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Drilling of percussion boreholes HFM42–HFM46 in Forsmark to be used as monitoring wells

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Abstract

Five boreholes, HFM42, HFM43, HFM44, HFM45 and HFM46, were drilled in solid rock using percussion drilling technique at the Forsmark site, selected by SKB for a future repository for spent nuclear fuel.

Borehole HFM42, which was drilled during the period April 10th to April 11th, 2018, is 195.30 m long, inclined 89° to the horizontal plane with direction towards S, and is drilled with a diameter of 141 mm. A water inflow of 18 L/min was encountered during drilling. The borehole was used primarily as a monitoring well for groundwater level detection during interference tests in the summer of 2018. Fiber cables and geophones were installed between August 7th and August 9th before the entire borehole was injected with cement. This type of borehole arrangement is intended to be used for future seismic measurements in the area.

Borehole HFM43, which was drilled during the period April 17th to April 23rd, 2018, is 200.00 m long, inclined 85° to the horizontal plane, directed towards WNW, and is drilled with a diameter of 141 mm. A large groundwater inflow, 600 L/min, was faced during drilling. The aim of borehole HFM43 was that it should be used first as a pump well during interference tests of fracture zone ZFMENE0159A, and later as a monitoring well for long-term detection of the groundwater level, and for hydrochemical groundwater sampling.

Borehole HFM44 was drilled during the period April 24th to April 26th, 2018, and is 199.60 m long with an inclination of 83° to the horizontal plane, and directed towards WSW. The borehole is drilled with a diameter of 141 mm. Also in this borehole a considerable water inflow, 500 L/min, occurred during drilling. This borehole was used as a monitoring well/pump well during interference tests across the Singö deformation zone and later as a monitoring well for long-term detection of groundwater levels, and for groundwater sampling.

Borehole HFM45 was drilled during the period May 02nd to May 04th, 2018. This borehole is 200.00 m long, drilled towards WNW with the inclination 85° to the horizontal plane and with a diameter of 141 mm. A water inflow of 100 L/min was observed during drilling. HFM45 was, like HFM44, used as a monitoring well/pump well during interference tests across the Singö deformation zone and later as a monitoring well for long-term detection of groundwater levels, and for groundwater sampling.

Finally, borehole HFM46, which was drilled during the period May 06th to May 08th, 2018, is 200.00 m long, inclined 85° to the horizontal plane, directed towards ESE, and is drilled with a diameter of 141 mm. A sizeable groundwater inflow, 400 L/min, was encountered during drilling. The purpose of HFM46 was the same as for HFM44 and HFM45, i.e. that the borehole should be used as a monitoring well/pump well during interference tests across the Singö deformation zone and later as a monitoring well for long-term detection of groundwater levels, and for groundwater sampling.

Sammanfattning

Fem hammarborrhål, HFM42, HFM43, HFM44, HFM45 och HFM46, borrades inom Forsmarks geologiska undersökningsområde inför byggandet av ett framtida förvar för använt kärnbränsle.

HFM42 borrades under perioden 10–11 april 2018. Borrhålet är 195,30 m långt, är ansatt 89° mot horisontalplanet i riktning mot S och borrat med diametern ca 141 mm. Under borrningen noterades ett vatteninflöde av 18 L/min. Borrhål HFM42 användas först som moniteringsbrunn för registrering av grundvattennivån vid interferenstester i området under sommaren 2018. Därefter installerades fiberkablar och geofoner, varefter hela borrhålet injekterades med cement. Denna typ av instrumentering är avsedd att användas vid kommande seismiska mätningar.

HFM43, som borrades under perioden 17–23 april 2018 är 200,00 m långt, ansatt 85° mot horisontalplanet i riktning VNV och borrat med diametern ca 141 mm. Under borrningen noterades ett mycket stort grundvatteninflöde, 600 L/min. Syftet med HFM43 var att hålet skulle användas om pumpbrunn vid interferenstester av zonen ZFMENE0159A och senare som moniteringsbrunn för långtidsregistrering av grundvattennivån och för grundvattenkemisk provtagning.

HFM44 borrades under perioden 24–26 april 2018. Borrhålet är 199,60 m långt, är ansatt 83° mot horisontalplanet i riktning VSV och borrat med diametern ca 141 mm. Även i detta borrhål uppmättes ett betydande vatteninflöde, 500 L/min. Borrhål HFM44 används som moniteringsbrunn/pumpbrunn vid interferenstester över Singözonen och senare som moniteringsbrunn för registrering av grundvattennivån och för vattenprovtagning.

HFM45 borrades under perioden 2–4 maj 2018. Borrhålet är 200,30 m långt, är ansatt 85° mot horisontalplanet i riktning VNV och borrat med diametern ca 141 mm. Under borrningen uppmättes vatteninflödet 100 L/min. Borrhål HFM45 användes, liksom HFM44, som moniteringsbrunn/pumpbrunn vid interferenstester över Singözonen och senare som moniteringsbrunn för registrering av grundvattennivån och för vattenprovtagning.

Borrhål HFM46, slutligen, borrades under perioden 6–8 maj 2018. Borrhålet är 200,00 m långt, är ansatt 85° mot horisontalplanet i riktning OSO och borrat med diametern ca 141 mm. Ett betydande vatteninflöde, 400 L/min, noterades under borrningen. Syftet med HFM46 var detsamma som för HFM44 och HFM45, dvs att borrhålet skulle användas som moniteringsbrunn/ pumpbrunn vid interferenstester över Singözonen och senare som moniteringsbrunn för långtidsregistrering av grundvattennivån samt för vattenprovtagning.

Contents

1 Introduction

The spent nuclear fuel from the Swedish nuclear power plants is planned to be deposited in a geological repository at about 500 m depth in the Forsmark area, close to the Forsmark power plants. To protect humans and environment in the long perspective, SKB recommends an underground repository built in crystalline bedrock.

During the period 2002–2009, SKB performed geoscientific and ecological site investigations at two sites in Sweden, Oskarshamn and Forsmark. After having assessed the Forsmark site as being the most favourable in 2009, a long term monitoring programme of a number of earth science parameters and biological objects was initiated.

In March 2011, an application for building a repository for spent nuclear fuel at the Forsmark site was handed in. At the same time the Spent Fuel Project was initiated with the assignment to plan, built and test the facility.

The facility consists of one part situated above ground which is connected to an underground part dimensioned to hold 6 000 copper canisters containing spent nuclear fuel, see Figure 1-1. Ramp and different vertical shafts connect the above ground facility with the sub-surface part. The sub-surface area is in turn divided into a central and a deposition area. The design of the facility is described in SKB (2016).

This document reports the data and results gained by drilling the five percussion boreholes HFM42, HFM43, HFM44, HFM45 and HFM46 as part of the preparatory investigation programme of Project Spent Fuel Repository at SKB. The percussion drilling operations were carried out at the site shown in Figure 1-2, in accordance with the activity plan AP SFK-17-033. Controlling documents for performing this activity are listed in Table 1-1. Both activity plans and method descriptions are SKB's internal controlling documents.

Protek AB, Norsjö, with subcontractor TSB Entreprenad, Sollefteå, Sweden, was engaged for the percussion drilling commission. For the first time a percussion rig supplied with an automatic rod handling system was employed for drilling at the Forsmark site. Support was provided from SKB-personnel regarding measurements and tests during drilling.

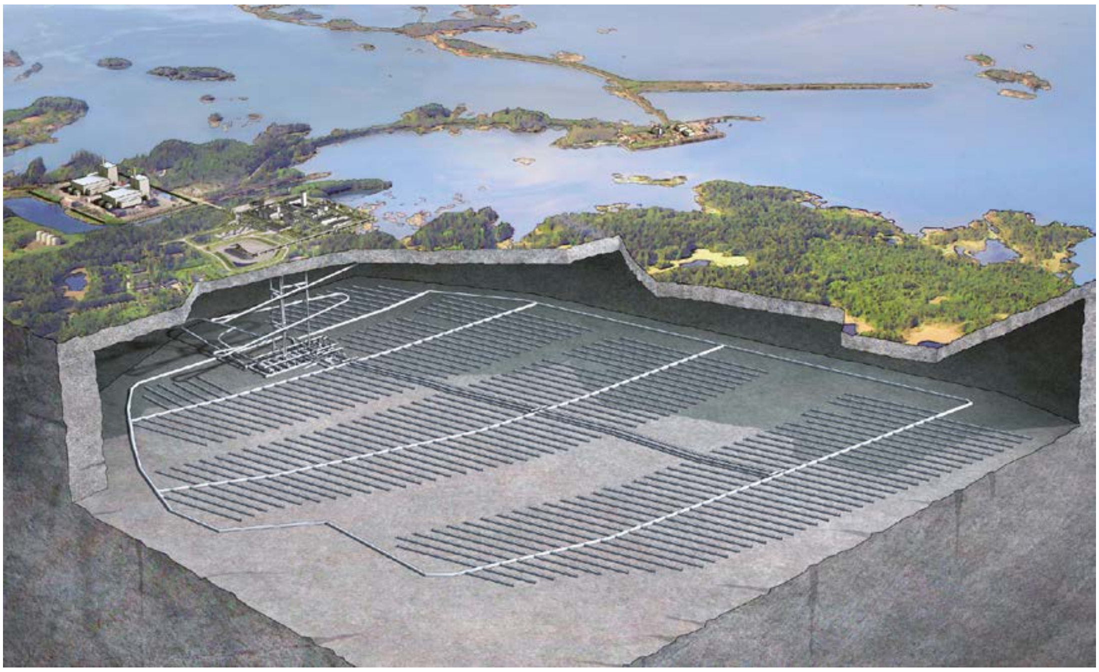


Figure 1-1. *Illustration of a possible design of the Spent Fuel Repository at Forsmark.*

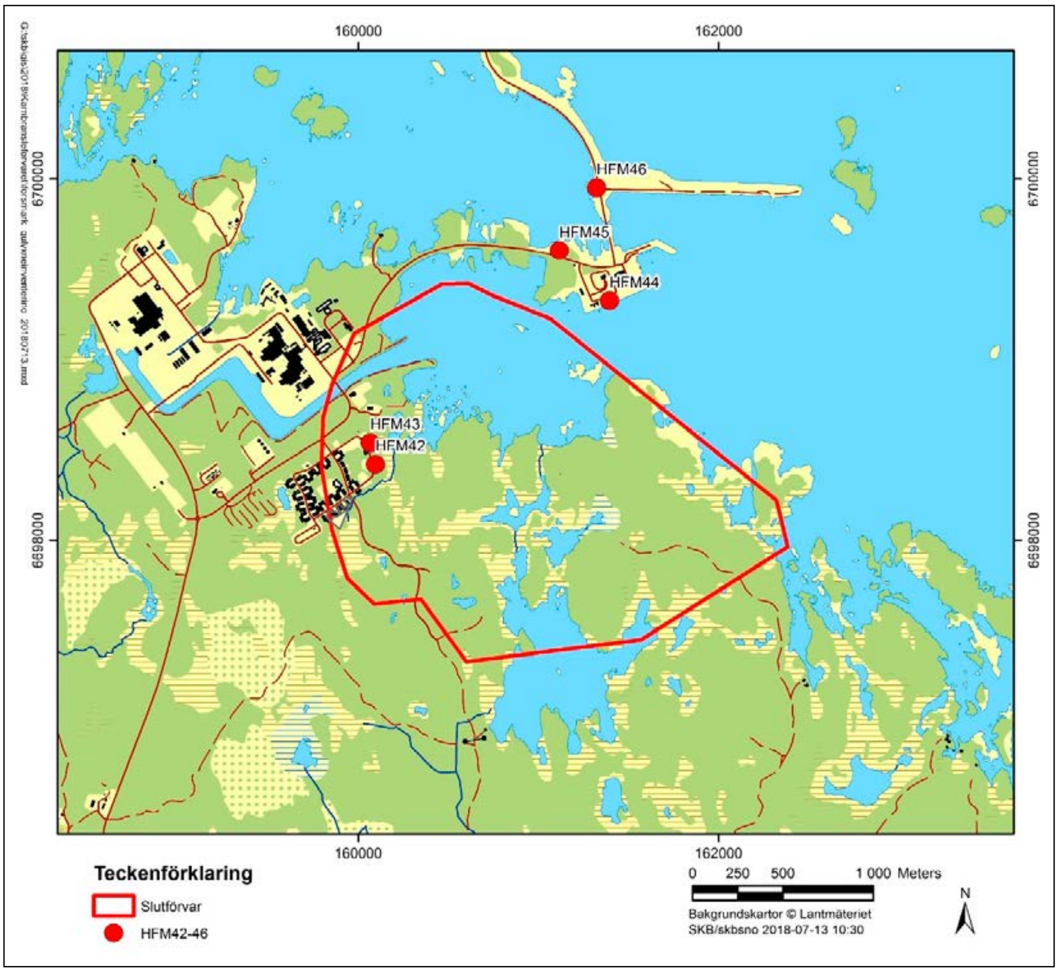


Figure 1-2. *Location of the five percussion drilled boreholes at Forsmark.*

Table 1-1. Controlling documents for performance of the activity.

Activity plan	Number	Version
Hammarborrning av 4 observationsborrhål och ett instrumenthål i Forsmark	AP SFK-17-033	1.0
Method documents	**Number**	**Version**
Method Description for percussion drilling	SKB MD 610.003	4.0
Method Instruction for Cleaning Borehole Equipment and certain Ground-based Equipment	SKB MD 600.004	1.0
Method Instruction for Chemical Products and Materials	SKB MD 600.006	1.0
Metodbeskrivning för genomförande av hydrauliska enhålspumptester.	SKB MD 321.003	1.0
Metodbeskrivning för krökningsmätning av hammar- och kärnborrhål	SKB MD 224.001	2.0

Five percussion boreholes were drilled during the period April 10th to May 8th, 2018. Original data from the reported activity are stored in the primary database Sicada. Data are traceable in Sicada by the Activity Plan number (AP SFK-17-033). Only data from Sicada are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in Sicada may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major revisions also entail a revision of the P-report. Minor revisions are normally presented as supplements, available at www.skb.se.

2 Scope

The site survey in 2002–2009 was primarily focused on investigating and describing the bedrock at storage depth. Now when the preliminary design of ramp and shaft is completed, a primary focus is directed to understanding the water drainage in the upper parts of the bedrock, and therefore a drilling program was designed and carried out.

The overall objectives of drilling percussion boreholes at the Forsmark investigation site are the following:

- to enable OPTV logging, as an aid for the geological/rock mechanical characterisation,
- to allow hydraulic borehole tests (single-hole tests as well as interference tests) for characterisation of the hydrogeological conditions,
- to permit long-term hydraulic and hydrogeochemical monitoring at different levels of the bedrock.

The drilling program associated with Activity Plan AP SFK-17-033 comprised five percussion boreholes, HFM42, HFM43, HFM44, HFM45 and HFM46, all of which were drilled during spring 2018. Two percussion drilled boreholes in the vicinity of Söderviken, as well as three percussion drilled holes adjacent to the VEGA- and SFR offices were aimed to be used as pumping-/observation boreholes for a series of interference tests. The interference tests were aiming at investigating:

- hydraulic characteristics of the Singö zone and the ZFMENE0159A zone,
- the hydraulic properties of the near surface bedrock in the area of ramp and shaft,
- existence of “sheet joints” in the SFR area west of Singö.

The boreholes HFM44, HFM45 and HFM46 were used for the interference tests across the Singö zone, whereas HFM43 served as an interference test pump well across zone ZFMENE0159A. The fifth borehole, HFM42, was supplied with geophones and fibre cables, after which the entire borehole was grouted. Later this hole will be used for seismic measurements.

3 Equipment

Drilling of the five boreholes was carried out with a HARDAR 5000H percussion drill rig (Figure 3-1). The machine was supplied with a variety of accessory equipment. In this chapter short descriptions are given of the drilling systems as well as the technique and equipment for gap injection of the borehole casings. Besides, the instrumentation used for deviation measurements performed after completion of drilling, and the equipment applied for measurements and sampling during drilling are briefly described.

Figure 3-1. *The HARDAR 5000H drilling machine at drill site HFM45. The automatic rod handling system has grabbed a new drill rod that is ready to be positioned as soon as drilling stops.*

Figure 3-2. *The downhole borehole equipment used is aimed for drilling straight boreholes. By using a precision hammer and a centralizer, combined with always starting a new borehole with a new drill bit gives best opportunities to obtain straight boreholes.*

3.1 Percussion drilling equipment

The HARDAR 5000H drilling machine (Figure 3-1) is equipped with separate engines for transportation and power supplies. In addition, the drill rig was fitted with an automatic rod handler. This system facilitates drilling, because the helper does not have to lift the heavy drill pipes, especially important in this project as the hard rock at Forsmark requires at least one replacement of the drill bit in a 200 m long borehole.

Water and drill cuttings were discharged from the borehole by an Atlas-Copco Drill Air Y35, 35 bar diesel compressor. The DTH drill hammer was of type Secoroc 5½″, operated by a Driconeq 76 mm pipe string, see Figure 3-2. All DTH-equipment and the drill rig were cleaned with a high-capacity steam cleaner before arriving to the drill site.

3.2 Grouting technique

In order to prevent surface water and shallow groundwater to infiltrate into deeper parts of the borehole, the normal procedure is to grout the gap between the borehole wall and the casing pipe with cement. The cement application may be performed by different technical approaches and equipment. Two variants of gap injection with cement are illustrated in Figure 3-3. In HFM43, HFM44, HFM45 and HFM46 only the borehole packer technique was applied.

In HFM42, that was aimed to be used as an instrumentation borehole, a standard casing was used without grouting the gap between the outer casing and the bedrock wall. Instead, after installation of fibre cable and geophones, the borehole was grouted completely, see Appendix 1 .

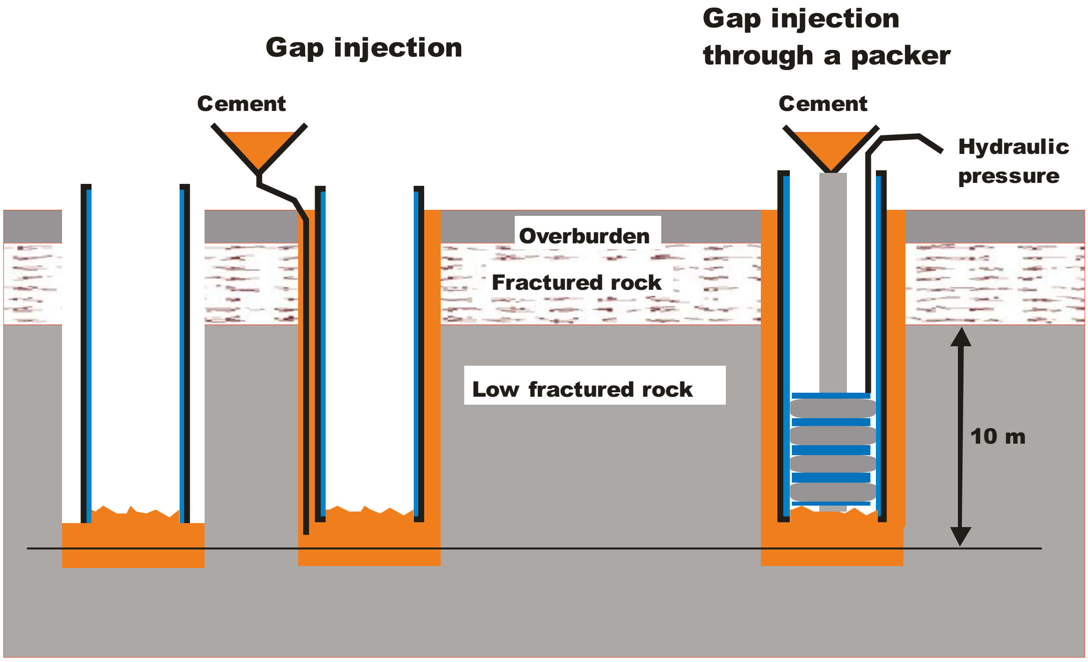


Figure 3-3. *Gap injection technique. In order to grout the gap between the borehole wall and the casing, different systems may be used. To the left, filling up a cement-water mixture with a flexible hose is shown. To the right, injection is performed through a borehole packer.*

3.3 Equipment for deviation measurements

After completion of drilling, a deviation measurement was carried out with a FLEXIT Smart Tool System, which is based on magnetic-accelerometer technique. Azimuth and dip are measured at every third metre. The collaring point coordinates and the measured values are used for calculating the coordinates of the position of the borehole at every measurement point.

Results from the deviation measurements stored in SKB's database Sicada are presented in Section 5.3.

3.4 Equipment for measurements and sampling during drilling

Flow measurements during drilling were conducted using measuring vessels of different sizes and a stop watch. Drilling penetration rate was measured with a carpenter's rule and a stop watch.

3.5 Equipment installed in borehole HFM42.

Borehole HFM42 was aimed to be used for seismic measurements. Uppsala University was responsible for purchase and calibration of two triaxle geophones and also provided one single-component geophone. Silixa Ltd, England, provided two fibre cables, as well as monitoring and analyse systems. The equipment was installed and thereafter the entire borehole was filled with cement from the bottom and upwards. Later, at the end of the summer 2018, the seismic field measurements were carried out. Both the equipment applied and the installation work performed in borehole HFM42 are narrated more in detail in Appendix 1.

4 Execution

Drilling of boreholes HFM42, HFM43, HFM44, HFM45, and HFM46, together with a number of undertakings associated with the drilling, followed the controlling documents presented in Table 1-1. Altogether the activity included the following items:

- preparations,
- mobilisation, including lining up the machine and measuring the position,
- drilling, measurements, and sampling during drilling,
- finishing off work,
- deviation measurements,
- data handling,
- environmental control,
- installation and grouting of fibre cables and geophones in HFM42.

4.1 Preparations

The preparations included the Contractor´s service and function control of his equipment. The machinery was obliged to be supplied with fuel, oil and grease exclusively of the types stated in SKB MD 600.006, Version 1.0 (Method Instruction for Chemical Products and Materials). Finally, part of the equipment was cleaned in accordance with SKB MD 600.004, Version 1.0 (Method Instruction for Cleaning Borehole Equipment and certain Ground-based Equipment) at level two, used for SKB boreholes of chemical type (the remaining part of the equipment was cleaned on-site). SKB MD 600.004 and SKB MD 600.006 are both SKB internal controlling documents, see Table 1-1.

4.2 Mobilisations

Mobilisation onto and at the site started with preparation of the drill site and transport of drilling and accessory equipment to the site. The mobilisation also comprised on-site cleaning of all DTH-equipment at level two according to SKB MD 600.004, lining up the machine and making a control of the inclination with a graduated arc and a final function control.

4.3 Drilling and measuring during drilling of HFM42–HFM46

The drilling operations were executed according to SKB MD 610.003, Version 1.0 (Method Description for Percussion Drilling), see Table 1-1.

4.3.1 Drilling through overburden

An ODEX-system was applied for drilling through the overburden and some metres into solid bedrock (Figure 4-1).

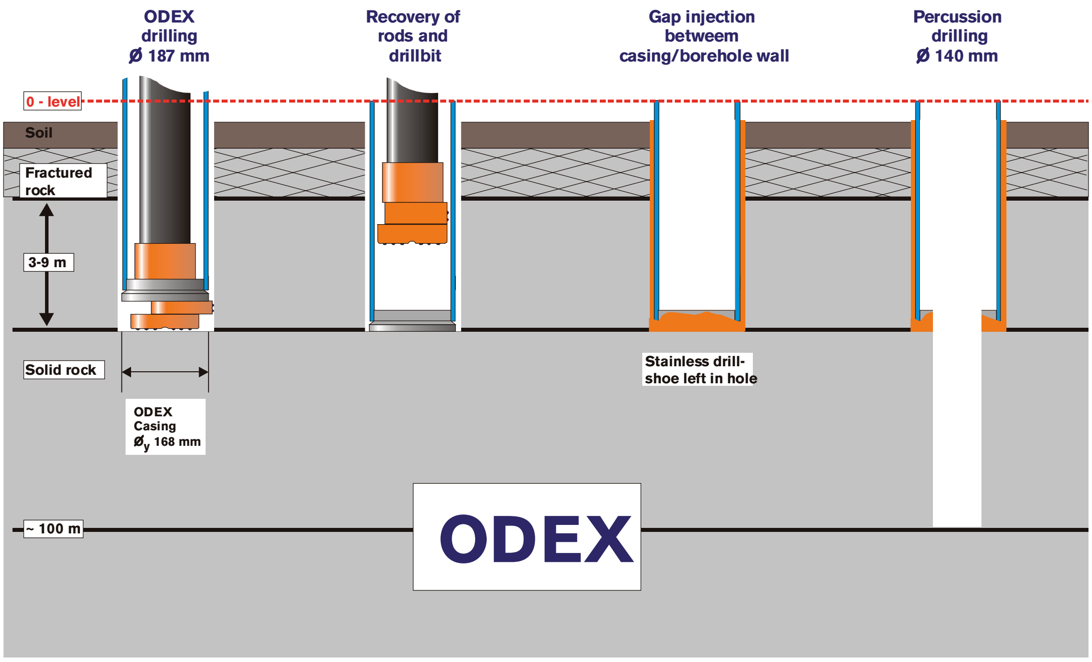


Figure 4-1. The different steps included in the performance of the percussion drilled boreholes HFM42–HFM46.

4.3.2 Gap injection

When the casing string had been firmly installed in boreholes HFM43, HFM44, HFM45, and HFM46, the narrow gap between the borehole wall and the external wall of the casing was grouted with a cement/water-mixture according to the borehole packer technique illustrated in Figure 3-3. However, as HFM42 was drilled to be instrumented and completely grouted, no gap injection was made in this borehole.

4.3.3 Percussion drilling in solid rock

After the casing was set, drilling could continue and was now performed to the full borehole length with conventional percussion drilling. Before start of drilling, the diameter of the drill bit was measured. In this last drilling step, the initial borehole diameter (approximately the same as the drill bit diameter) is normally 140 mm, see Figure 4-1. However, a diameter decrease of about 1 mm/100 m drilling length is to be expected when drilling in the rock types prevailing at Forsmark, and normally the drill bit has to be grinded after about 100 m of drilling.

4.3.4 Sampling and measurements during drilling

During drilling, a sampling and measurement program was carried out, which included:

- measurements of the penetration rate (one measurement per 20 cm drilling length). The time needed for the drill bit to sink 20 cm was recorded manually in a paper record, see Figure 4-2,
- performing one observation of discharged groundwater flow rate (if any) and water colour per 20 cm drilling length and a measurement of the flow rate at each major flow change observed. The measured values were noted in a paper record.

The results from the items above were used as supporting data and gave on-site information about rock quality as well as hydraulic and hydrogeochemical characteristics of the penetrated aquifers at the respective drill sites.

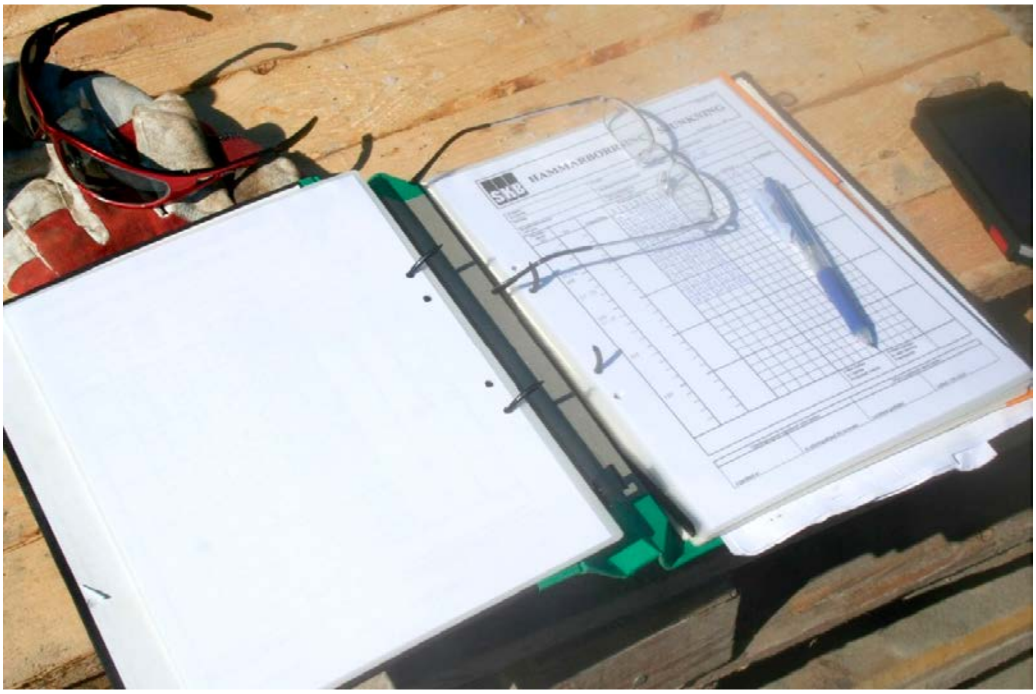


Figure 4-2. Documentation of penetration rate (one measurement per 20 cm drilling length) and observation of water inflow were recorded manually in a paper record.

4.4 Finishing of works

Finishing off work included rinsing of the borehole from drill cuttings by a "blow out" with the compressor at maximum capacity during 30–60 minutes. By measuring the flow rate of the discharged groundwater, a rough estimate of the water yielding capacity of the borehole at maximum drawdown was achieved. The drilling pipes were then retrieved from the hole, and the diameter of the drill bit was measured. A deviation survey of the borehole completed the measurement programme during and immediately after drilling. The borehole was secured by a stainless steel lockable cap, mounted on the casing flange, which finishes off the casing. Finally, the equipment was removed, the site cleaned and a joint inspection made by representatives from SKB and the Contractor, to ensure that the site had been satisfactorily restored.

4.5 Installation and grouting of fibre cables and geophones in HFM42

Borehole HFM42 was aimed to be used for seismic measurements and was therefore drilled vertically. Three geophones and two fibre cables were attached on the grouting tube with tape and cable ties for every metre. After connecting the computers to the cables, the crew confirmed that all sensors functioned, meaning that the installation could be completely grouted from bottom and upwards in the 195.3 m long borehole. A detailed description of the installation is given in Appendix 1.

4.6 Nonconformities

No departures from the Activity Plan were made.

5 Results

All data were stored in the Sicada database, where they are traceable by the Activity Plan number AP SFK-17-033. A summary of the acquired data is presented in the sections below.

5.1 Overview of drilling of HFM42, HFM43, HFM44, HFM45 and HFM46

Administrative, geometric, and technical data for HFM42, HFM43, HFM44, HFM45 and HFM46 are presented in Table 5-1. The technical design of the boreholes is illustrated in Figures 5-1, 5-2, 5-3, 5-4 and 5-5.

Table 5-1. Administrative, geometric, and technical data for boreholes HFM42, HFM43, HFM44, HFM45 and HFM46.

Parameter	HFM42	HFM43	HFM44	HFM45	HFM46
Drilling period	From 2018-04-10 to 2018-04-11	From 2018-04-17 to 2018-04-23	From 2018-04-24 to 2018-04-26	From 2018-05-02 to 2018-05-04	From 2018-05-06 to 2018-05-08
Borehole inclination (collaring point)	−89.12° (−= downwards)	−85.21° (−= downwards)	−83.19° (−= downwards)	−84.98° (−= downwards)	−85.41° (−= downwards)
Borehole bearing	173.28°	303.79°	255.72°	291.20°	108.13°
Borehole length	195.30 m	200.00 m	199.60 m	200.30 m	200.00 m
Borehole diameter	From 0.30 m to 6.03 m: 0.185 m (cased part). Below casing, from 6.03 m to 108.00 m: decreasing from 0.1407 m to 0.1395 m. From 108.00 m to 195.30 m: decreasing from 0.1395 m to 0.1384 m.	From 0.35 m to 6.03 m: 0.185 m (cased part). Below casing, from 6.03 m to 111.00 m: decreasing from 0.1407 m to 0.1391 m. From 111.00 m to 132.00 m: decreasing from 0.1391 m to 0.1383. From 132.00 m to 200.00 m: decreasing from 0.1383 m to 0.1366.	From 0.35 m to 9.03 m: 0.185 (cased part). Below casing, from 9.03 m to 108.00 m: decreasing from 0.1405 m to 0.1396. From 108.00 m to 172.00 m: decreasing from 0.1396 m to 0.1361 m. From 172.00 m to 199.60 m: decreasing from 0.1361 m to 0.1340 m.	From 0.30 m to 6.28 m: 0.185 (cased part). Below casing, from 6.28 m to 120.00 m: decreasing from 0.1405 m to 0.1396 m. From 120.00 m to 200.30 m: decreasing from 0.1396 m to 0.1389 m.	From 0.00 m to 6.03 m: 0.185 m (cased part). Below casing, from 6.03 m to 114.00 m: decreasing from 0.1408 m to 0.1397 m. From 114.00 m to 200.00 m: decreasing from 0.1397 m to 0.1377 m.
Casing length	6.03 m	6.03 m	9.03 m	6.28 m	6.03 m
Casing diameter	$\varnothing_o/\varnothing_i$ = 168.3 mm/158.3 mm to 6.00 m $\varnothing_o/\varnothing_i$ = 168.3 mm/142.5 mm between 6.00 and 6.03 m	$\varnothing_o/\varnothing_i$ = 168.3 mm/160.3 mm to 6.00 m $\varnothing_o/\varnothing_i$ = 168.3 mm/142.5 mm between 6.00 and 6.03 m	$\varnothing_o/\varnothing_i$ = 168.3 mm/160.3 mm to 9.00 m $\varnothing_o/\varnothing_i$ = 168.3 mm/142.5 mm between 9.00 and 9.03 m	$\varnothing_o/\varnothing_i$ = 168.3 mm/160.3 mm to 6.25 m $\varnothing_o/\varnothing_i$ = 168.3 mm/142.5 mm between 6.25 and 6.28 m	$\varnothing_o/\varnothing_i$ = 168.3 mm/160.3 mm to 6.00 m $\varnothing_o/\varnothing_i$ = 168.3 mm/142.5 mm between 6.00 and 6.03 m
Drill bit diameter	Start of drilling: 0.1407 m End of drilling: 0.1384 m	Start of drilling: 0.1407 m End of drilling: 0.1366 m	Start of drilling: 0.1405 m End of drilling: 0.134 m	Start of drilling: 0.1405 m End of drilling: 0.1389 m	Start of drilling: 0.1408 m End of drilling: 0.1377 m
Collaring point coordinates (system SWEREF 99 RH2000)	Northing: 6698418.32 m Easting: 160094.17 m Elevation: 4.21 m.a.s.l.	Northing: 6698537.92 m Easting: 160064.53 m Elevation: 4.33 m.a.s.l.	Northing: 6699322.21 m Easting: 161395.20 m Elevation: 2.94 m.a.s.l.	Northing: 6699603.14 m Easting: 161117.22 m Elevation: 3.86 m.a.s.l.	Northing: 6699951.07 m Easting: 161324.55 m Elevation: 1.70 m.a.s.l.

5.2 Geometrical design of the percussion drilled boreholes

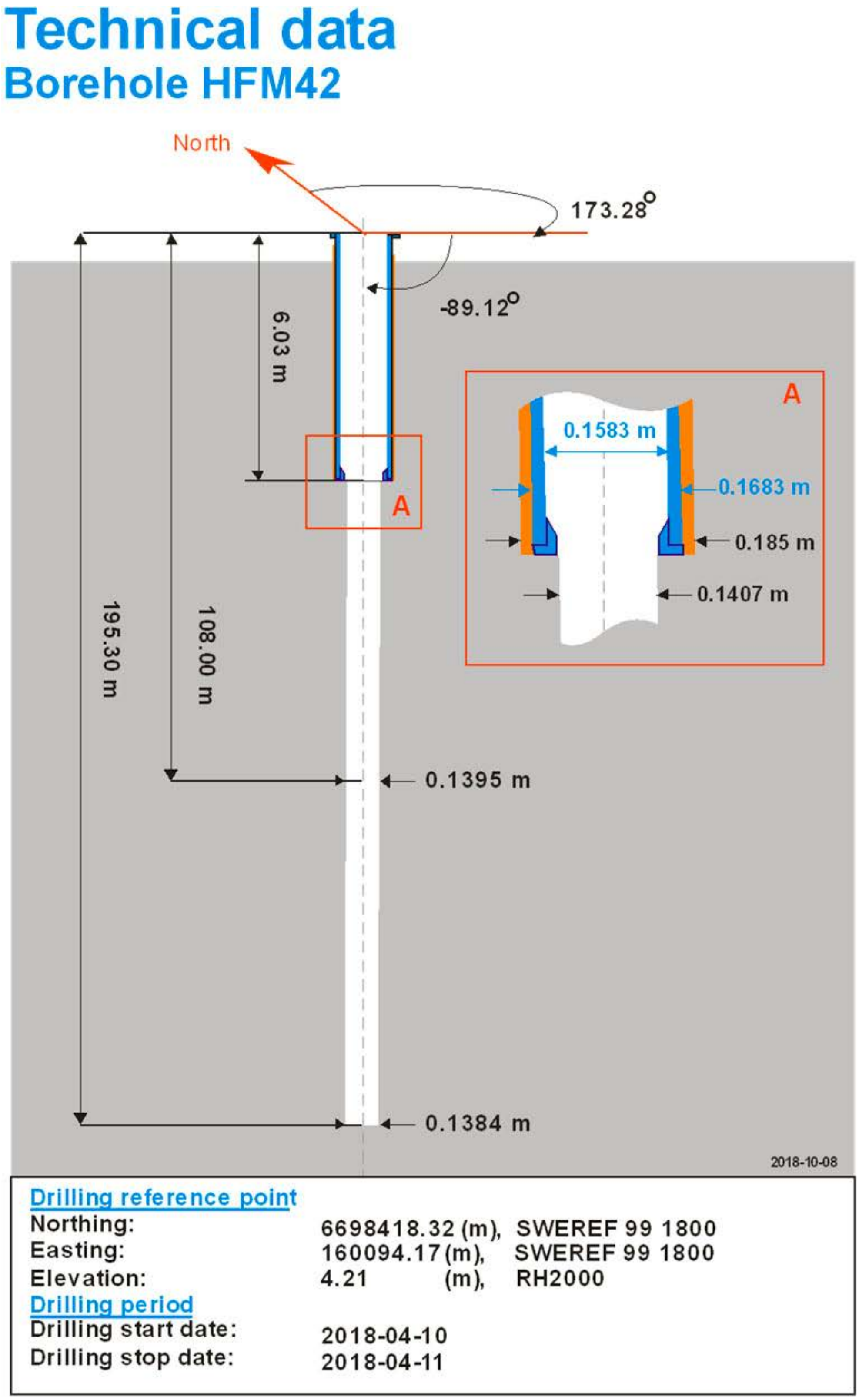
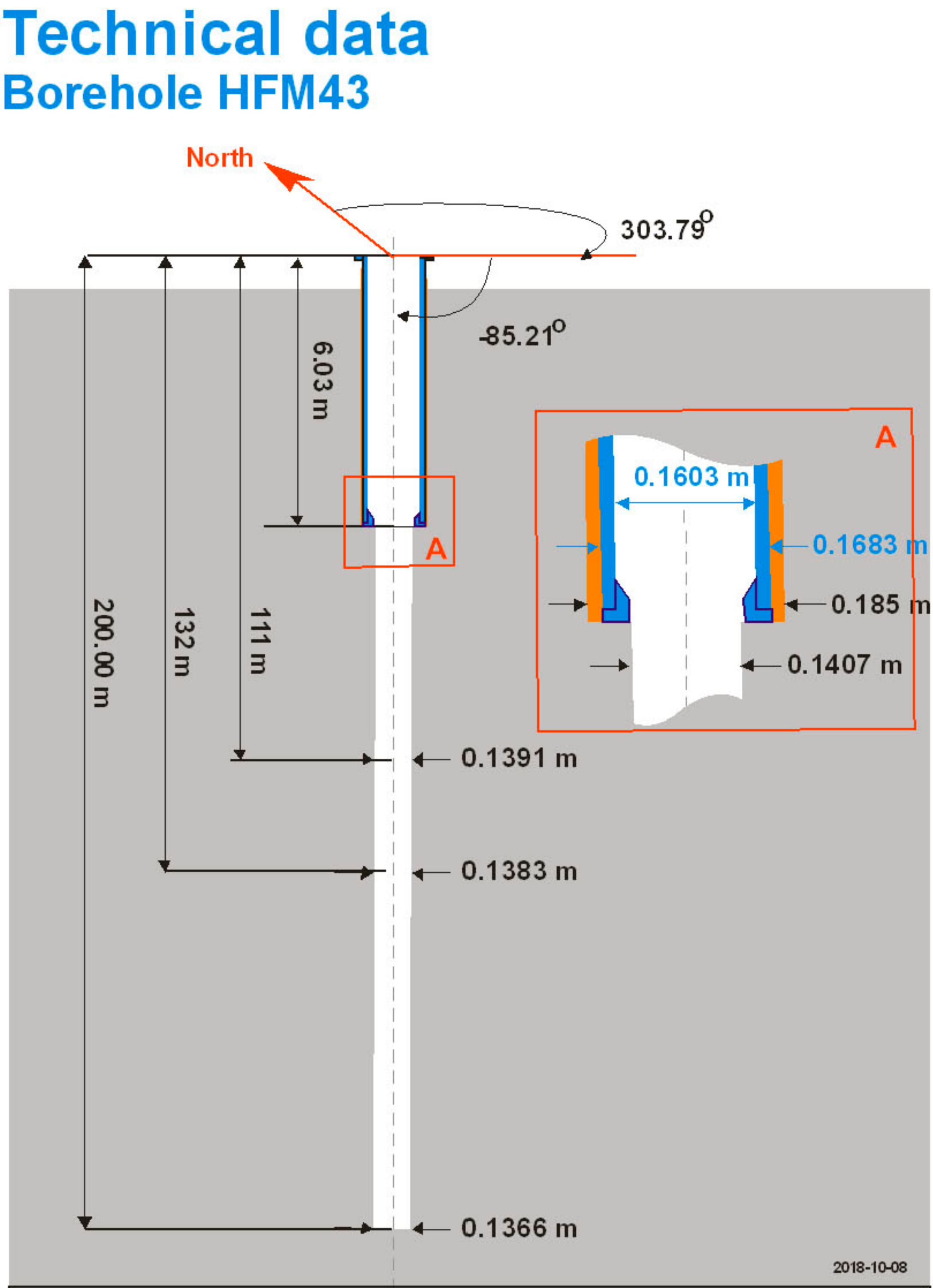


Figure 5-1. *Technical data for borehole HFM42.*



Drilling reference point

Northing:	6698537.92 (m), SWEREF 99 1800
Easting:	160064.53 (m), SWEREF 99 1800
Elevation:	4.33 (m), RH2000

Drilling period

Drilling start date:	2018-04-17
Drilling stop date:	2018-04-23

Figure 5-2. *Technical data for borehole HFM43.*

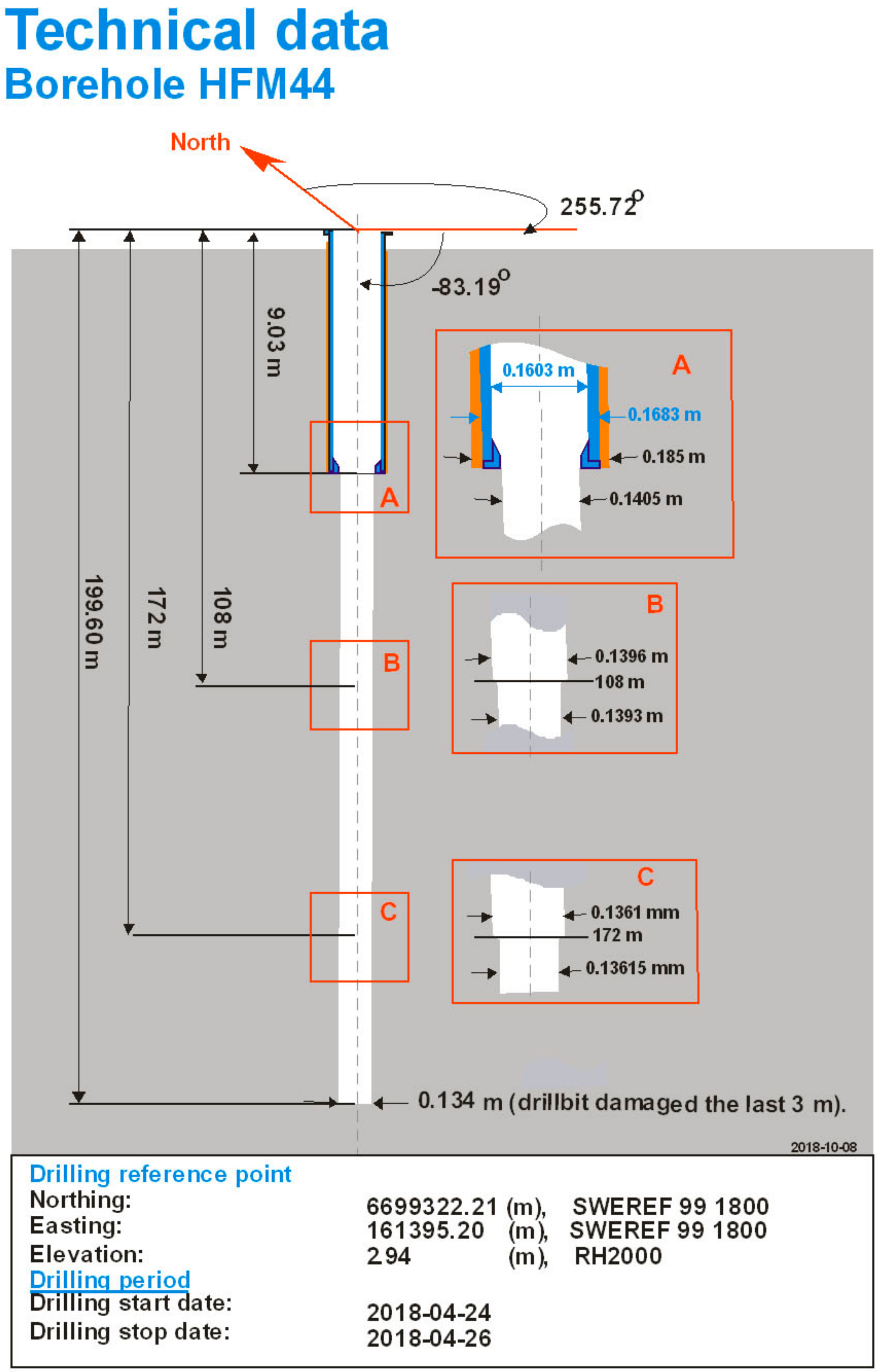


Figure 5-3. *Technical data for borehole HFM44.*

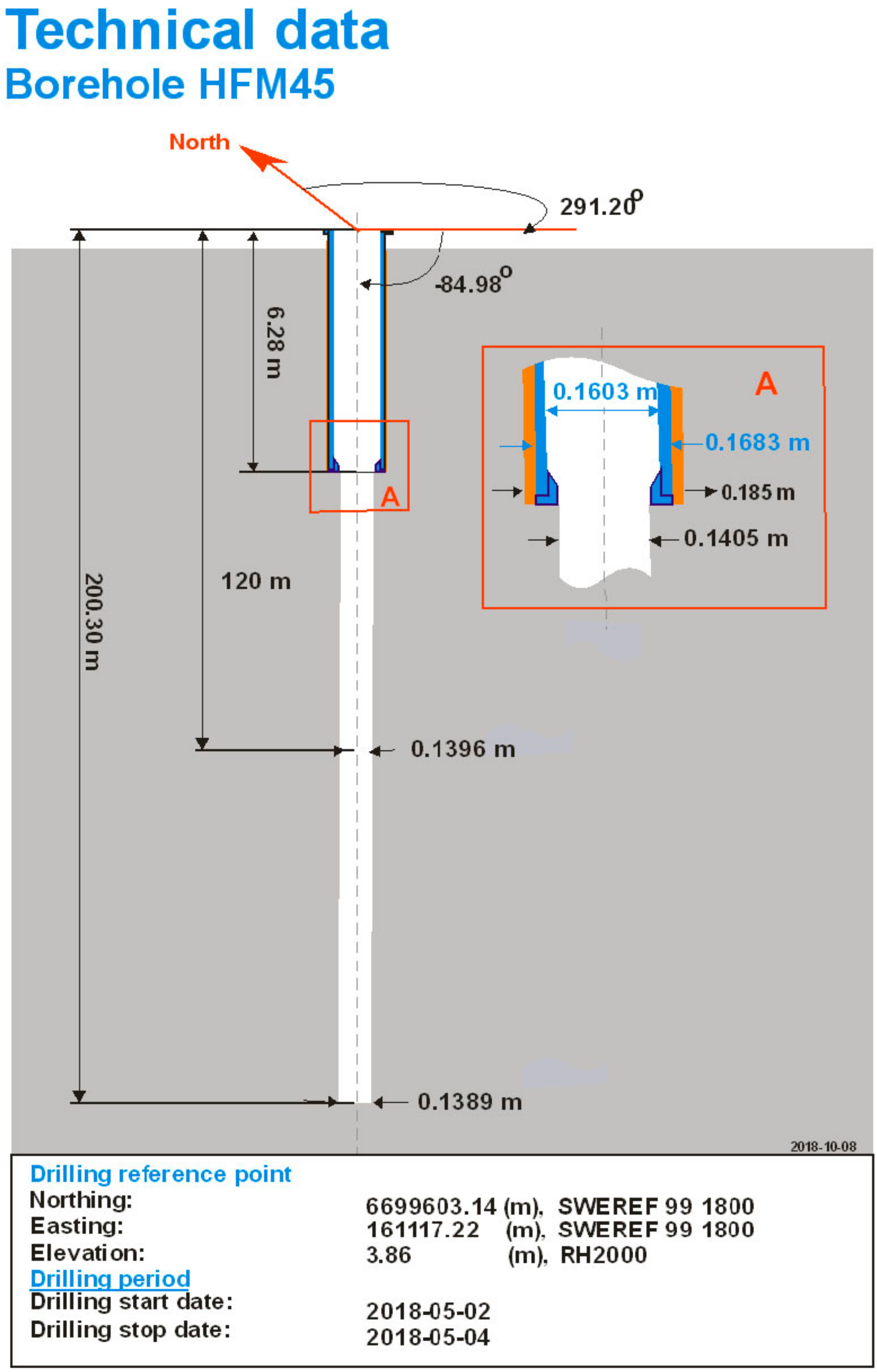


Figure 5-4. *Technical data for borehole HFM45.*

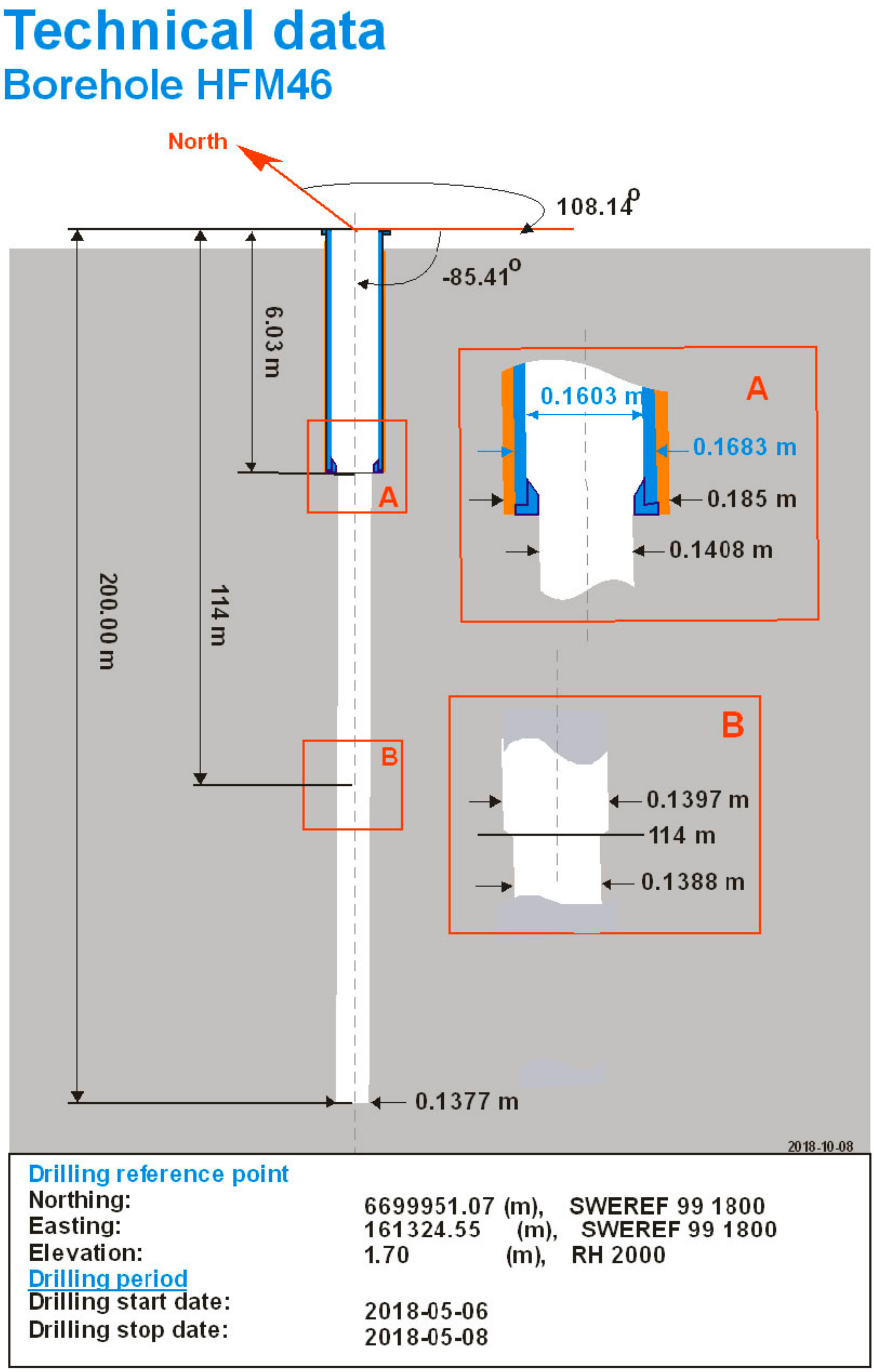


Figure 5-5. *Technical data for borehole HFM46.*

5.3 Deviation measurements

The principal method applied for deviation measurements in percussion drilled boreholes is based on magnetic-accelerometer technique. For the five boreholes in solid rock described in this report, the FLEXIT Smart tool system was used. To ensure high quality measurements with the FLEXIT tool, the disturbances of the magnetic field at the site have to be limited. A measuring station in Uppsala gives one-minute magnetic field values available on the Internet at www.intermagnet.org and provides sufficiently accurate information. The magnetic field variations on April 12th, April 24th, April 27th, May 5th, and on May 09th, 2018, are displayed in Figure 5-6, and show only minor disturbances when the FLEXIT surveys in HFM42 (between 3:00 and 4:00 PM), in HFM43 (6:00 and 7:00 PM), in HFM44 (8:00 and 10:00 AM), in HFM45 (08:30 and 09:30 AM), and in HFM46 (10:00 and 11:00 AM) were performed.

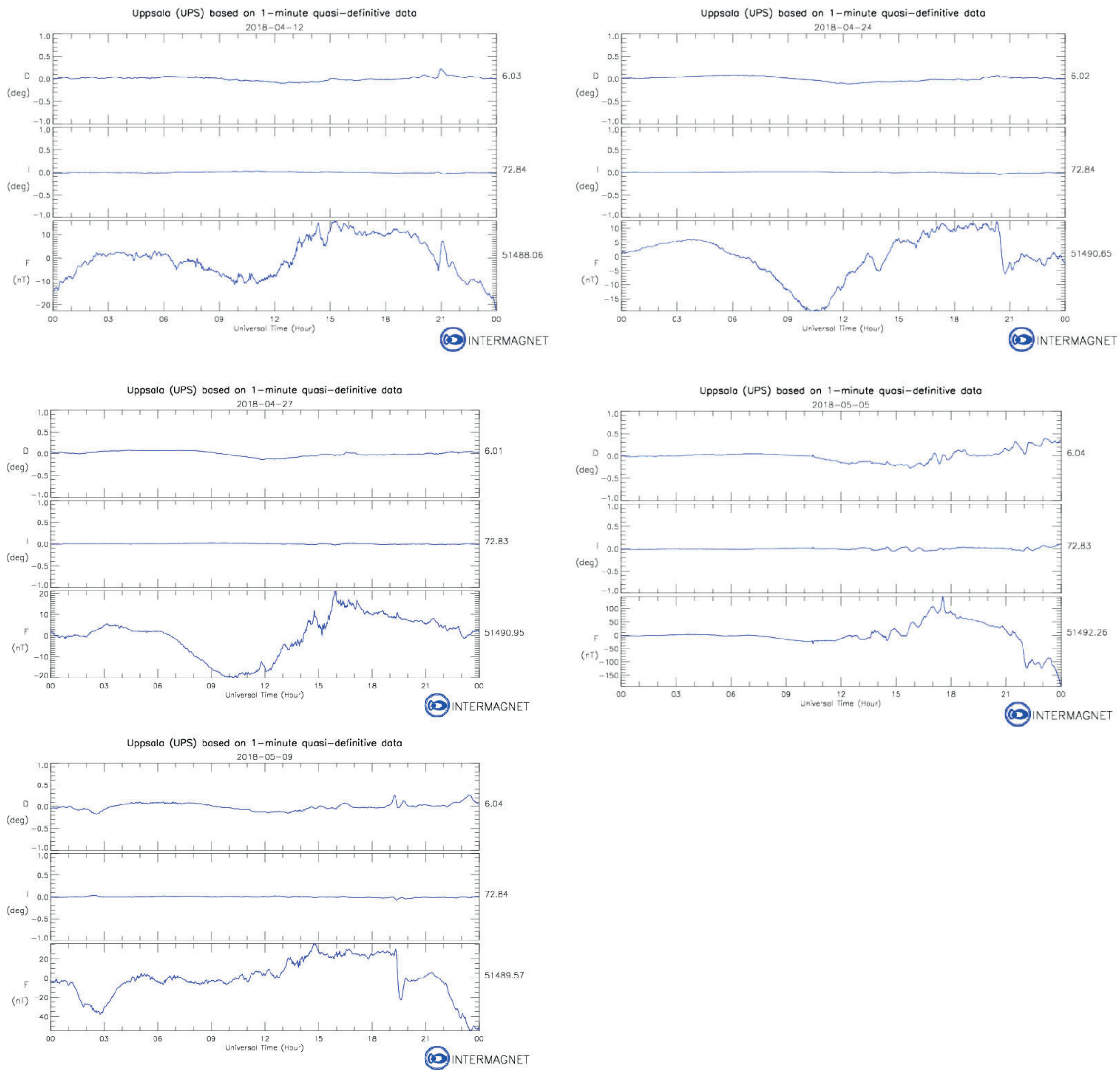


***Figure 5-6.** Magnetic field variation during the FLEXIT survey performed on April 12th, 2018, in HFM42, on April 24th, 2018, in HFM43, on April 27th, 2018, in HFM44, on May 5th, 2018, in HFM45, and on May 9th, 2018, in HFM46.*

The deviation measurements in the five boreholes were carried out every 3 m downwards and upwards, to 192 m borehole length in HFM42 and to 198 m borehole length in HFM43, HFM44, HFM45, and HFM46, respectively.

It was important that borehole HFM42 became vertical in order for the later on installed geophones to function optimally. The deviation calculations (EG154-file) for borehole HFM42 show that the borehole deviates upwards with an absolute deviation of 5.2 m (see Figure 5-7) compared to an imagined straight line following the dip and strike of the borehole start point. Uppsala University, which was responsible for installation of the geophones, approved the borehole deviation, and the installed instruments worked as expected.

The deviation calculations (EG154-file) for borehole HFM43 show that the borehole deviates upwards and to the left with an absolute deviation of 19 m compared to an imagined straight line following the dip and strike of the borehole start point.

The EG154-file from borehole HFM44 displays that the borehole deviates downwards and to the left with an absolute deviation of 10.3 m compared to an imagined straight line following the dip and strike of the borehole start point. The borehole is though almost straight in the horizontal direction.

The EG154-file from borehole HFM45 illustrates that the borehole deviates upwards and to the left with an absolute deviation of 9.4 m compared to an imagined straight line following the dip and strike of the borehole start point.

Finally, the calculated deviation (EG154-file) for borehole HFM46 demonstrates that the borehole deviates upwards and to the right with an absolute deviation of 13 m compared to an imagined straight line following the dip and strike of the borehole start point.

The "absolute deviation" is here defined as the shortest distance in space between a point in the borehole at a certain borehole length and the imaginary position of that point if the borehole had followed a completely straight line with the same inclination and bearing as that of the borehole collaring.

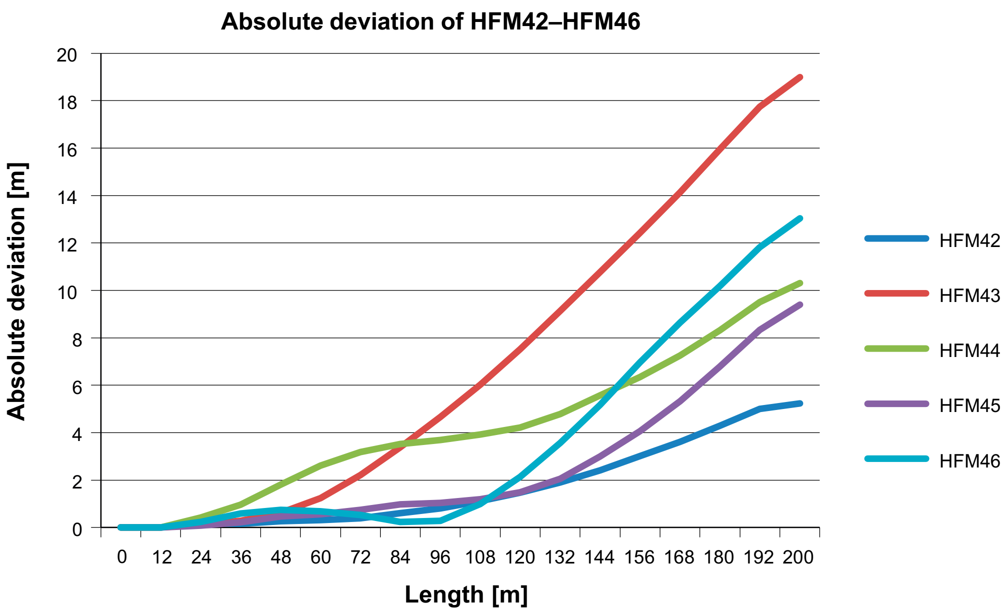


Figure 5-7. *The figure shows the absolute distance defined as the shortest distance in space between a point in the borehole at a certain borehole length and the imaginary position of that point if the borehole had followed a straight line with the same inclination and bearing as that of the borehole collaring.*

5.4 Hydrogeology

5.4.1 Observations during drilling

Generally, the upper section (down to about 200 m) of the bedrock within the Forsmark area contains water yielding fractures, resulting in very large water-inflows, up to several hundred L/min, in many of the existing percussion drilled boreholes in the area. However, HFM42, located close to drill site no. 7 (DS7), seems to represent an exception from the rule. During drilling of the borehole, a minor water-inflow of 15 L/min was observed at 91 m, and air flushing at the final depth 195.3 m resulted in an accumulated inflow of 18 L/min. This discharge is, however, in the context of drilling for drinking water supply a considerable well capacity, but rather limited compared to that of many other percussion drilled boreholes at the Forsmark site.

An obvious hydraulic connection between HFM42 and the neighbouring borehole HFM21 (Claesson and Nilsson 2004) was verified, since the drilling performance of HFM42 caused a significant draw-down in the lower sections in HFM21, see Figure 5-8. Later, when flow-logging was carried out in HFM42, pumping indicated a much higher water inflow in HFM42 than previously, probably due to that water-yielding fractures were cleaned from drilling debris during these pumping activities.

At 96 m drilling length in borehole HFM43, an inflow of 100 L/min was encountered. When drilling continued, the accumulated groundwater inflow rapidly increased to 400 L/min. When drilling restarted at c 114 m, the accumulated water inflow rate increased even more, to at least 600 L/min, see Figure 5-9.

Boreholes HFM44, HFM45 and HFM46 are located outside the tectonic lens. HFM44 was drilled close to the car parking place at the SKB office (Vega), see Figure 1-2. At c 70 m, an inflow of 320 L/min was observed. When drilling continued, the accumulated groundwater inflow increased to 500 L/min at 164 m drilling length, see Figure 5-9.

In HFM45 a minor inflow of 5 L/min was measured at 120 m drilling length. No other inflow during drilling was observed, but when air-flushing at the borehole bottom (at 200 m) was carried out, the inflow had increased to c 100 L/min, see Figure 5-10.

Finally, in HFM46, an inflow of 32 L/min was encountered at 76.5 m length. The inflow rapidly increased to 400 L/min at 164 m, see Figure 5-10.

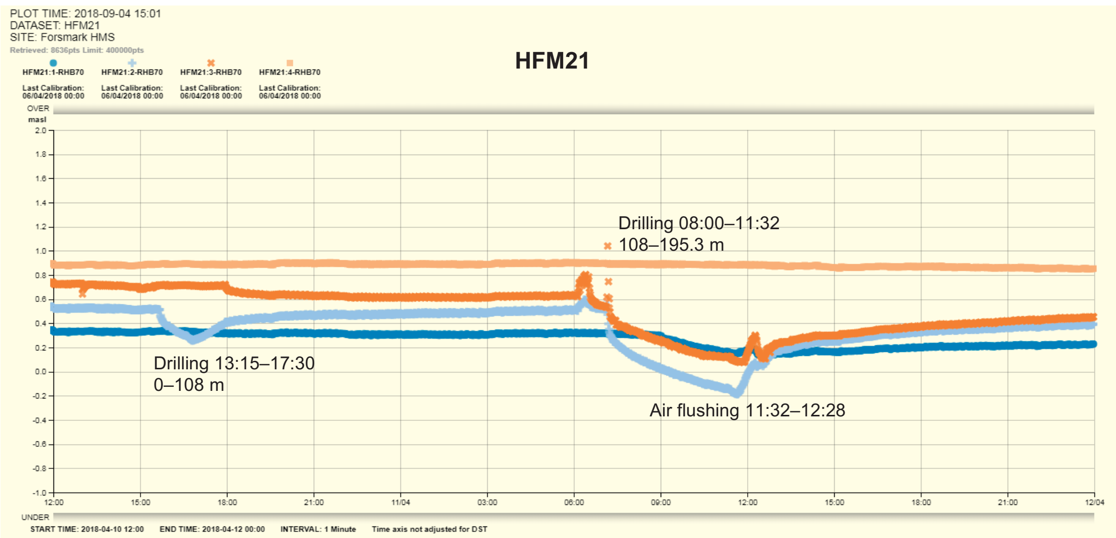


Figure 5-8. *HMS Monitoring. A significant draw-down was observed in the nearby situated borehole HFM21 during drilling and cleaning of the percussion borehole HFM42.*

Figure 5-9. *Left: In HFM43 the water inflow was measured with a stopwatch and a 200 L measuring vessel. A water inflow of 600 L/min was observed at 114 m drilling length. Right: In HFM44 the accumulated water increased to 500 L/min at 164 m drilling length.*

Figure 5-10. *Left: In HFM45 the accumulated water inflow increased to c 100 L/min at the complete borehole length, 200 m. Right: In HFM46 the accumulated water inflow increased to 400 L/min during air flushing at the final drilling length at 200 m.*

5.5 Location of geophones and fibre in HFM42

On August 8th, 2018, all equipment, two fibre cables and three geophone, where installed in borehole HFM42. The two fibre cables, ∅25 mm and ∅6.5 mm, were fastened to a steel pipe with cable ties for each m. As the pipe was lowered into the borehole, three geophones were mounted at 188 m, 74 m, and 6.5 m borehole length, respectively.

On August 9th grouting of the entire borehole was carried out. Fortunately, four tons of cement was delivered to the drill site, because it required 3 933 L to fill the entire borehole. The theoretical volume of the borehole minus the installation is approximately 2 800 L. That is, approximately 1 100 L of grout was injected into fractures in the surrounding bedrock.

A detailed description of preparations, installation and grouting in HFM42 is given in Appendix 1.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

Claesson L-Å, Nilsson G, 2004. Forsmark site investigation. Drilling of two flushing water wells, HFM21 and HFM22, one monitoring well in solid bedrock, HFM20, and one groundwater monitoring well in soil, SFM0076. SKB P-04-245, Svensk Kärnbränslehantering AB.

SKB, 2016. Detaljundersökningsprogram vid uppförande och drift av Kärnbränsleförvaret. SKB R-16-10, Svensk Kärnbränslehantering AB. (In Swedish.)

Appendix 1

A1.1 Background

To get a better knowledge of the geologic characteristics of the upper part of the bedrock at Söderviken, where ramp and shaft for the repository will be built, see Figures 1-1 and 1-2, a detailed reflexion seismic survey of the area is planned to be performed. For installation of geophones, the project needed a vertical borehole drilled as straight as possible. In connection with this investigation, SKB also intends to test fibre technology, now commonly used in the oil industry. The advantage of this technology is that it delivers data continuously throughout the entire borehole length. In addition to measuring the temperature, it is of interest to investigate whether the fibre also can record and identify the different sound waves generated during the seismic survey.

A1.2 Installation and grouting

When the 195.3 m long vertical borehole HFM42 was drilled in April 2018, the ground surface at Forsmark was still covered with snow, and the temperature was below zero, at least during the night. However, when the installations of two fibre cables and three geophones were conducted, and the borehole thereafter grouted in August 2018, the temperature was almost 30° C, see Figure A1-1.

Originally, the installations were planned to be carried out in June 2018. However, they were delayed due to both late deliveries and broken equipment. Finally, the installations could eventually be executed on August 7th–9th, 2018. The installations in HFM42 included different kinds of equipment provided by three different suppliers, supported by SKB staff and assisting contractors.

- Fiber technology: Silixa Ltd, England.
- Data analysis: Hydroresearch AB.
- Seismic equipment: Uppsala University.

To obtain a high quality of measurement data in the planned seismic survey, it was necessary to perform a robust installation in the borehole. As field staff from Silixa had long experience for installation of fibre cables in projects for the oil industry, and they supported with precise advice, that were adopted by SKB so that careful preparations could be undertaken, see Figure A1-1 and A1-2.

A two-stage working podium above the borehole provided enough space for mounting the equipment. This was especially valuable for installing the fibre cables for which too much bending must be avoided, see Figure A1-1. From the upper stage, the six meter long grouting tube (∅33 mm) could easily be placed in the hole, while the crew fasten the fibre cables with tape and cable ties for every metre. To protect the ends of the fibre cables, a bull-nose was welded on the first pipe, and for extra safety, when lowering the installations into the borehole, an 8 mm steel wire was attached to the steel pipe, see Figure A1-2.

On August 8th all equipment, two fibre cables and three geophones, where installed in the borehole. The two fibre cables, ∅25 mm and ∅6.5 mm, were fastened to a steel pipe with cable ties for each m. As the pipe was lowered into the borehole, three geophones were mounted at 188 m, 74 m, and 6.5 m, respectively.

Finally, after connecting the computers to the cables, the crew confirmed that all sensors functioned, entailing that the final step with grouting the borehole could start.

By using a cement receipt with VCT 0.8 (50 kg cement and 40 L water), a viscosity was obtained that has a good filling capacity, and which is quite easy to pump. As soon as the grouting starts, it is very important to keep the cement moving through the tube and then fill the complete borehole from the bottom and upwards.

On August 9th, 2018, grouting of the entire borehole was carried out. By using two separate mixers it was possible to keep a constant pumping flow into the borehole, see Figure A1-3. By studying the temperature data delivered from the fibre cable it was possible to observe how the grout raised in the borehole during the grouting sequence. Four tons of cement was delivered to the drill site, which turned out to be a necessary amount, because it required 3 933 L to fill the entire borehole. The theoretical volume of the borehole minus the installation is approximately 2 800 L. That is, approximately 1 100 L of grout was pumped out into fractures in the surrounding bedrock.

Figure A1-1. *Left: When performing drilling of HFM42, the ground surface was covered with snow (April 2018). Right: Installations in HFM42 from a two-stage podium. On August 8th the temperature had raised to 30° C.*

Figure A1-2. *Left: A steel wire was attached to the steel pipe (grouting tube) and welded together with a bull-nose aimed to protect the ends of the two fibre cables. Right: The two fibre cables were fastened to a rod with cable ties for each m. As the pipe was lowered into the borehole, three geophones were mounted at 188 m, 74 m, and 6.5 m borehole length.*

Figure A1-3. *To the left: The completed cement paste was poured into a screw pump that pressed the paste into the pipe so that the borehole was filled from bottom and upwards. To the right: As the cement rose in the borehole, the water column was lifted at TOC, meaning that the entire borehole had been injected.*

Arkitektkopia AB, Bromma, 2018

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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