Careful alignment for drilling and installation of the casing.
- A powerful drilling rig so that drilling can be carefully controlled and not just run at full throttle.
- The directional core barrel must be in good condition, complete and available at the site at the start of the drilling operations. A variety of soft and hard drill bits, including the different dimensions of the reamer and stabilizer, must be in place.
- Experienced staff that understands the purpose of the borehole and is familiar with the drill and control equipment, including the use of deviation measurement instruments.
- Finally, and perhaps decisive in order to obtain a straight borehole, is that the staff must have a good feeling for how the rock, drilling and measuring equipment function together.
- A clear strategy facilitates all decision-making, which often must be undertaken quickly at the drill site.

6.2.1 Technical data K08028F01

Table 6-1 presents geometrical data for the starting point of borehole K08028F01. These values are used when calculating the straight borehole orientation, and the deviations are calculated as a distance given from that straight line.

Table 6-1. Technical data for K08028F01. Borehole orientation is measured on casing as built.

	ID	X	Y	Z	Azimuth	Inclination	Coord. and North ref.
Start	K08028F01	2386.035	7450.637	–396.584	320.37	2.18	Äspö 96

6.2.2 Guidelines

If deviation measurements aided by two instruments based on independent measurement principles indicate a significant trend towards a discrepancy in vertical magnitude of 0.1° (10 mm) respectively 0.5° (50 mm) in horizontal direction over 6 m, a steered drilling (session) should generally be implemented. But if the trends are not fully unanimous or if it seems to be a borderline case at hand, an additional 6 m section should be drilled before an assessment is done again. A decision to activate steered drilling is made mutually by the activity leader and steering contractor and is always based on the overall assessment of the data available. Ideally, this may be accomplished so that the borehole will basically follow along the theoretical trajectory during the remaining drilling. If not, the following criteria will be considered:

- The local inclination (I) should never fall below 1°, and a margin for this should always be maintained. Actions should be taken at $I \leq 1.3°$. Correspondingly, the local inclination should never exceed 3°, action must be taken at $I \geq 2.8°$.

At the beginning of the drilling operation, the theoretical "sub rectangles" as shown in Figure 6-2 are small, but grow successively as drilling progresses. This means that the tolerances, measured as actual distance, increase with increasing borehole length. The steered drilling strategy also includes the challenge to always target the borehole as centrally positioned as possible within each sub-rectangle (Figure 6-1), in case a deviation arises and begins to accelerate. A guideline is that action should be taken if the measurements fall outside 50 % of the current sub-rectangle, but with the reservation that the first sub-rectangles (about 0–30 m) are relatively small, and more data may be needed before action is taken. It is fundamental that the borehole trajectory is never permitted to end up outside the sub-rectangles presented in Figure 6-2.

6.2.3 Steered drilling

The steered drilling shall be carried out as carefully as possible, equivalent to full control of change of angular directions of about 0.1° with up-to-date drilling and measurement equipment. However, if the deviation in some sections does not manage to fulfil the requirement the subsequent stepwise reaming to 1.85 meters will probably have some levelled out effect of the final drift.

6.2.4 Deviation measurements

The deviation measurements using the selected instruments (Devico Pee-Wee and the Reflex Gyro) generate data on inclination and azimuth and the corresponding interpreted (x, y, z) coordinates. Initially, at the commencement of drilling, only one set of measurements exists (first measurement at 6 m), but during the course of the drilling process successively more data are generated (each new measurement gives data for the full borehole length). For the assessment made by the drilling contractor and by the activity leader, the accumulated data set will serve as the basis for decisions regarding the number of and type of performance of steered drillings.

6.2.5 Handling of indications of borehole deviation

If the borehole starts to deviate from its original direction, experience shows that this process normally accelerates during continued drilling. Linear extrapolation from the measurement point indicating the first deviation from the borehole end point will therefore generally not provide the correct position of the latter. Instead the deviation initially observed should serve as a memento to prepare for further deviation controls and, eventually, steered drilling.

7 Site preparations

Normally an underground drill-site at the Äspö HRL is prepared according to SKB routine procedures. However, due to the strict borehole deviation requirements in the KBS-3H project, additional efforts were made related to the platform design as well as for the pre-drilling activities. These actions are described in the following sections.

7.1 Platform

Since the collar for borehole K08028F01 is located some 3.5 m above the tunnel floor, a solid fundament was a crucial element for the construction of a stable drill-site. Firstly, gravel was hard-packed and flattened out on the tunnel floor. Steel plates (10 mm thick) placed on top of the gravel pack provided a solid ground for the transport tube cradle that was used as the basic construction element at the drill-site. A traditional building scaffold, fulfilling all working environmental requirements, was mounted around the rig. Finally, a 20 mm steel plate, serving as the floor upon which the drill rig was placed, was bolted to the fundament. The steel plate also allowed the drill rig to be properly fastened during the drilling activities. The spacious platform was supplied with two staircases that gave drillers and other technicians easy access to the drill rig, from either side of the platform, see Figure 7-1.

7.2 Pre-drilling for casing

Pre-drilling and installation of casing is another important activity aimed at achieving the decided borehole start coordinates and start direction. If this activity is performed successfully, the initial core drilling can start immediately, and it is expected that less steered drilling operations have to be carried out in order to fulfil the KBS-3H requirements, see Chapter 2. This could entail a significant positive effect both on the project budget and the time schedule.

The KBS-3H project prioritized development and use of techniques and equipment specially adapted to achieve a correct initial drillhole orientation. Different contractor proposals were requested and analysed after which a robust solution was chosen.

This solution included a steering tube bolted on a stainless steel plate, exactly designed to fit the Ø 116 mm core barrel used for the pre-drilling. The plate was bolted to the tunnel wall and accurately aligned geodetically. Pre-drilling was carried out using a minor drill rig usually employed for drilling holes in concrete constructions, se Figure 7-2.

Figure 7-1. *A solid fundament was placed on top of the aligned and hard-packed tunnel floor. A scaffold was built around the fundament, completed with safety equipment. Two separate staircases give access to the drilling rig from both sides of the scaffold.*

Figure 7-2. *A steel plate was bolted to the tunnel wall perpendicular to the borehole axis. A steering tube adapted to the pre-drilling core barrel used was bolted on the steel plate and surveyed. The tight steering (small annular space between the steering tube and the core barrel), forced the core barrel to drill in the correct direction. A small drill rig was used for pre-drilling of the 2.28 m long casing borehole.*

The single core barrel and bit generated a borehole with the diameter 116 mm and a core with a diameter of 101.5 mm that ends with an orthogonal core break (relative to the borehole axis) at 2.28 m, see Figure 7-3.

The resulting inclination of the casing hole was 1.94° from the horizontal. In hindsight one perceives that just centralizing the casing in the middle of the borehole would have provided the best accuracy. However, the casing was already manufactured and the original strategy which included a fine-tuning step was carried out.

7.3 Casing installation

A specially designed casing was installed in the 2.28 m long pre-drilled borehole. The casing, with an inner diameter of 76.2 mm (a variety of the 80.0 mm previously used in the Detum-1 hole (K03009F01)) was length adapted to fit in the borehole. When installing the casing there has to be sufficient space between the end of the casing and the borehole bottom such that the cement paste can penetrate and fill the annular gap between the casing and the borehole wall from bottom to top. On the other hand, the axial space between the centralizer with the bottom plug and the borehole bottom should not be too long, as that could deteriorate later measurements in the borehole because borehole tools may get stuck in this section if the grouting is diluted. A gap of approximately 0.10 m is suitable to aim at, see Figure 7-4. Secondly, to obtain an appropriate assemblage at the borehole collar, a long casing sticking out from the rock wall will increase instability, but on the other hand there must be sufficient space for the tools used to fasten the beam that holds it in place.

Figure 7-3. *Pre-drilling core with a 101.5 mm diameter ending at 2.28 m with a core break at 90° angle relative to the core axis.*

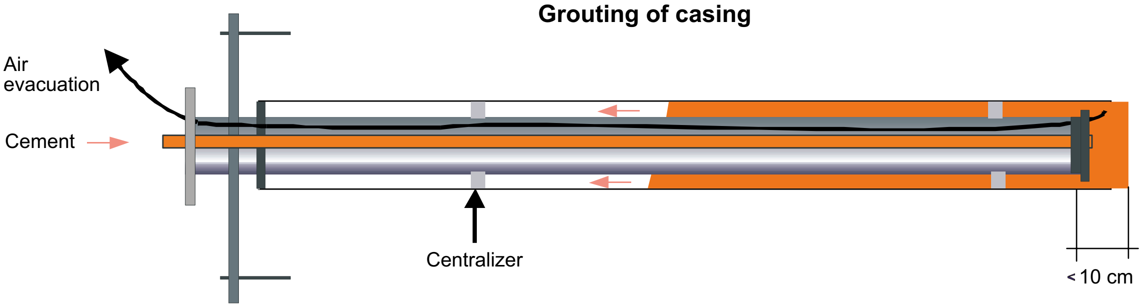


Figure 7-4. The casing is grouted from inside and out. With c. 10 cm axial gap the cement paste can pass through and fill the annular gap between the casing and the borehole wall from bottom to the top.

Preparations for grouting comprised attaching a 3 m long aluminium tube to the bottom plug together with an air evacuation pipe. The bolts previously used for the plate on the rock wall at the borehole collar were applied for positioning a frame with adjustable bolts, se Figure 7-5. For orienting the casing, a 2 m long tube was bolted to the flange. That tube was used for surveying the casing direction, see Figure 7-6. This step did, however, not improve the accuracy. Instead, it rather turned out that it got slightly worse, the empty borehole inclined 1.94° while mounting of casing changed it to 2.18°. In the future, the casing can most likely quite simply be centered in the casing hole, i.e. the drilling with the rock plate showed sufficient fulfillment of alignment. Grouting was done with standard cement and using a standard pump normally used for filling rock bolt holes.

Figure 7-7 shows a photograph of the complete drill site for borehole K08028F01 at test site TAS08 in operation.

***Figure 7-5.** The casing was grouted from inside and out. Left: A plastic plug with lead-throughs for pumping in grout and evacuating the air was glued inside the casing. Standard cement was pumped through the aluminum tube and the plug and then filled the annular gap between the casing and the borehole wall. Right: Air evacuation pipe 8 mm and a frame with adjustable bolts.*

Figure 7-6. *The casing was positioned and aligned prior to grouting. The bolts previously used for the plate on the rock were now used for positioning.*

Figure 7-7. *The complete drill site for borehole K08028F01 in TAS08 in operation. The drillers are working on the left side while other technician's workspace is to the right. Flush watering (tracer marked) is supplied from the two tanks in front of the platform, and a bench for retrieval of drill core from the core barrel is seen to the left. Return water from the borehole is lead to the Äspö HRL drainage system after sedimentation.*

7.4 Drilling equipment

The use of a powerful drilling rig enhances the possibility to influence the drilling execution. Therefore, a core drilling machine from Sandvik, type DE140, was employed for drilling the cored borehole K08028F01. The drilling machine was powered with an electrically-driven hydraulic system (see Figure 7-8).

The AC Corac N3/50 core barrel with split inner tube of stainless steel constitutes the wireline system best apt to fit SKB's need for a "triple tube wireline system" with a core dimension slightly exceeding 50 mm. With a normal wireline core (double) barrel, it is common to experience a steady deviation caused by drilling parameters, equipment wear and/or structures in the geological formation. To reduce the effect of these parameters, an especially stable core barrel using shorter outer tube sections, multiple reamers and a top stabilizer was built.

Core drilling with a wireline system involves a wire winch for recovery of the core filled inner-tube through the drill pipes. During the drilling of borehole K08028F01, a 3 m triple tube core barrel was used. The nominal core diameter for the AC Corac N3/50 is 50.8 mm. Minor deviations from this diameter may however occur.

To reduce the risk of an operator error during the steered drilling, a reducer valve was installed on the control panel that prevents the flushing water pressure to be less than 30 bars, see figure 7-9. At the former pressure the DeviDrill is locked in correct orientation during the steered drilling period.

Figure 7-8. *The drilling rig Sandvik DE140 was used for drilling of K08028F01.*

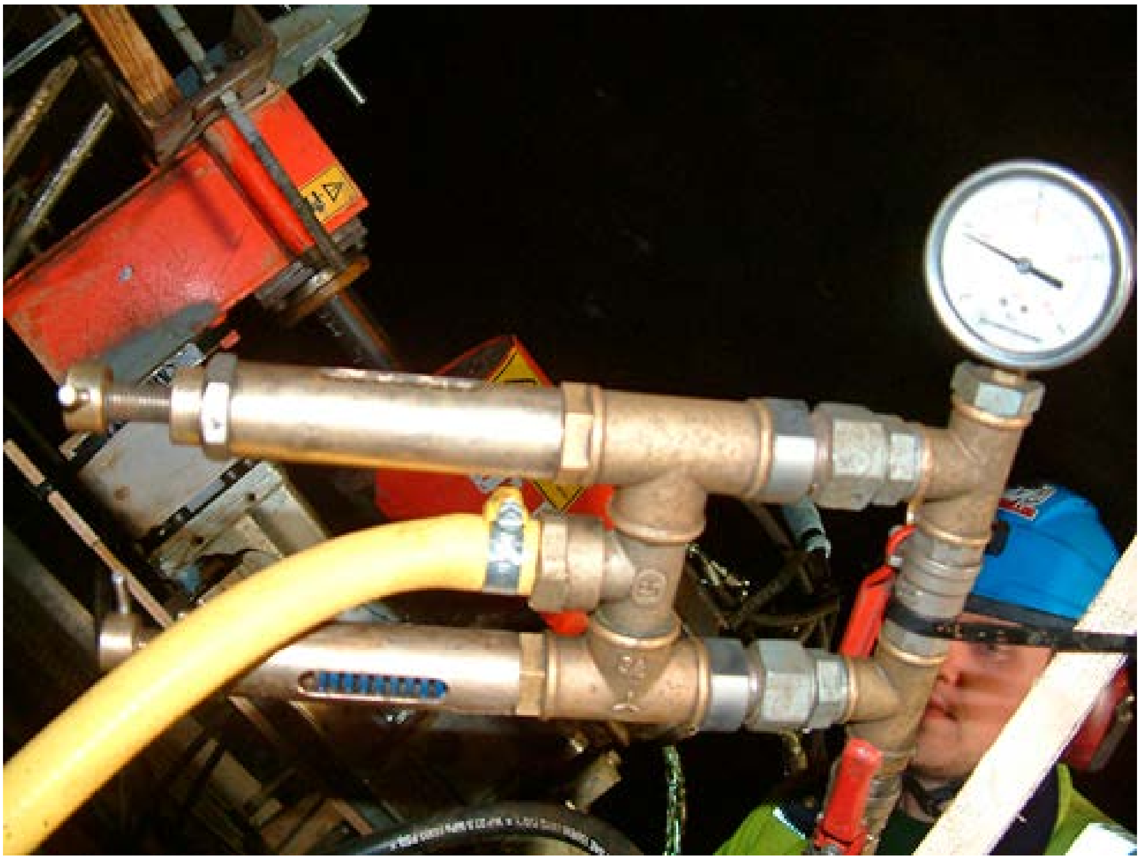


Figure 7-9. *An adjustable reducing valve is mounted on the hose from the flush water pump preventing the water pressure to drop below 30 bars while the DeviDrill is in use.*

8 Steered core drilling of K08028F01

After necessary preparations, technological development, testing and evaluation, a decision was made to carry out steered drilling of K08028F01 in accordance with the strategy outlined in Chapter 6. Necessary guiding documents were developed and the purchasing procedure resulted in engaging the Swedish contractor Drillcon Core AB to drill borehole K08028F01 with Devico Sweden AB (branch office of Devico AS) providing the directional equipment and expertise. The drilling operations were carried out between June 1 and June 12, employing continuous 12 hours dayshifts, see Figure 8-1.

8.1 Drilling operations

8.1.1 Drilling

The different drilling techniques employed when drilling borehole K08028F01provide different borehole- and core dimensions. Casing drilling, described in Section 7.2, gives a larger core diameter, 101.5 mm in a Ø 116 mm borehole between 0–2.28 m, while the nominal core diameter for the Ø 75.8 mm part of the borehole is 50.8 mm, see Section 7.4.

However, the equipment used during steered drilling in K08028F01, in this case in two sections between 64.86–66.04 m and 72.78–74.05 m, respectively, provides a smaller core diameter, 31.5 mm, over a total core length of 2.41 m. Even if the Devi drillbit gives a borehole diameter of Ø 75.3 mm, that section will be restored to 75.8 mm by reamers mounted on the core barrel when the standard WL-drilling continues. Dimensions from borehole and the core from borehole K08028F01 are summarized in Table 8-1 and visualized in Figure 8-2.

Table 8-1. Borehole sections with different dimensions in K08028F01.

ID	Length [m] Sec up	Sec low	Core diameter [mm]	Hole diameter [mm]	Comments
K08028F01	0.00	2.28	101.5	116	Casing
K08028F01	2.28	64.86	50.8	75.8	
K08028F01	64.86	66.04	31.5	75.3 but reamed to 75.8	Steered drilling 1
K08028F01	66.04	72.78	50.8	75.8	
K08028F01	72.78	74.05	31.5	75.3 but reamed to 75.8	Steered drilling 2
K08028F01	74.05	94.39	50.8	75.8	

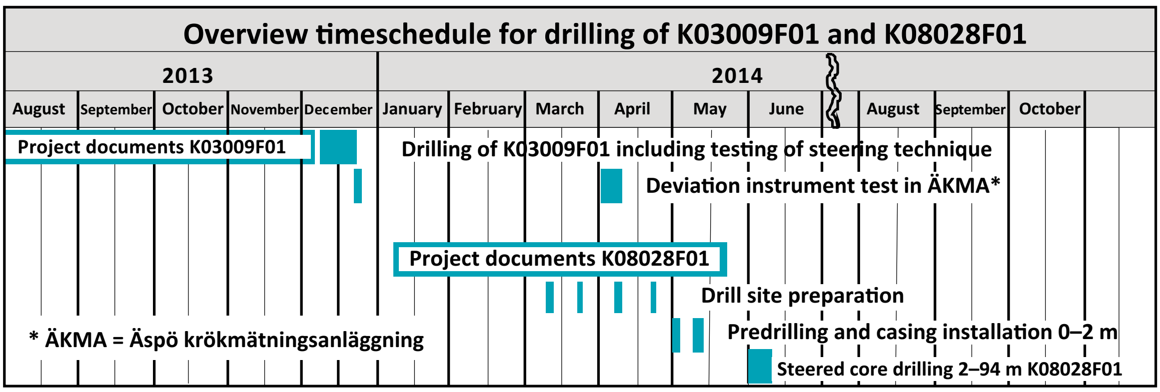


Figure 8-1. Overview time schedule of the preparations and drilling of borehole K08028F01.

Figure 8-2. Display of drill bits and example core. Conventional triple-tube drilling 76 mm (N-size) gives a core diameter of 50.8 mm (right). When using the directional core barrel a core with 31.5 mm diameter is produced (left).

Much effort was devoted to secure an exact starting orientation, see Section 7-2. The measured in data from Sicada presented in Table 8-2 give an inclination of 2.18°, although it was aimed to be 2°. On the other hand the initial measurement with the deviation measurement equipment showed that the start inclination value differs with approximately 0.1° and is closer to the desired value 2°.

When drilling K03009F01, the casing preparations and installation followed the standard routines at Äspö HRL, which resulted in a larger error with a casing of −0.37° when aiming at −1.0°, see Section 5-5. Similarly the deviation measurement equipment gave a better value which was 0.23° closer to −1.0 than the geodetically measured value of −0.37°. There is no certain explanation of this outcome, as there can be uncertainness both in the geodetic measurements performed, as well as in the accuracy of the deviation instruments used. The conclusion is that careful alignment when casing drilling and using tight centralizers when mounting the casing tube improves the ability to get the correct start orientation, which in turn improves the ability to perform steered drilling within the stipulated requirements.

Table 8-2. Borehole coordinates and direction at the start-point (0-m) in K08028F01.

	ID	X	Y	Z	Azimuth	Inclination	Coord. and North ref.
Start	K08028F01	2 386.035	7 450.637	–396.584	320.37	2.18	Äspö 96

8.1.2 Hydraulic measurements

Flushing water used for drilling of K08028F01 was delivered from the Äspö HRL fresh water supply. During the drilling period, sampling and analysis of flushing water for analysis of the contents of the added fluorescent tracer (uranine) was carried out systematically for every second water tank filled, see Figure 8-3. As borehole K08028F01 was drilled below the groundwater table, all added flushing water as well as the accumulated inflow of groundwater to the borehole were recovered as a return water outflow at TOC (*top of casing)*. According to notations in the drillers log and a rough calculation of the accumulated return water volume from opening time of the borehole gives a water balance of 1.14. The relatively low quotient is due to a low water-yielding capacity of the borehole.

The hydrogeological prognosis (Chapter 3) pointed at a low groundwater inflow along the entire borehole length (6 L/min). At borehole length 35 m the water inflow increased from 0.25 L/min to c. 1.5 L/min, see Figure 8-4.

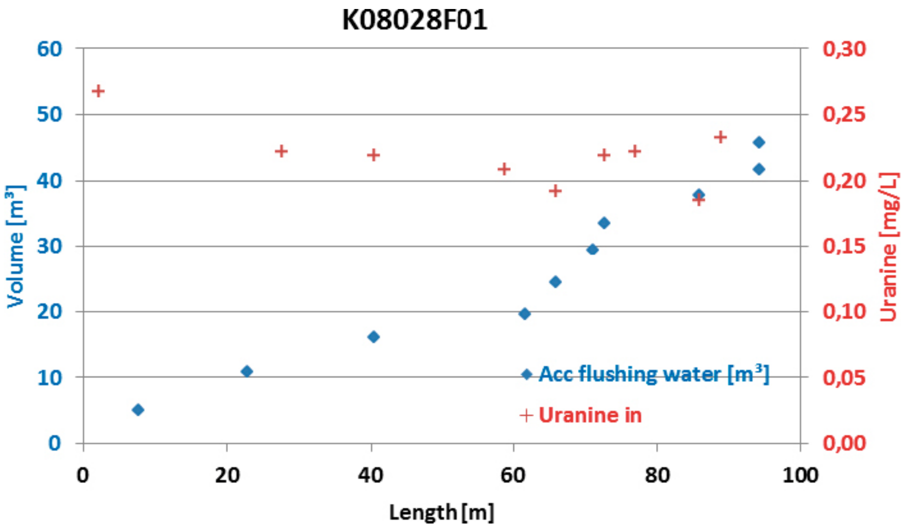


Figure 8-3. *Uranine contents in the flushing water consumed (red crosses) and accumulated flushing water volume (blue squares) versus drilling length during drilling of K08028F01.*

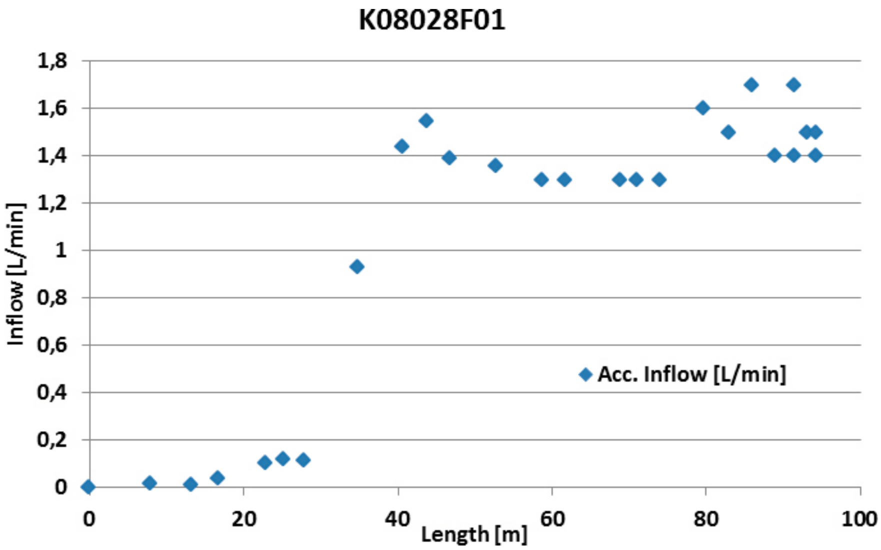


Figure 8-4. *Accumulated inflow to the borehole measured after completed drilling, but with the drill string still left in the borehole.*

8.1.3 Core sampling

The average summed up drill core length retrieved per drilling run was 2.36 m (Section 2.28–94.39 m but excluding the two steering sections at 66 and 74 m). Fracture minerals were relatively well preserved. A preliminary core logging was carried out continuously in conjunction with the drilling.

8.2 Deviation measurements

Following the adopted strategy, which is reported in Chapter 6, and by using the instruments tested in Äspö deviation facility, and by otherwise making use of experiences obtained, increased the chance of a successful implementation. The resulting measurements using the Reflex Gyro in the completed borehole are shown in Figure 8-6 and 8-7. Like in Chapter 6, for all deviation measurements a file consisting of inclination and azimuth data was created. All subsequent measurements are imported into this file that continuously upgrades the average calculation. In Figure 8-5 the number of measurements performed at each point of the borehole is presented.

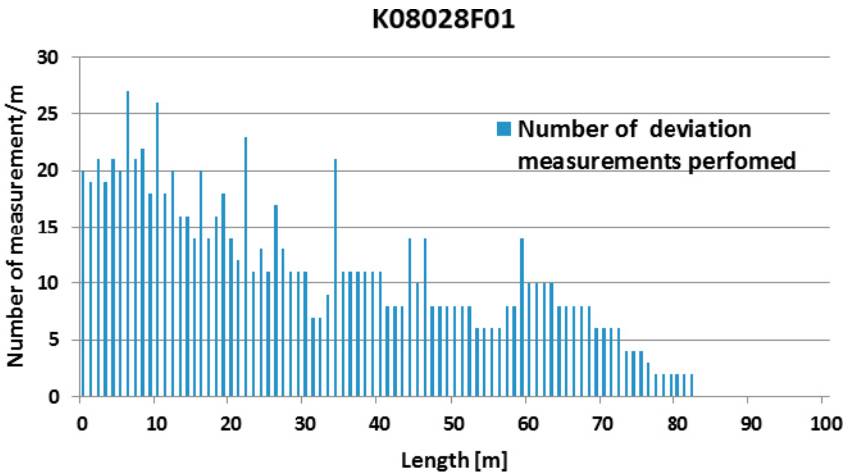


***Figure 8-5.** The figure shows the number of deviation measurements performed at each length in borehole K008028F01. Every new measurement is used for average calculation of a working file.*

8.2.1 Devico Pee-Wee

The magnetic Devi shot instrument (Pee-Wee) is by design adapted for use together with wire-line technology, and is pumped through the drill pipe and through the drill bit. The tool (Ø=31 mm) is functioning both for DeviDrill and Corac N3 core tube. This means that the measurements (including data management and input to decision making) can be carried out rapidly, including data management up to the final result. The instrument was used to orient the directional core barrel (tool face) and to make quick measurements especially of the inclination.

8.2.2 Reflex Gyro

Data from Reflex Gyro are most important for determination of whether the borehole fulfils the strict requirements. Measurements must be carried out in an open (non-cased) borehole, which means that it is time-consuming, especially at larger depths, since the drill rods have to be taken out. The instrument must be handled carefully to acquire data of high accuracy.

8.3 Evaluation and decision process

The evaluation and decision process followed the strategy reported in Chapter 6. Repeated measurements that are superimposed decrease the uncertainty.

8.4 Steering with the rig and basic core barrel

As earlier emphasized, much of the success of a high accuracy borehole is determined already when drilling and installing the casing, described in Sections 7.2–7.3. In this case an especially stable core barrel with shorter outer tube sections than normally was utilized, as well as multiple reamers and stabilizers with various sizes and degrees of wear. The result was a stiffer core barrel than normally, less likely to be affected by the geological formation. However, the barrel still enabled adjustment of the position and sequence of the reamers, which, combined with frequent surveys, would give some directional control of the borehole in both the vertical and horizontal plane. By using this capability, it was possible to drill 2/3 of the borehole length according to the stipulated demands before the first steered drilling had to be carried out at roughly 65 m borehole length.

The changes at around 20 m, 30 m and 35 m are all very small, cf. Figures 8-6 and 8-7, but were due to fine-tuning of the equipment's calibration rings, i.e. deliberate 'mini-steering' actions.

8.5 Steering with DeviDrill

Figures 8-6 and 8-7 should be read in such a manner that the area between the plot and the theoretical line represents the accumulated deviation, i.e. staying below the line for a long time means that the inclination (or azimuth) is decreasing, whereas staying above means an increase. So when the areas cancel out, the hole is exactly on track with respect to inclination (or azimuth).

8.5.1 Steering at 65 m

In Figure 8-5 the number of measurements performed at each point of the borehole is presented. Maximum 27 measurements of the same length have been carried out. These measurements are added to each other and by average calculation an updated working file is created. In Figures 8-6 and 8-7 the curves represent the average calculated file that was used for decision making of the drilling activity.

Already from start the borehole had constantly been positioned to the right of the straight line, and at 63 m length the distance was 12 cm to the right and 4 cm downwards, corresponding to c. 30 % of the allowed rectangle, see Section 6.1. The steering strategy in Section 6.2 claims that if the borehole deviates 50 %, a steering shall be carried out. However, if the borehole continues deviating to the right, the risk for performing a late steered drilling increases, which would be difficult to evaluate if it is carried out to close to the borehole end. The first steering action was prompted based on these conditions.

The DeviDrill directional core barrel was prepared with a low offset angle and directed to the left (tool face 270°) and with a drilling length of 1.2 m. Thereafter the borehole was extended to 72.74 m and the deviation measurement carried out to 72 m showed that the effect of the steered drilling was as expected with the borehole turning left (0.014°/m between 64–72 m), however along with a larger upward inclination (0.017°/m between 64–72 m), but still within the requirements.

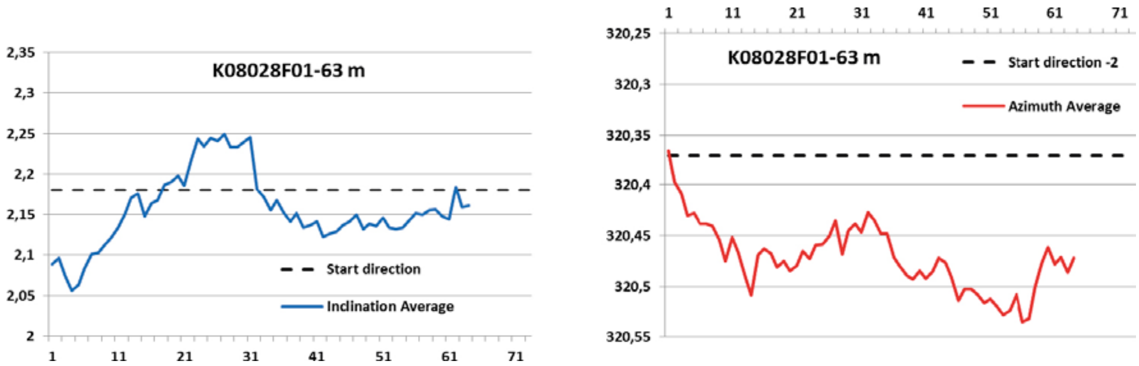


Figure 8-6. *Average calculated file to 63 m from all measurements with Reflex Gyro and Pee-Wee tools, inclination to the left and azimuth to the right. Also the straight reference line is presented in the diagrams.*

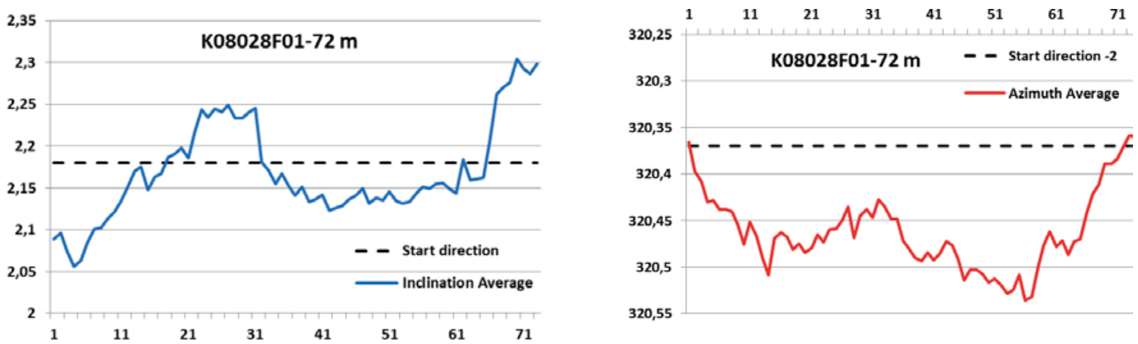


Figure 8-7. *Average calculated file to 72 m from all measurements with Reflex Gyro and Pee-Wee tools, inclination to the left and azimuth to the right. Also the straight reference line is presented in the diagrams. From start the borehole had a consistent trend to the right that was corrected with steered core drilling towards the end, bringing the borehole path almost straight towards the target.*

8.5.2 Steering at 73 m

The existing base for decision making at 72.78 m length is presented in Figure 8-7. As mentioned above, the former steering was successful in azimuth and with significant trend towards left, but still within the requirements (± 50 mm/6 m). For the inclination, no individual m-value exceeds the requirement of ± 10 mm/6 m.

Based on these results a second steering had to be carried out as it was necessary to retard the inclination, but still continue the azimuth to the left. The correction at 73 m was directed 235° and drilled 1.2 m. The outcome of the steering can be seen in Figures 8-8 and 8-9, measured after the borehole was extended. It worked out as the rise in inclination was retarded and a smooth left turn was obtained, pointing the hole almost directly on target.

When the (x,y,z-) coordinates are calculated, the deviation of the hole at 94.39 m is interpreted to be 1.8 cm to the right and 1.2 cm upwards from target. The borehole was even heading exactly towards the bulls-eye if it had been drilled to 100 m length. However, due to heavy foliation at the last core recovery, indicating an increased risk for massive inflows, the project manager canceled the drilling at 94.39 m length.

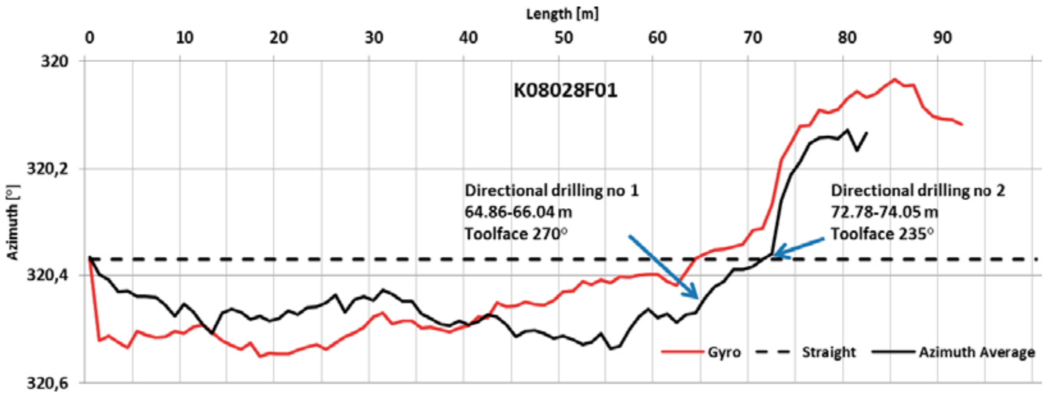


Figure 8-8. *Final deviation measurement with Reflex Gyro (red) and average calculated file (black) in K08028F01, and with the azimuth and the straight reference line presented in the diagram. From start the borehole had a consistent trend to the right that was corrected with steered core drilling towards the end, bringing the borehole path almost straight to the target.*

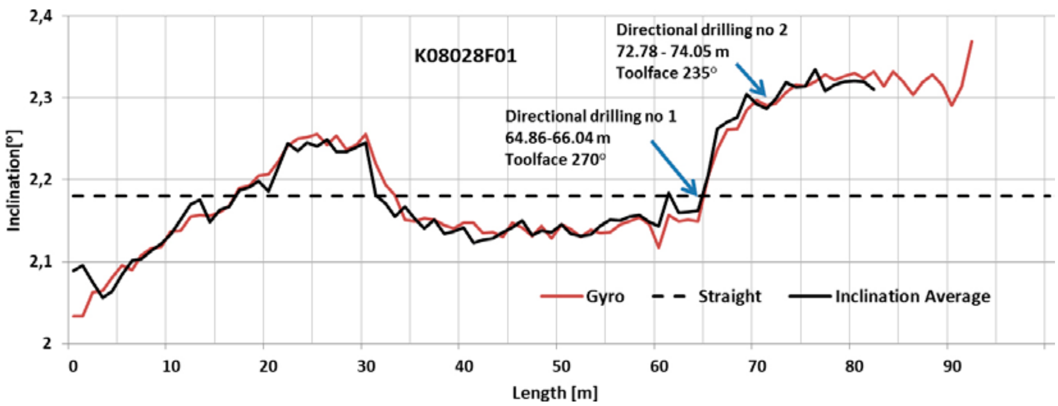


Figure 8-9. *Final deviation measurement with Reflex Gyro (red) and average calculated file (black) in K08028F01, and with the inclination and the straight reference line presented in the diagram.*

9 Results for K08028F01

9.1 Drilling operation

The employment of the Sandvik DE140 system for the KBS-3H project at the Äspö HRL revealed some technical problems; cf. Figures 9-1 and 9-2. Repeated disturbances of the hydraulic rotation unit were troublesome and initially delayed the drilling process. In addition a minor oil leak had to be sealed and the spillage decontaminated. Furthermore, a drill bit was broken at commencement of the drilling (Figure 9-2).

The plastic plug glued into the casing destroyed an N drillbit when drilling started. The reason was that the plastic material caulked the water channels, whereby the drillbit was over-heated resulting in melting of the alloy (iron-cobalt) with which the diamond chips are fastened to the drill bit body. Unfortunately, the plastic plug was oversized and can in the future be much slimmer and made of a more favourable plastic material or aluminium.

However, after exchanging the rotation unit, and using fresh drill bits, the drilling of K08028F01 could be carried out within the time schedule.

Figure 9-1. *Technical problems with the hydraulic rotation unit initially caused a delay in the drilling process and also caused a minor oil leak, which had to be taken care of. Still, after exchanging the rotation unit, the drilling of K08028F01 could be completed on schedule.*

Figure 9-2. *The plastic plug glued into the casing destroyed an N drillbit when drilling started. The reason was that the plastic material caulked the water channels, whereby the drillbit was overheated, resulting in melting of the alloy (iron-cobalt) with which the diamond chips are fastened to the drill bit body.*

9.2 Revisit of outcomes of steering in relation to stipulated requirements

The final deviation measurements in the completed K08028F01 with the Reflex Gyro instrument were used for determination of resulting inclination and azimuth, respectively. In addition, 41 measurements with the gyro and the Pee-Wee tool were carried out during the drilling operation. These measurement data have continually been merged, and by an average calculation procedure an upgraded working file has been created. This working file is presented together with the final gyro measurements in Figure 9-3. Only minor discrepancies in inclination occur, but larger discrepancies are found in azimuth, probably due to difficulties to centralize the 41 mm tool in a 76 mm borehole.

Steering operations applied in ordinary drilling campaigns are generally much rougher than those applied in the KBS-3H case. Data and results from this project illustrate that the very delicate steering actions carried out resulted in changes in direction within the strict KBS-3H requirements. It should also be noted that the subsequent steps in the reaming process towards realization of a full diameter experimental drift are expected to smoothen out existing undulations in the borehole further.

When the (x,y,z-)coordinates later on were calculated, the deviation of the hole at the borehole end (94.39 m) is c. 1.9 cm to the right and 1.2 cm upwards, see Figures 9-4 and 9-5. The two steered drillings at 64 m and 73 m respectively, managed to redirect the orientation so that the borehole was even heading towards the bulls-eye if it had been drilled to 100 m length. However, as mentioned in Section 8.5.2, due to heavy foliation at the last core recovery, indicating an increased risk for massive inflows, the project manager canceled the drilling at 94.39 m length.

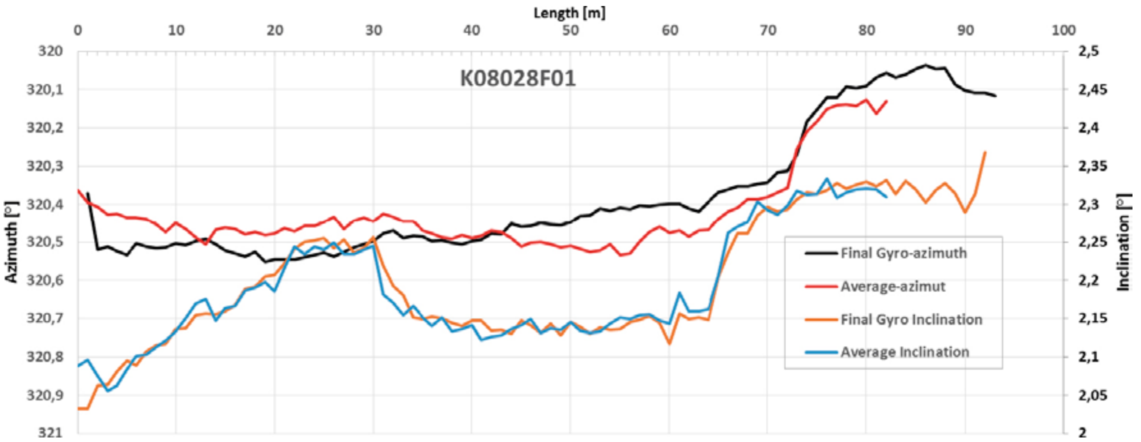


Figure 9-3. Final deviation measurements (azimuth and inclination) with Reflex Gyro and average calculated files in K08028F01.

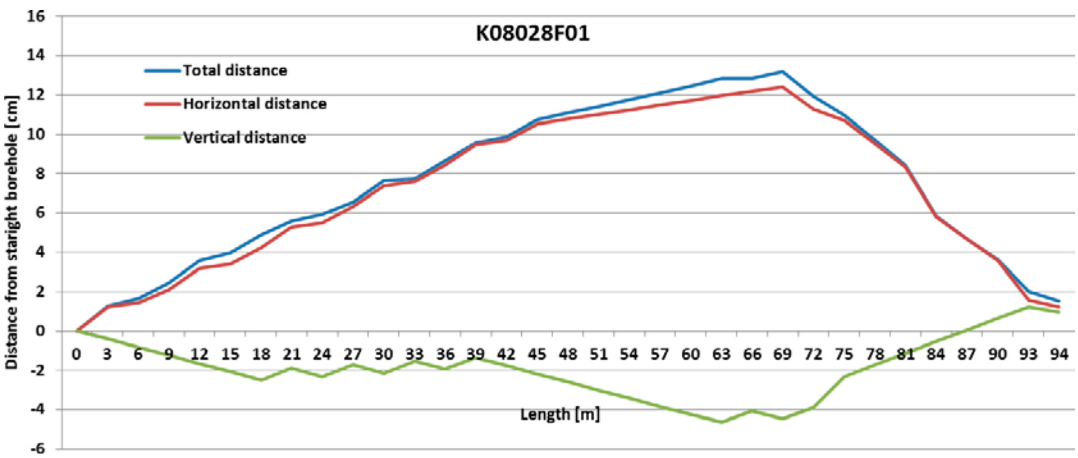


Figure 9-4. Final distance from the straight borehole is presented with the vertical distance (green), horizontal distance (red) and the total distance (blue).

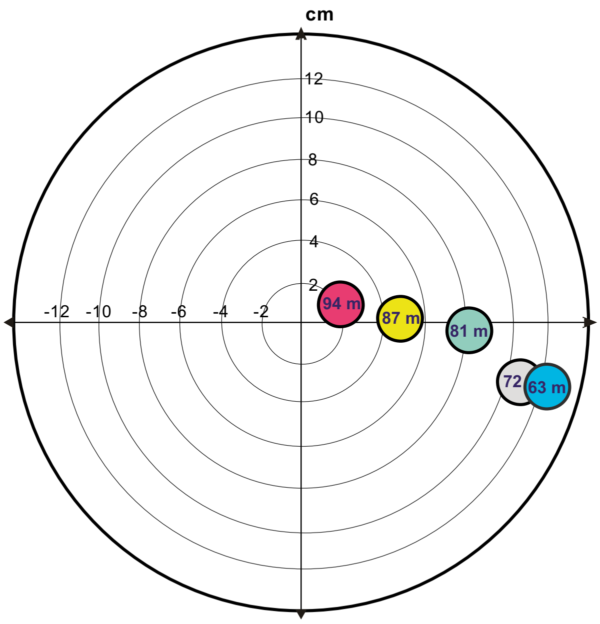


Figure 9-5. Presentation of borehole positions for K08028F01 at different lengths according to the target point. At the borehole end (94.39 m) the deviation is 1.9 cm to the right and 1.2 cm upwards.

9.2.1 Detailed analysis of the deviation data from K08028F01

With data from the final deviation measurements and given start coordinates, the borehole position can be calculated as coordinates (x, y and z) for every metre of the borehole length. In Figure 9-6, these coordinates are represented by the blue points n, n+1, ..n+6 for every metre over a 6 m reference length. The method of analysis used is described further below.

The calculation is performed so that the 3D-vectors from point (n) to (n+1), n to n+2, .. n to n+6 are divided into a horizontal component by using the z-value and a vertical component from the x- and y-values. Simultaneously, by a successive angular calculation of the distance to the reference line in vertical and horizontal, respectively, five columns with the angular distances are created, and by using the sinus theorem the distances in mm are calculated. By incrementally moving one metre ahead, a file is created that specifies the horizontal and vertical distances for the entire borehole. The results presented in figure 9-7 and 9-8 shows that the requirements are fulfilled with margins.

The changes (differences) in inclination are plotted metre by metre in Figure 9-7, and a corresponding plot for the azimuth is presented in Figure 9-8. None of the values for inclination exceeds ±10 mm/6 m and, correspondingly, all values for azimuth are far below ±50 mm/6 m. Hence, the KBS-3H requirements are complied with by a comfortable margin.

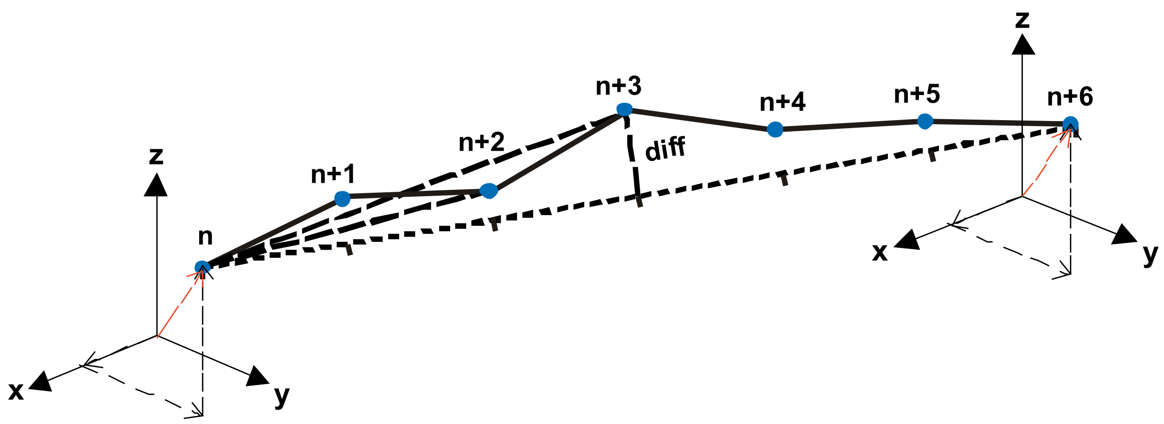


Figure 9-6. The schematic figure describes the evaluation works by calculating the distance to the line n to(n+6) for every metre (n+1), (n+2)... (n+6) over a 6 m reference length from starting point n.

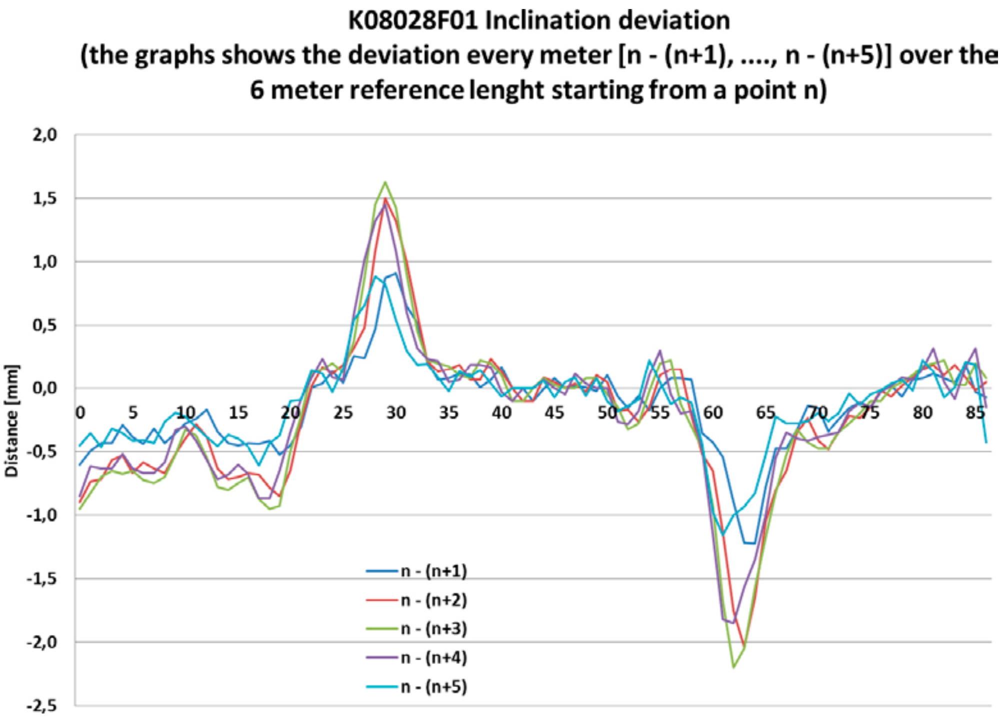


Figure 9-7. *The graphs show the vertical deviation at every metre [n−(n + 1),…. n−(n + 5)] over the 6 m reference length starting from a point n. The graph illustrates that the drilling fulfils the straightness requirement in vertical (inclination) with margin.*

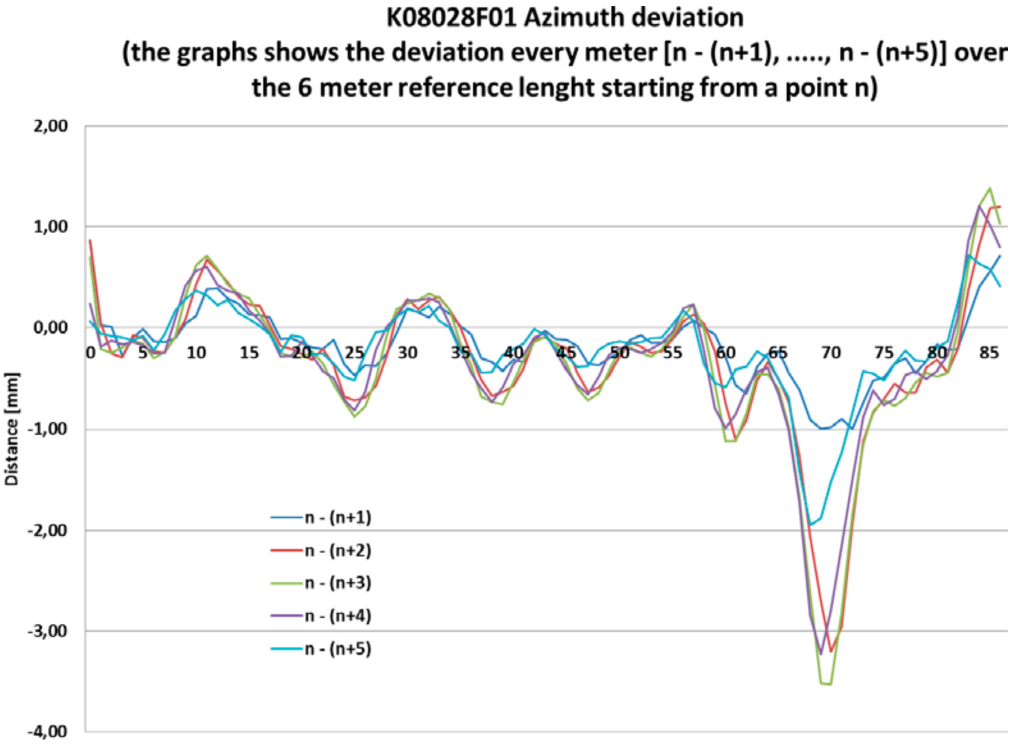


Figure 9-8. *The graphs show the horizontal deviation at every metre [n−(n + 1),…. n−(n + 5)] over the 6 m reference length starting from a point n. The graph illustrates that the drilling fulfils the straightness requirement in horizontal (azimuth) with margin.*

10 Conclusions

Drilling of the two boreholes (K03009F01 and K08028F01) aimed at: investigation of pilot borehole drilling techniques (KBS-3H) and; testing of techniques and methodologies to identify and quantify fractures/structures and their size characteristics (DETUM – Large fractures).

The hydrogeological prediction for K03009F01 turned out to be accurate, and at about 10 m borehole length the water inflow was found to be c. 250 L/min. The borehole was extended to 15.5 m, after which the entire borehole was grouted. Grouting was successful and a decrease in flow from over 200 L/min to less than 1 L/min was achieved. Borehole K08028F01 (below) provides an important second borehole for further investigations in the DETUM-project.

Prior to start of drilling of K08028F01, there remained, despite extensive and careful preparations undertaken, some uncertainty whether it was feasible to fully comply with the tough requirements set by the KBS-3H project. With the experiences from the completed project in hand, it can be concluded that the factors listed below are imperative for a successful outcome in relation to the KBS-3H requirements.

- A professional working team with the ability to cooperate internally and responsive to participants of different skills. Good communication is needed both in advance so that drill rig and the equipment for steering are designed to perform careful steered drilling. During drilling performance it is important that the crew is fully aware that high quality aspects have a higher priority than production capacity.
- A drill rig aligned accurately along the target hole trajectory, including high precision in fixating the casing.
- Drilling equipment adapted for drilling straight holes, implying that a well-served and a sufficiently powerful drill rig is used, that the direction core barrel is well-served, that drill bits with different hardness and reamers and stabilizers of various sizes are available.
- High quality instruments for deviation measurements, meaning that the instruments used have been tested and approved in the Äspö deviation facility. As the Reflex Gyro functions in all types of rock formations, also in the magnetically disturbed rock at the Äspö HRL it was the only instrument available in this project. The instrument needs careful handling to produce accurate data and cannot be used in combination with WL-technique (wire-line).
- Equipment for smooth correction/re-orientation of the hole in case it reveals tendencies to deviate from the planned path.

10.1 Comments on the steering strategy employed in K08028F01

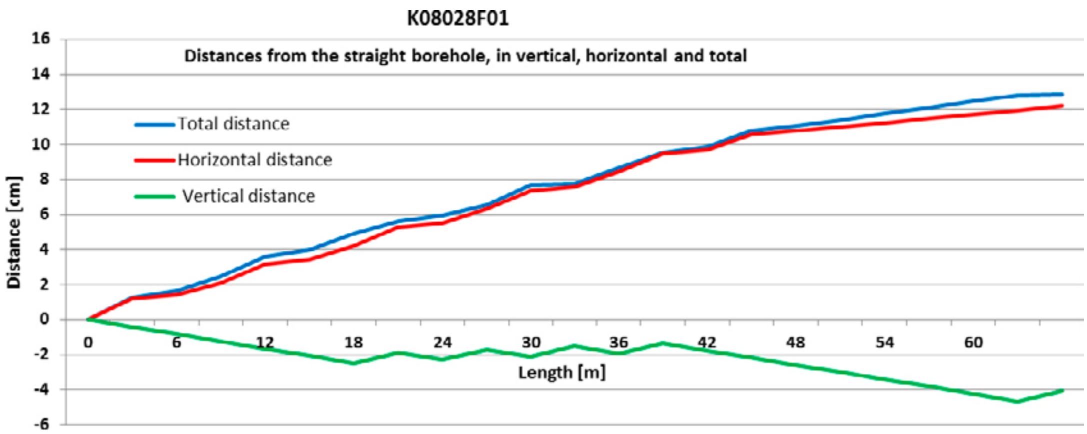
The KBS-3H requirements comprise both angles (inclination and azimuth) and distances. In the steering strategy (Chapter 6) these items are clarified and outlined in the form of different guiding criteria. The deviation instruments (Reflex HT Gyro and Pee-Wee) produce data that are successively added to each other and by an average calculation a decision file is created that is updated every time a new measurement is carried out. With the decision file, the requirements for inclination and azimuth can be valued by simple calculations in Excel. However, calculation of the distance between the straight borehole line and the actual borehole position is more complex without accurate software available. By creating macros in Excel also coordinates in three dimensions and distance calculation with Pythagoras theorem can be executed but are still time consuming and associated with some uncertainties. It would be a safer process if accurate software for this purpose was available, which however is not yet the case.

During the period of writing this report, some reassessment has resulted in that the requirements ± 10 mm/6 m in the vertical and ± 50 mm/6 m horizontal have been loosened up, see Figures 6-3 and 6-4. As the stricter interpretation prevailed during the drilling activity, the activity leader and Devico staff primarily wished to keep the borehole as close as possible to the straight borehole line. This could be achieved by shifting positions of stabilizers and reamers on the Corac core barrel and was successful up to 2/3 of the borehole length. At 63 m the borehole showed a steady trend going to the right, see Figure 10-1. Although the distance was only 30 % of the allowed distance, it was decided to perform the first steering to cancel the clear trend sideways. It would also be difficult to check the effect of a delayed steering as the borehole planned to end at 100 m. Therefore, the decision was made to correct the direction at 65 m and fine-tune the direction at 72 m resulting in that the borehole was almost on target.

In practise, perhaps the steering strategy would claim to keep the borehole as close as possible to the straight borehole line to 100 m length. During that period lessons will be learned on the rock behaviour and its effect on the deviations. After 100 m the conventional drilling lengths could increase and with less brakes for deviation measurement, which would have a considerable effect of both budget and time.

Technical development of deviation instruments as well as of equipment for steered drilling has steadily improved. Employment in the KBS-3H project of up-to-date technical equipment was one of the most important factors behind the successful results. Other important sources to the positive outcome were comprehensive efforts to prepare the drill site coupled with employing highly skilled drillers and deviation measurement engineers with clear objectives defined by the project.

For future drilling operations the following general advices and predictions can be made based on the experiences from the KBS-3H project: The crew will have to vary between drilling and deviation measurements quite often at the beginning to acquire a good idea about the response of the rock to drilling and steering (which is site specific). Later on some of the gyro measurements (which are time consuming) can probably be replaced by the quicker magnetic measurements (especially in non-magnetic rock), making the total operation less time consuming.



Figur 10-1. *The borehole position at 63 m and the trend to the right called for steered drilling in order to redirect the borehole close to the straight borehole line.*

11 Predictions and recommendations for a 300 metre steered borehole

The projected maximum length of deposition drifts in the KBS-3H disposal concept is 300 m.

The overall challenge in high accuracy pilot drilling is expected to increase quite a lot when taking the step from a 100 m to a 300 m pilot borehole, although the basic project strategy can still be quite similar. The important actions to consider when preparing a new drill site and carry out a 300 m steered drilling (tentatively in the ONKALO research facility at Olkiluoto, Finland) are listed below. More detailed descriptions of the measures and the selected technique are presented earlier in this report. Despite detailed technical descriptions, a basic rule for a successful outcome is to always use experienced staff and proven up-to-date technology for projects of this character.

- **Starting orientation.**
  With a precise starting orientation, i.e. casing alignment, there are good opportunities to avoid steered drilling in the first part of the borehole, thereby saving both cost and time. The influence of the physical rock properties (hardness, geometry of discontinuities and foliation) will tend to deviate the borehole from it stipulated path. This natural deviation of the borehole is important to understand in order to be successful with mini-steering operations by using reamers and stabilizers.
- **Platform with a stable foundation.**
  The length of the platform used for drilling of K08028F01 in TAS08 was 7 metres from borehole collar. Manual deviation measurements (by hand) can be managed to about 100 m length, but to reach further depths it is necessary to use an insertion equipment for pushing/pulling the deviation tools into or out from the borehole. An insertion rig must be located in line with the borehole direction and behind the drilling rig, entailing that the length of the drilling platform must be extended 4 m to a total length of 11 m. 300 m drill pipes (3 m each) weigh about 2,300 kg and require space to the left of the drill rig.
- **Underground field office.**
  A steered borehole requires much data processing and documentation. Therefore it helps if a sheltered working place for that purpose is available near the borehole. Access to Intranet is a bonus.
- **Access to the working place and working regulations.**
  Olkiluoto is classed as a nuclear facility and all rules concerning safety, access to the site, and working hours for nuclear facilities must be complied with.
- **Drill rig.**
  In the first place, for drilling a 300 m steered borehole, a powerful drilling rig is required. If the control panel is supplemented with a reducer valve, this reduces the risk of operator error during the steered drilling. The valve prevents the water pressure to be less than 30 bars and will keep the DeviDrill locked in correct orientation during the steered drilling period. Suitable drilling rigs to meet the work are such as Sandvik DE140 or Atlas Copco U8. Both of these can also be supplied with computerized control systems, often called CCD (Computer Controlled Drilling). For a CCD rig the drilling operation is fully automatic, including in-out transport of the drill rods that certainly is a great advantage for this type of work due to the frequent need of an open borehole for the repeated deviations measurements with Reflex Gyro. The operator can make changes or take over manually during any phase of the drilling. All drilling parameters used are stored on a logger that provides the ability to later evaluate the drilling activity.
- **Drilling equipment (hard and soft drillbits, Corac or hexagon core barrel).**
  The hexagon core barrel is assumed to be stiffer than other barrels, but due to lack of experience of using that tube, at least in Sweden, it must be valued by other experts. Due to long time use of the Corac core barrel and high access supply of suitable spare parts, it is recommended to use the Corac core barrel for 300 m long boreholes. This also includes drill bits, stabilizators and reamers.
- **Overall discussion of drilling a triple length (300 m) steered borehole.**
  During drilling of the first 100 m it is most important to perform a large number of deviation measurements both with the Reflex Gyro and the Devico Pee-Wee tool in order to understand the influence from the local rock formation structures and its effect on the natural borehole deviation.

If the magnetic disturbances are small and the Pee-Wee measurement appear as trustworthy, that will significantly decrease the measuring time. On the other hand, if these measurements do not work, measuring with the Reflex Gyro will be necessary, and the measurement process is much more time consuming.

In K08028F01, the average drilling capacity up to 100 m length was around 10 m/day including the frequent deviation measurements and two steerings performed, see Figure 11-1. Core drilling of a complete 3 m core recovery is usually performed in less than one hour. Obviously, it is the deviation measurements and associated activities like emptying the borehole, measurements, data calculation, evaluation and decision-making that are most time consuming before core drilling or steered drilling can continue. If the deviations measurements can be reduced by 33 %, estimation indicates that the drilling progress between 0–100 m would be 15 m/shift, between 100–200 m: 12 m/shift and from 200 m to 300 m: 10 m/shift. If that drilling capacity can be achieved, a steered borehole of 300 m length could be completed in 6 weeks, except for pre-drilling and casing installation that demands another week.

It should be noted that the bedrock and hydraulic conditions at the Äspö HRL are site-specific, and an experimental rock volume at for instance the selected repository sites Forsmark or Olkiluoto can never be expected to fully reflect the geological and hydraulic conditions at Äspö.

However, by careful allocation of an experimental site in relation to the *in situ* stress field as well as to major conductive structures and fracture sets, the information and results collected in boreholes and tunnels should serve as a sufficient basis to formulate and argument for investigation and development strategies to be applied at Forsmark and Olkiluoto, in the event KBS-3H is pursued as an alternative. The characterisation steps specific to the KBS-3H concept outlined in this document are also expected to satisfy the needs of, and will also provide added value to, the KBS-3V concept.

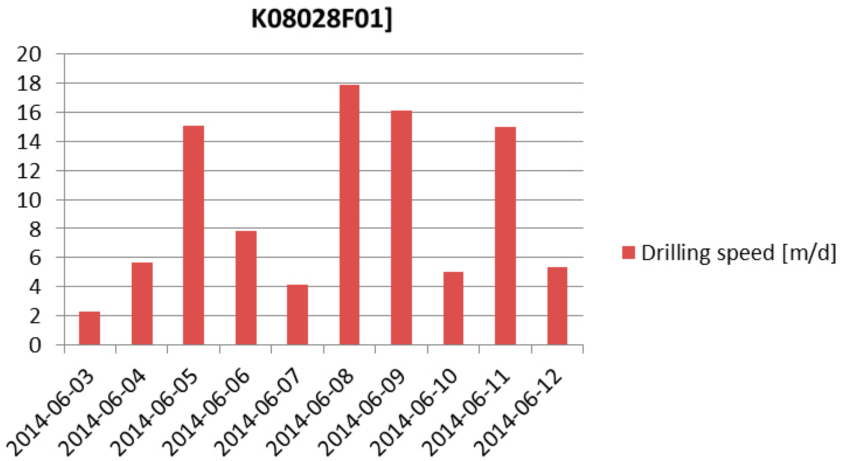


Figure 11-1. *Drilling production in K08028F01 varies between 4–18 m per shift (12h).*

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