MSF Environmental Health Toolkit

Technical training Manual on Borehole Drilling and Construction

Tool kit component 1.3

MSF Mission Zimbabwe

Contents

1- Introduction

The purpose of this manual is to assist MSF field engineers and Environmental Health experts to supervise boreholes drillings for providing sustainable water points to the communities. The manual is a practical guide to MSF standard drilling techniques and implementing drilling programs in places with a hydrogeological potential. It provides a step by step methodology based on the experiences in drilling boreholes in peri-urban and urban settings in Harare, Zimbabwe. Drawing on these experiences and using the expertise available within the countries, programs can be tailored to the needs and the means of different country programs.

2- Preliminary

2.1- Collection of data/information

Prior to drilling intervention, certain number of technical, financial and logistical factors must be taken into account to ensure its feasibility. The hydrogeological potential of the zone must be assessed to determine the type of drilling rig and drilling techniques, the foreseeable flows and the chances of success. It is highly recommended to gather the existing geological and hydrogeological literatures, the boreholes data of the target location and National Drilling Protocol of the country.

The borehole drilling reports gives valuable information on depths of the existing boreholes, static water level, borehole yield, presence and depth of different aquifers, water quality both chemical and bacteriological and on the design and construction of the boreholes. In areas, with no prior hydrogeological information and the area with a difficult hydrogeological context, (i.e. with little or no aquifers and multi layered aquifers with saline water levels), it is advisable to drill prospection boreholes to indicate the presence and quality of the ground water and nature of the aquifers present. This also allows calibration of readings taken during the geophysical exploration. Such prospections boreholes are drilled using a smaller diameter drill bit (max up to 100 mm) and after prospection phase are either maintained as piezometers, or blocked or abandoned.

The possibility of finding locally a drilling rig and borehole construction material is an important factor to take into consideration, as this could seriously impact the program by delaying the overall intervention. Accessing the skills of local drillers and means of transport to move from site to site is an important phase of assessment.

2.2- Drilling protocol

MSF drilling protocol shall also be in alliance with the national drilling protocol of the country. If MSF drilling protocols clashes with the national one, it is advised to have a meeting with the authorities to brief them on the differences and the importance of MSF drilling protocol. An agreement shall be attained before the start of the drilling intervention.

2.3- Selection of drilling companies

Experienced drilling companies with competent staff and good equipment are crucial for the successful completion of the intervention. Before starting any intervention it is strongly advised to do a proper market survey to identify potential contractor for the job. Ensure that pre-qualification lists are put into the public domain, such as the Newspaper or website for the tender process.

2.4- Drilling contract

The drilling contract includes all the specifications needed for drilling and construction of the borehole according to MSF drilling standard. This includes the choice of the right drilling technique in accordance with the geology of the ground, drilling to the identified depth based on the information acquired through geophysical survey, installation of a proper sanitary seal, lowering of borehole assembly with PVC casings, screen and end cap, gravel pack, cleaning and development of boreholes, pump tests, borehole disinfection and water quality testing both chemical and biological. At the end of the intervention the contractor shall provide a complete borehole drilling report including; well identification and location, drilling information, formation log, yield test, well completion and any additional relevant information.

2.5- Contractors drilling equipment

It is strongly advised to visit the contractor and examine their equipment prior to the drilling intervention. Its capacity shall be sufficient to cope with the works as stated in the Contract. The equipment shall at all times be kept in full working order and good repair.

If the MSF staff considers that the drilling equipment or any accessories in use on the site are unsuitable, inefficient or inadequate in capacity, he/she has the right to call upon the contractor to put such equipment in good or alternatively to remove such plant and replace it with additional plant or equipment to meet the requirements of the contract. In the event that this requirement of the contract is not satisfied, the MSF personal reserves the right to terminate the Contract immediately. No extra payment shall be made to the contractor for the change of drilling equipment, labor or other equipment required completing the specified works.

2.6- Site selection

A proper geophysical survey should be conducted to identify the potential sites for drilling of a borehole. The drilling site should be socially accepted by the communities and ideally should be close to the target population and in no case more than 500 m from the beneficiaries. The site should definitely not be in a place that gets flooded in the rainy season and should be away from the flood plain area of any streams or rivers in the locality. Special care must be taken to ensure that the sites chosen are at least 30 meters away from toilet pits or any other sources of pollution such as grave yard, stagnant pools of dirty water or animal pens. The site should have a free passage for the movement of drilling rig and have enough space for making other installation during the drilling intervention. For further details on siting boreholes using geophysical techniques please consult "*EH Tool Kit component 1.4*"

3- Drilling techniques

Several techniques of drilling for water have been developed to suit the type of borehole required and the geological context. Rotary and "down-the-hole" (DTH) hammer techniques are the most widely used and are the most suitable in drilling for water.

3.1- Rotary drilling

The rotary technique is used only in unconsolidated sedimentary formations. A rotary drill bit also known as a tri-cone is used during the mud rotary drilling. The circulation of the drilling mud brings the cuttings up to the surface. Rotary drilling can be carried out using only air. This technique allows quicker drilling and can sometimes get to a good depth in dry and stable formations. If water is reached however, drilling becomes more difficult, with increased risk of collapse, and here mud drilling must be used. This technique is also often applied over the first few meters of the borehole (10-20 m) to ensure that the borehole side formations are stabilized.

Figure 1: 260 mm tri-cone drill bit used for mud rotary drilling in top unconsolidated formations

Drilling mud

The drilling mud is made up of water, clay (bentonite) or a polymer and it moves in a closed circuit during the drilling process. The drilling mud is injected down the center of the hollow drill pipes to the level of the drill bit and returns to the surface via the annular space between the drill pipes and the sides of the hole. When it arrives at the surface, it is channeled into a series of pits or a mud pan with different chambers, which allows the cuttings to settle down and the mud is then re-pumped and injected under pressure down the drill string.

Drilling mud plays an essential role in the drilling process: it brings the cuttings to the surface, stabilizes the sides (by covering the borehole sides) and lubricates the drill bit. The intrinsic characteristics of drilling mud (density, viscosity) are regularly checked and modified during the drilling process. The density of the drilling mud influences the transport of the cuttings to the surface and the stabilization of the borehole sides. Heavy drilling mud has better transport properties, and the cuttings float better. The viscosity influences the lubrication of the drill bit as well as the transport of the cuttings (thrusting effect).

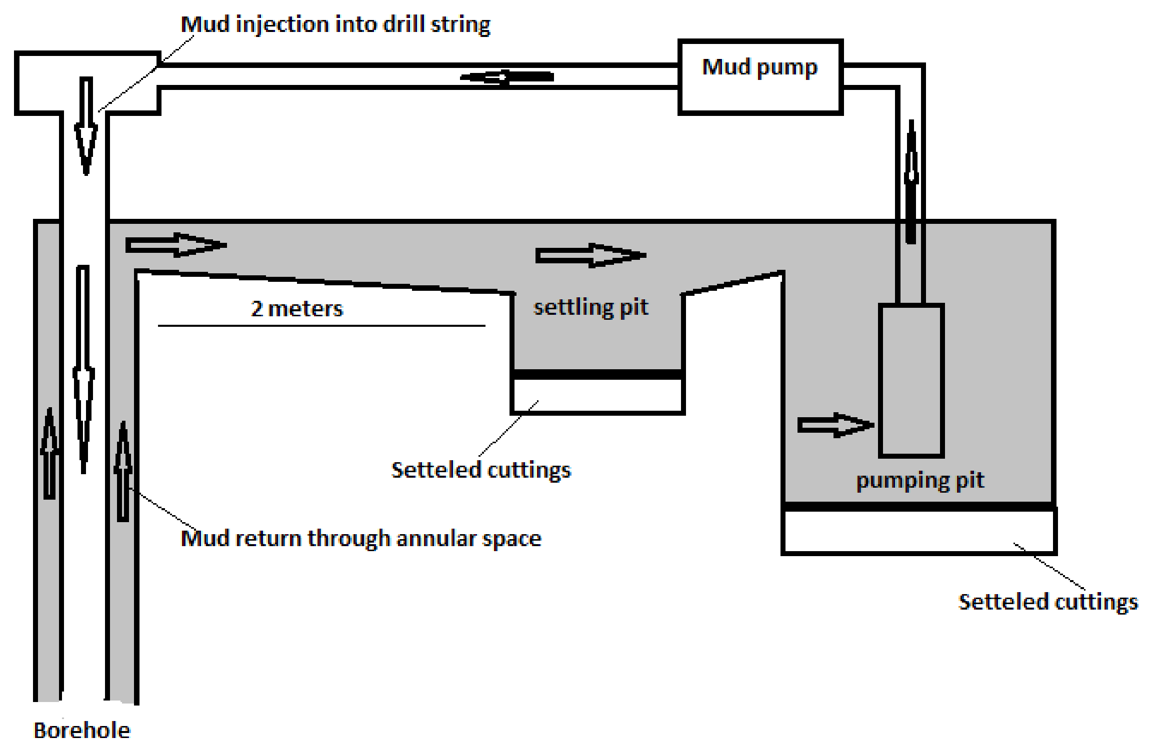
Mud pits

Two mud Pits are used while mud drilling technique; the setting pit and the pumping pit. The drilling mud coming out from the borehole first passes through the settling pit, allows the sediments to settle down while allows the drilling mud to move to the pumping pit from where the mud is pumped back into the borehole. The dimensions of the mud Pits are calculated bearing in mind the depth of the borehole to be drilled. Ideally, the total volume of the pits must be equal to three times the volume of the borehole, with (dimensions in m).

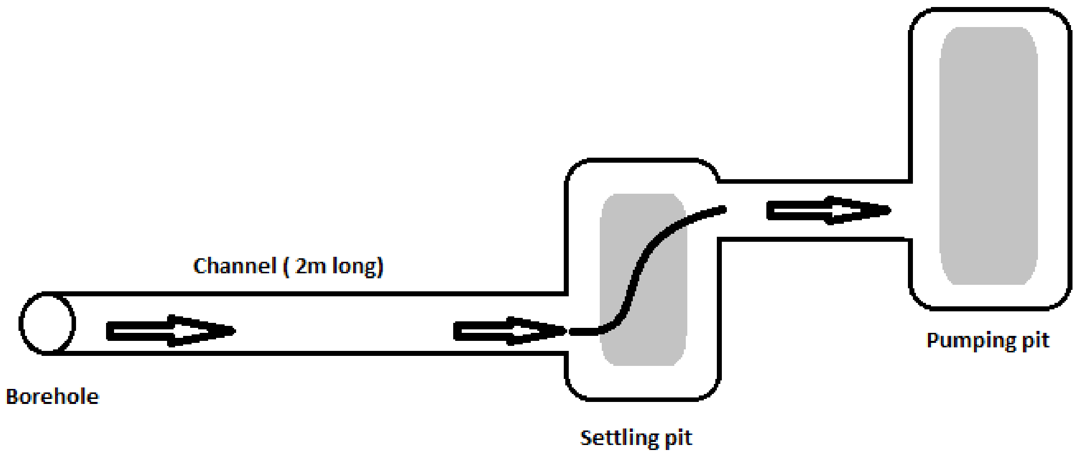
Mud pit design

Settling pit	Pumping pit
Width = as for the settling pit	Width = 3√ (volume borehole in liters x 0.57)
Length = 2.5 x width	Length = 1.25 x width
Depth = 0.85 x width	Depth = 0.85 x width

A first channel of 2 m in length and 0.20 x 0.20 m cross section is dug from the location chosen for the borehole, emptying into the first pit. It must be long enough for the pit to be beyond the edge of the slab of the future water point in order to avoid differential settling under the slab. The first pit (settling pit) facilitates the sedimentation that is started in the channel. The axis of the second channel must be offset from that of the first one, so as to deflect and attenuate the flow to facilitate settling. The second pit (pumping pit) is a reservoir from which the drilling mud is pumped to be injected into the drill string. The pits and channels are regularly scraped out and cleaned of sediments formed in the course of the drilling process.


Mud injection into drill string
Mud pump
2 meters
settling pit
Setteled cuttings
pumping pit
Mud return through annular space
Setteled cuttings
Borehole

A



B

Figure 2: Mud Circulation: A: Plan View; B: section view

Mud pan

A mud pan comprised of different compartments can be used for mud drilling intervention. Different compartments in the mud pan serves as a settling and pumping pit. The cuttings from the steeling and pumping compartments are constantly removed to have the space for the free movement of drilling mud.

Figure 3: Mud pan for mud rotary drilling

3.2- Down-the-hole (DTH) hammer drilling

This technique allows drilling in hard formations. A cutter with tungsten carbide buttons, fixed directly onto a pneumatic hammer (DTH), is rotated with a hammer action to break and grind the rocks. Using compressed air delivered by a compressor, the cuttings are brought to the surface. The drilling process comprise of two phases; percussion and blowing.

Percussion: The compressed air operates the piston of the hammer, which strikes the drill bit pressed on the rock; part of the air then escapes into the annular space, carrying the cuttings with it.

Blowing or removal of the cuttings: The drill bit is withdrawn slightly, so that all the air flow passes around the hammer without operating it, and then escapes into the annular space.

Figure 4: 6.5” DTH hammer drill bit attached to a drill rod

3.3- Drilling fluids

Drilling fluids are either lubricated air (with or without foam) for use with DTH hammers, or water incorporating a given amount of drilling mud for rotary drilling. These fluids play several roles, summarized in the tale below:

Drilling technique	Type of fluid	Role of the fluid
Rotary	Drilling mud: – water – bentonite – polycol	Cuttings removal Binding and stabilising the sides (cake formation) Lubrication, cooling of the drill string and drill bit
DTH	Lubricated compressed air Lubricated compressed air + foam (foaming agent)	Operating the hammer Improved cuttings removal (blowing) Lubrification of the hole

4- Borehole drilling intervention

The borehole drilling protocol mentioned below refers especially to drilling boreholes in urban settings, where anthropogenic pollution is high. The borehole is drilled with telescopic diameters, to put in place a good thickness of sanitary seal in the top formations followed by the placement of permanent casing and gravel pack. This drilling protocol needs to be adapted according to different context; however the principle of using different borehole drilling techniques remains the same.

4.1- Choice of the right drilling technique

The choice of the drilling technique depends on the nature of the formations to be drilled but also on their water contents. The collected data including the existing borehole drilling reports can give a clear identification on the nature of the ground and type of drilling technique to be used. The table below gives an indication of the drilling technique to be used based on visual geology of the ground.

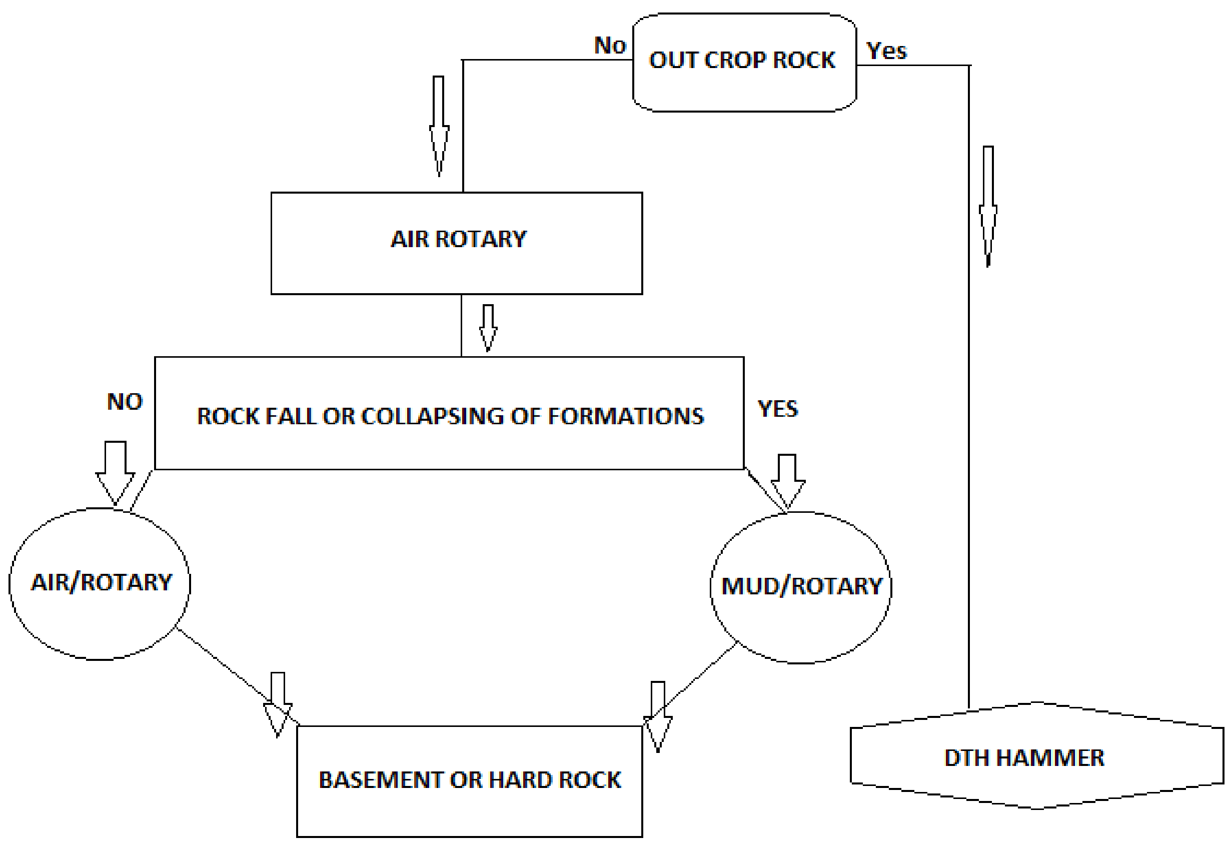


Figure 5: Flow chart for selection of drilling technique

4.2 - Site preparation

Following points shall be taken into consideration while preparing the site for the borehole drilling

- Clearly delimited work zone, with a fence if necessary
- Access for vehicles
- Water supply (water tanks)
- Area for digging of mud pits or placement of mud pan
- An area for writing work
- An area to preserve the borehole cutting
- A leveled area to facilitate setting of the machine vertical
- Positioning the compressor so that it is not exposed to drilling dust (do not locate it down
- wind of the borehole)
- Installation of all pumping units, hydraulic pressure units, and engines on a horizontal surface

4.3- Drilling of a pilot hole

A borehole drilling shall start with drilling a pilot hole. The type of the drilling technique used depends on the nature of the ground. In consolidated formations, a smaller diameter drill bit i.e. 4”drill bit using DTH hammer is advised. The small diameter drill bit allows fast penetration in the ground. If not available, a 6.5” drill bit should be used to drill till the final depth. The pilot hole allows understanding the type of subsurface formations and depth of water bearing formations (both shallow and deep).

4.4- Analysis of cutting

The cuttings which come to the surface are a source of essential information: their geological analysis helps to identify the formations traversed, and to know their nature, whether they are permeable (indicating a reservoir) and capable of providing water. Normally the cutting samples are collected at each meter of the borehole drilled. They are then preserved in plastic bags marked with the name of the borehole and the depth at which the sample was taken. In mud rotary drilling, the samples are always covered in drilling mud, which makes them difficult to interpret, so they have to be rinsed with clean water before analyzing.

Generally, the bigger the cuttings, the more friable the drilled formation is, and the finer they are (dust), the harder the drilled rock is. The presence of fractures is usually identified by larger cuttings. Additionally, any signs of erosion on these cuttings could indicate a water flow (current or historic).

Figure 6: Borehole cuttings during drilling of the pilot hole (DTH hammer drilling technique)

4.5- Back filling of the pilot hole

Pilot hole gives the first impression of the subsurface and a rough idea on the yield of the aquifers present. It also helps in taking early decision i.e. if it's necessary to continue the drilling process or abandoned the drilled hole as the hole is dry or the amount of water is not sufficient.

This also helps in identifying the depth of both shallow and deep water aquifers. Shallow water aquifers can be highly contaminated in the urban setting because of anthropogenic pollution. Such aquifers shall absolutely be sealed properly so no water from such aquifers can contribute to the water from the borehole.

If the decision is taken to move ahead with the drilling process, the pilot hole is back filled with the clean river sand up to the desired height. This is to make sure that all the productive aquifers/zones of interest are protected by river sand leaving behind the shallow water aquifers, which needs to be sealed. This is an important process as during further reaming of the pilot hole, the clay/impermeable cutting can fall back into the pilot hole, hence blocking all the productive aquifers. Also during the process of putting in place the sanitary seal, the drilled hole has to be closed in order to stop the grout sinking back into the hole hence sealing all the zones of interest.

4.6- Widening of the pilot hole

Using DTH hammer

The drilled pilot hole is then further reamed with a 300 mm diameter drill bit up to the depth where the river sand closes the hole. This is done to have a big diameter hole in the top 10 to 20 meters, to ensure a good thickness of the sanitary seal in the upper part of the borehole.

Using mud rotary technique

A 300 mm tricone bit shall be used for mud rotary drilling in the top unconsolidated formations to get a good annulus for the placement of sanitary seal. In rotary mode, the risk of erosion of the borehole sides and collapsing is reduced, even at great depths, because the drilling mud stabilizes the sides by caking.

Preparation of drilling mud for mud rotary drilling

In clay formations, it is preferable to drill with water only, to avoid blocking the aquifer. The water will become loaded with clay from the ground as drilling proceeds. If there is no reliable information about the nature of the formations to be drilled, the drilling water must be mixed with bentonite or a polymer to increase its density. Polymer is normally mixed in a proportion of 2.5 to 5 kg per m3 of water but it's always advised to check the specifications written on the user document for the quantity of polymer to be used.

Clean water should be used for drilling mud. It is essential to have a 5 – 10 m3 water store (bladder or water barrel) for the site, to be able to make up any loss of drilling mud as quickly as possible. The density of the drilling mud must be adjusted as the drilling advances.

To obtain a homogenous mixture, the polymer or bentonite must be sprinkled over the water jet while filling the pit.

Figure 7: Drilling mud being sprinkled on the water jet for homogenous mixing

The drilling mud is circulated from pit to pit or inside the mud pan so that it remains homogenous before the effective start of drilling. While mud drilling, the settled cuttings from mud pan or mud pits should be removed constantly to ensure a free circulation of drilling mud.

Figure 8: Circulation of drilling mud inside the mud pan to keep the mixture homogenous before drilling

Use of the clay cutter

In the absence of bigger drill bit (both DTH hammer and tri-cone) a 300 mm diameter clay cutter can be used to ream the top unconsolidated formations of the borehole. A pre-casing must be used to avoid the collapsing of the borehole formations. Once the clay cutter could go further down, as the formations get harder, it should be replaced with a max size DTH hammer drill bit diameter available to continue drilling till the depth identified for the placement of the sanitary seal.

Figure 9: Different sizes of clay cutter at District Development Fund (DDF) ware house, Zimbabwe

Pre-casing

While widening the pilot hole if the side formations of the borehole start to collapse the drilling should be stopped immediately and a pre-casing should be placed to stabilize the formations. The internal diameter of the pre-casing must be several millimeters larger than the diameter of the drill bit used to drill through the underlying terrain. PVC pre-casing can be removed if it is less than 20 m deep. Beyond that depth it becomes impossible to remove without risking breakage. The use of steel pre-casing allows extraction from any depth, assuming enough lifting force from the machine (weight of the casing plus friction).

5- Placement of sanitary seal

At the end of the drilling process (both mud and DTH hammer) the sanitary seal should be placed ASAP, as the risk of collapsing increasing with time, this can compromise the quality of the sanitary seal.

5.1- Steel casings and centralizers

Preparation of steel casing and centralizers are the first step of process. Sanitary seal is put in place around the steel casings i.e. between the steel casings and the borehole formations. The diameter of the steel casing depends on the size of pump to be installed as well as on the diameter of the drill bit to be used to drill through the steel casing. Normally a 166 mm outer diameter (OD) steel casing is used for the placement of the sanitary seal. Using the bigger diameter steel casing decreases the thickness of the sanitary seal if the annulus is not bigger.

The use of steel casing is important as the risk of deformation and breakage of the casing while lowering it down the borehole decreases to zero, whereas with PVC casing the risk is much high. Also the life of a steel casing is much longer then the PVC casing which ensures the longevity of the sanitary seal.

The bottom of the first steel casing is reinforced by welding a circular ring in order to avoid the bending of the bottom in case it encounters any hurdle while being pushed down in the hole.

Figure 10: Reinforcing the bottom of the steel casing

In order to keep the casings straight throughout the length, three centralizers are weld at the bottom of each steel casing before lowering it down. Centralizers could easily be made at the site by cutting 1” wide flat metal bar at equal lengths, giving them a long U shape and welding them at the bottom of each of the steel casing.

Figure 11: Centralizers to keep steel casing straight down the hole

Small metal bars are weld at the top of the each steel casing to help placing them in the borehole as well as it prevents the steel casing falling into the borehole once the two casing are being weld together.

Figure 12: Lowering the steel casing into the borehole

Steel casings are weld together one by one while lowering them down the borehole. The number of the casings used will depends on the depth till which the sanitary seal will be placed.

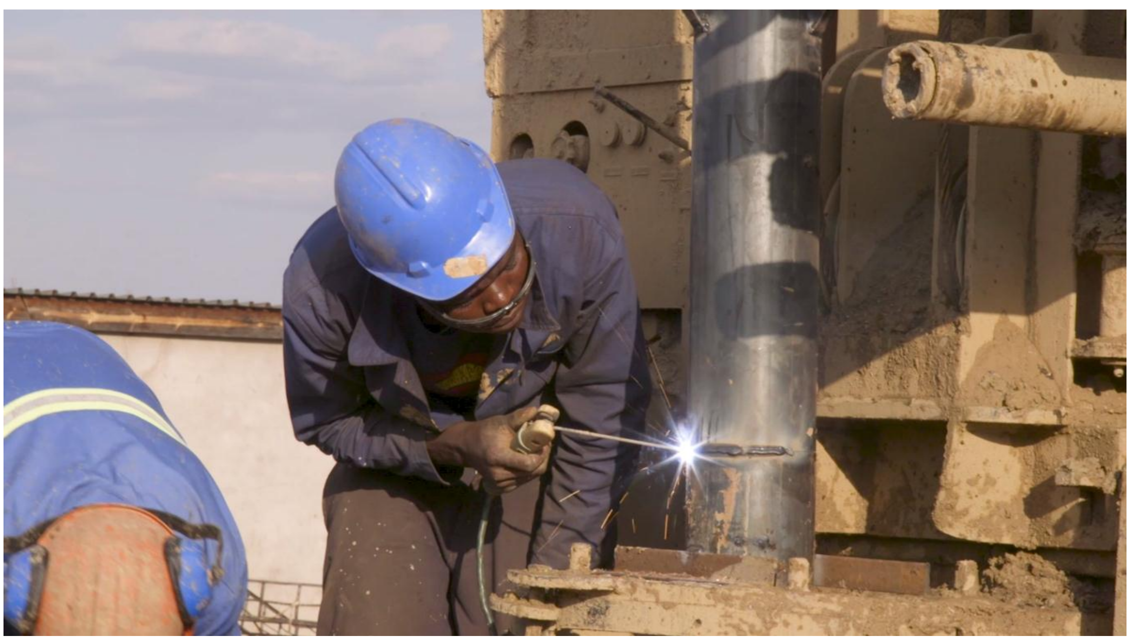


Figure 13: Welding of two steel casings together while lowering down the borehole

The steel casing assembly is hanged inside the borehole in way that there is approximately 50 cm left between the end of the steel casing and the bottom of the borehole. This is done to make sure there is free space at the bottom for the free circulation of grout. A metal bar weld at the top of the steel casing help the casing assembly to hang properly inside the borehole, without falling it down.

Figure 14: Steel casing assembly hanging in the borehole with a support of a metal bar welded at the top

5.2- Placement of flange

A flange fitted with gasket and valve is welded on the top of the steel casing. This is done to further inject water inside the casing under pressure, once the grout has been poured inside the borehole. Once the flange is welded, the upper part of the flange is removed in order to have an open space to pour the grout inside the steel casing.

Figure 15: Welding of the flange on the top of the steel casing

5.3- Importance of Welding process

For the successful implementation of the sanitary seal the welding process is of high importance. It is strongly advised to weld all the parts with high precision to make sure no void spaces are left behind. This is to make sure that there are no leaks in the welded joints as this can seriously compromise the quality of the seal or even make it nonfunctional even though sanitary seal is put in place.

5.4- Preparations before the start of making the grout

Placement of cement mixer and custom made cement pouring funnel

Before grout preparation, a setup has to be put in place to make sure the cement mixer is placed at an appropriate height with the cement pouring funnel leading the cement from the cement mixer straight into the borehole. This is done to make sure the grout goes straight into the borehole passing through the steel casing as soon as the grout is ready. Any delay can cause the grout to start steeling down and makes it movement difficult inside the borehole.

Figure 16: Custom made funnel to pour the concrete inside the borehole

Figure 17: Adjustment of concrete mixer and funnel above the borehole

Calculation of the volume of grout for the annulus

The amount of grout needed to fill in the annulus has to be calculated before to make sure all the material is ready before the start of the process. No more grout shall be poured inside the steel casing.

Calculation of grout

Diameter of the borehole = 300 mm
Diameter of the steel casing placed inside the borehole = 166 mm
Depth till which the grout shall be placed = 20 m

Calculating the diameter of the annulus of the borehole

Diameter of the annulus = 300 mm – 166 mm = 134mm
Diameter of the annulus = 0.134 m
Volume of the grout needed= pie x d^2***/4 x h***

Volume = 0.281 m^3
Volume = 281 litres

Hence, 281 liters of grout is needed to fill in the annulus of the borehole up to 20 meters depth.

Composition and preparation of grout

The grout for the placement of the sanitary seal is the mixture of cement and water to give it the form of cement slurry. Both are mixed to acquire the density of 1.8 kg/m^3 of the mixture. This cement slurry is poured inside the borehole through the steel casing.

The grout is made using the following combination:

54 liters of water + 100 kg's of cement = 85 liters of grout (density 1.8 g/m^3)

Calculation of the amount of water to be injected inside the steel casing

Once the grouting/cement slurry is poured inside the steel casing, it settles down at the bottom of the hole. This slurry needs to be pushed up inside the annulus of the borehole. This is done by injecting the clean water under pressure inside the steel casing. Due to the different in the densities of water and cement slurry, the injected water makes a few centimeters transition layer (a layer mixed with cement and water) and then pushes the slurry down which penetrates few centimeters inside the river sand and then bounced back into the annulus replacing the water inside the annulus by pushing it up. The amount of water being injected inside the steel casing should be a little less than the volume needed to fill in the steel casing. This is to make sure no water enters into the annulus. Any extra amount of water which enters the annulus will weakens the sanitary seal as it will change the composition of cement slurry.

The volume of water needed to fill in the 97 percent of the steel casing can be calculated as under:

Diameter of the steel casing = 166 mm = 0.166 m
Total length of the steel casing = 19 m
Effective length of the steel casing (the length to be filled in with water) = 19m x 97/100 = 18.43m

Volume of the water needed = pie x d^2/4 x h

Volume of the water needed = 0.398 m^3
Volume of the water needed = 398 liters

5.5- Pouring of grout inside the steel casing

The grout is made at the site, by mixing cement and water in the mixer and pouring it directly inside the steel casing. This process has to be finished as soon as possible as with any delay the already poured grout will start to settle down at the bottom of the borehole. This will make it difficult to push it upwards by injecting water. To flow of water out from the annulus indicate that the poured grout is replacing the water inside the annulus.

Figure 18: Pouring of grout inside the steel casing

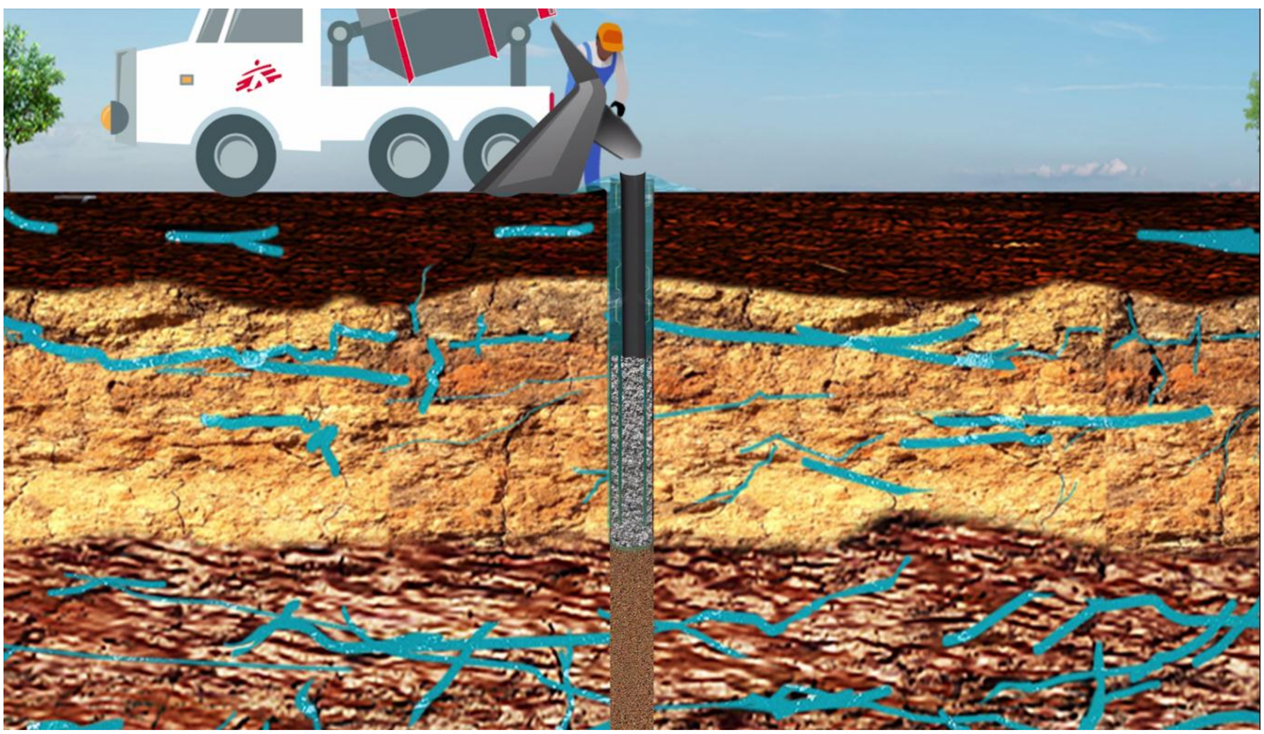


Figure 19: Animation shows how grout is settled at the bottom of the hole

Once all the grout is poured inside the steel casing the flange is screwed back onto the borehole in order to inject the water.

Figure 20: Fitting back the upper part of the flange with a gasket and valve

Injection of water inside the steel casing

After the placement of the flange the water is injected inside the steel casing using a piston pump with 20 bar pressure. If such pump is not available, a submersible pump with the same pressure can be used to inject water inside the steel casing. The water is injected inside the steel casing using a flexible pipe. Once the required amount of water is injected inside the steel casing, the valve attached to the flange is closed to maintain the pressure, so no grout goes back into the borehole.

Figure 21: Water being injected inside the steel casing

Figure 22: Closing of flange valve to maintain the pressure

The system is left under pressure for a maximum of 48 hours in order for the grout to get dried.

5.6- Drilling through the steel casing

After 48 hours, the flange is removed from the casing and borehole is drilled using a 6.5 " drill bit which passing through the steel casing up to the final depth of the borehole. This removes all the cement inside the steel casing and river sand which was used to back fill the pilot hole.

6- PVC casing, screen and gravel pack

Equipping the borehole (installing casing and screen) is an essential stage in the construction of a water borehole. The casing plan and the position of the screen have a great influence on the yield of the borehole, as well as its longevity.

6.1- Choice of the casing and screen

The PVC casing must be strong enough to avoid pipe deformation during installation, as holes are not always circular, and during pumping, which applies pressure on the pipe. It should be U-PVC Class 10, drinking water standards, non-toxic and in standard lengths of three (3) meters in length. The diameter of the PVC casing depends on the size pump installed but in normal circumstances it should be 125mm outer diameter (OD). The diameter of the PVC casing should also be in alliance with the national guidelines of drilling borehole. Increasing the size of the PVC casing decreases the size of the annulus which in turn results into very small thickness of gravel pack. Centralizers should be placed around each PVC casing to ensure the straightness of the casing down the hole.

The screen size slot depends on the aquifer grain size but usually the slots should be 0.5 mm to 2mm wide. The table below shows the choice of screen slot and gravel pack per aquifer grain size.

Aquifer grain size	Gravel pack grain size	Screen slot size
0.1 to 0.6 mm	0.7 to 1.2 mm	0.50 mm
0.2 to 0.8 mm	0.1 to 0.5 mm	0.75 mm
0.3 to 1.2 mm	1.5 to 2.0 mm	1.00 mm
0.4 to 2.0 mm	1.7 to 2.5 mm	1.50 mm
0.5 to 3.0 mm	3.0 to 4.0 mm	2.00 mm

6.2- Placement of the PVC casing

The borehole must not remain unprotected for any length of time, because there is always the risk of losing the borehole through collapse of the sides. The casing plan (length and position of casing and screen) is established according to the geological profile of the borehole where the different strata and points of ingress of water are noted. Diagraphy test can be carried out before casing to improve the casing plan, especially in sedimentary formations, where mud rotary drilling technique has been used, as with such drilling technique it is difficult to find the aquifer horizons.

The issue is to find a good compromise between having screens long enough to reduce the velocity of the water moving towards the borehole, and short enough to allow the installation of the pump above the screen, to avoid draw-down of the water table below the level of the screen.

Placing the pump within the screen itself can damage the screen: the high velocity of water causes erosion of the slots, and the pump hits the screen when starting. The gravel pack and the aquifer around the screen are also destabilized in the long term. The pump may also be damaged by drawing fine material into it and by causing cooling problems (water flow must arrive down the pump to cool the motor; a shroud can be used to orient the flow). These rules have to be strictly applied for a motorized borehole (the pump should be installed above the screen or should have a shroud if installed below it).

Moreover the bottom section of the casing must be a length of unslotted casing of about 0.5 m, plugged at the bottom. The top of the casing must extend to about 0.5 m above the surface of the ground.

6.3- Gravel pack

The gravel pack allows for a larger screen slot size to be used, increasing the yield from the borehole by reducing the velocity of the water entering the screen (therefore reducing head-loss). The gravel pack also helps in the stabilization of the surrounding aquifer.

The gravel pack must be washed, graded and rounded and must not be bigger than 4.0 mm in diameter. In practice, the gravel pack grain size is defined by the grain size of the aquifer and the slot size of the screen: the gravel must be as fine as possible without passing through the screen.

The gravel pack can be poured inside the annulus by lowering down a tremie pipe attached to a funnel till the bottom of the borehole and start pouring the gravel pack inside. Water rising up through the casing indicates that the gravel is falling correctly. When the level of gravel reaches the top of the screen, the mud no longer comes up through the casing, but through the annular space. If the falling gravel blocks the annular space, circulation of water can clear it.

Volume of the gravel pack

Empirical calculation of the volume of the gravel filter:

$$\mathbf{V = h \times pie \times (D^2 - d^2) \times 0.16}$$

V = volume of gravel pack in liters
h = height of the gravel column in meters
D = Diameter of borehole in inches
d= Diameter of PVC casing in inches

23: Calculation for the volume of the gravel filter

7- Borehole Development

The development of a borehole is a very important step, which removes the majority of fine particles from the aquifer and gravel pack that have entered the borehole, as well as the remaining drilling-mud cake, and sorts the aquifer around the screen in order to increase its permeability.

This operation allows borehole yield to be increased significantly. The aquifer is progressively brought into production and freed from fine particles, with a consequent increase in permeability and water flow. As the maximum yield of a borehole in use should be around two thirds of the yield obtained at the end of the development process, it is important to estimate maximum yield during development.

If the yield during use is higher than the maximum obtained during development, there is a danger of drawing fine material into the borehole and damaging the pump. Development is not finished until the water coming out of the borehole is perfectly clear: this operation can last for several hours, and sometimes more than one day. To verify whether the water is clear, it should be collected in buckets and checked for any suspended matter (bucket or stain test). By spinning the water one can observe the suspended particles concentrated in the center of the bucket. If the circle created is as big as a coin then the development must be continued.

8- Borehole drilling report

All information related to the borehole must be noted:

- name of the site or village, GPS coordinates whenever possible;
- working dates, starting, stopping and restarting times;
- name of the drilling firm and, where necessary, of the driller;
- Penetration rates
- Drilling cutting with depth
- time counters of the machines (compressor, engine);
- technique used, progress by drill pipe or metre, drill-pipe addition;
- any major incidents or important operations such as pulling up a drill string, stopping machinery,
- equipping the borehole;
- estimated yield and drawdown through development
- casing plan, with the exact lengths of casing and screen, their diameters, the position of the
- gravel pack

Essential geological information is also included, e.g. nature of the ground drilled, signs of water and flow estimated after each ingress of water. Finally, the driller keeps an up-to-date log book which collates all information on consumption of materials (cement, casing, bentonite), fuel and lubricants.

When the borehole is completed, essential information is summarized in the borehole report, whether the borehole is dry or wet. The hydro geologist in charge is responsible for writing this document.

These reports are an invaluable source of information for the project, and also provide a hydrogeological data bank. They must therefore be centralized at project level and also delivered to the relevant local authorities, who may, in certain cases, recommend a common approach for all organizations involved in the same area.

9- Borehole design