CHAPTER 8

Boreholes

A BOREHOLE DRILLING

This chapter is a practical guide to standard drilling techniques and implementing drilling programmes in places with a hydrogeological potential that are accessible with light drilling machinery. The performance of this type of machinery makes it very versatile, and suitable for difficult contexts of humanitarian operations. Three machines have been developed by ACF in collaboration with a Thai manufacturer (PAT, see Annex 11A):

– ACF-PAT 201 is a light and fairly inexpensive machine, but limited to unconsolidated sedimentary formations;
– ACF-PAT 301 is used to drill boreholes in consolidated or unconsolidated formations;
– ACF-PAT 401 is a more powerful machine than the ACF-PAT 301 with simpler implementation logistics.
Over the past few years, PAT have continued to improve these models on their own.

1 Drilling for water

1.1 Exploration

In a difficult hydrogeological context (for example, with little or no alluvial aquifer, or in the presence of multi-layered aquifers with some saline water levels), it is advisable to drill prospection boreholes. These indicate the presence and quality of groundwater and the nature of the aquifer, and allow calibration of the readings taken during geophysical exploration. Generally such boreholes are narrow, with small-diameter casing (43 to 100 mm). After the prospection phase they are either maintained as piezometers, or blocked up and abandoned. Simple pumping tests verify the presence of water.

1.2 Exploitation

The work carried out enables an underground aquifer to be reached and exploited, even if it is situated at great depth (more than a hundred metres). In ACF's programmes, most boreholes are equipped with handpumps to provide drinking water to rural and/or displaced populations.

In some countries, national regulations impose boreholes rather than wells (for the preservation of groundwater quality). In addition, boreholes are particularly appropriate in the following cases:
– pollution of shallow aquifers (poor bacteriological or physicochemical water quality);
– digging wells is too long or costly to meet the needs of the populations (displaced people's camps);
– geological context which does not allow well-digging, due to formations that are too hard or too deep;
– impossible to maintain an emergency water treatment station (not taken on by the community);
– boreholes which allow rapid response to urgent needs.

However, a certain number of technical, financial and logistical factors must be taken into account before beginning a borehole programme, in order to ensure its feasibility:
– the hydrogeological potential of the zone must be assessed by a preliminary study to determine the type of drilling rig required, the foreseeable flows and the chances of success. These may be low, so this must be provided for in the action plan;
– the choice of pump to be installed (manual or electric submersible), depending on the hydrogeological potential and the required flow;
– the possibility of finding a drilling rig in working order locally, or the need to import it (air, sea and/or land transport);
– local technical skills (driller, mechanic, geologist). It is possible to train a driller in drilling techniques, but can it take some time at the beginning of the programme. Normally the use of an ACF-PAT 201 (see Section 3) does not present problems;
– time required for import and starting (1 month minimum);
– local means of transport from site to site.

1.3 Examples of borehole costs

Since 1991, ACF has drilled more than 4 000 exploitation boreholes equipped with handpumps in Asia (Cambodia, Myanmar) and Africa (Liberia, Sierra Leone, Ivory Coast, Guinea, Sudan, Sudan, Uganda, Mozambique, Angola, Ethiopia, Honduras, Guatemala, Chad), using ACF-PAT 201, 301, 301T and 401 rigs.

In Cambodia, the cost of a 30-m borehole equipped with a handpump (suction pump type VN6) is USD 300 (equipment only).

In Guinea, the cost of an equipped borehole with an average depth of 40 m, using a Kardia handpump (USD 2 500), amounts to USD 4 000 (equipment).

A programme of 30 boreholes at an average depth of 40 m with an 80% success rate, taking into account the depreciation of one ACF-PAT 301 rig, corresponds to a cost of USD 7 000 per borehole.

As a comparison, a borehole drilled by a contractor, without a pump, can be costed as follows:

– in Haïti, 35 m deep, 8” diameter: USD 8 500;

– in Mali, 120 m deep, 6” diameter: USD 12 000;

– in Angola, a programme of at least 10 boreholes at a depth of 60 m: USD 8 000 with cable-tool drilling rig, and USD 13 000 with a rotary drilling rig;

– in Southern Sudan / Uganda, at a depth of 50 m and with a 6” diameter: USD 12 000-15 000.

2 Drilling techniques

Several techniques of drilling for water have been developed to suit the type of borehole required and the geological context.

Cable-tool drilling is the oldest technique. It is conceptually simple, and is especially useful in coarse sedimentary formations (gravels, pebbles), which are excellent reservoirs. This technique is not covered in detail in this book. Material removed is lifted to the surface mechanically, using a cylindrical bailer or scoop (Beneto-type machines).

Rotary and ‘down-the-hole’ (DTH) hammer techniques are the most widely used and are the most suitable in drilling for water. Certain rotary drills are very large and can drill down to several hundred metres.

For the lightweight machinery used by ACF, the ACF-PAT 201 model comes only in a rotary version, whereas the ACF-PAT 301 and 401 are DTH models (combined rotary and percussion).

2.1 Rotary drilling

The rotary technique (Figure 8.1) is used only in unconsolidated sedimentary formations with lightweight machinery (high-power rotary machines such as that used for oil drilling can however work in hard formations).

A rotary drill bit, known as a tricone bit, is driven from surface level via drill pipes. The drill bit works by abrasion of the ground, without percussion, using only rotation and pressure. This is provided by the power of the machine but, above all, by the weight of the drill pipes above the drill bit: when drilling large boreholes, weighted drill pipes, are used for this purpose.

At the bottom of the hole, the drill bit cuts away pieces of ground (cuttings). The circulation of a liquid, the borehole drilling mud, brings the cuttings up to the surface. The drilling mud is injected down the centre of the hollow drill pipes (or drill string) to the level of the drill bit and returns to the surface via the annular space between the drill string and the sides of the hole. While it is rising, the drilling mud covers the borehole sides and stabilises them (cake). This drilling mud is made up of water, a clay (bentonite) or a polymer, usually polycol. It moves in a closed circuit: when it arrives at the surface, it is channelled into a series of pits which allow the cuttings to settle, and it is then re-pumped and injected under pressure down the drill string.

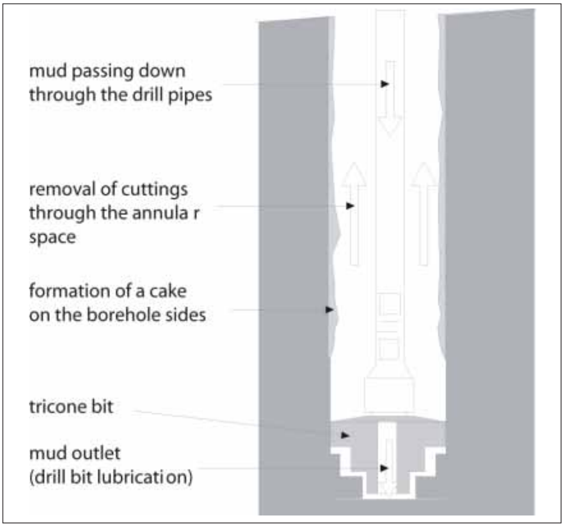


Figure 8.1: Working principle of rotary drilling.

2.2 Down-the-hole 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. The hammer works like a pneumatic road drill, using compressed air delivered by a compressor. The air flow raises the cuttings to the surface.

There are two phases, percussion and blowing (Figure 8.2).

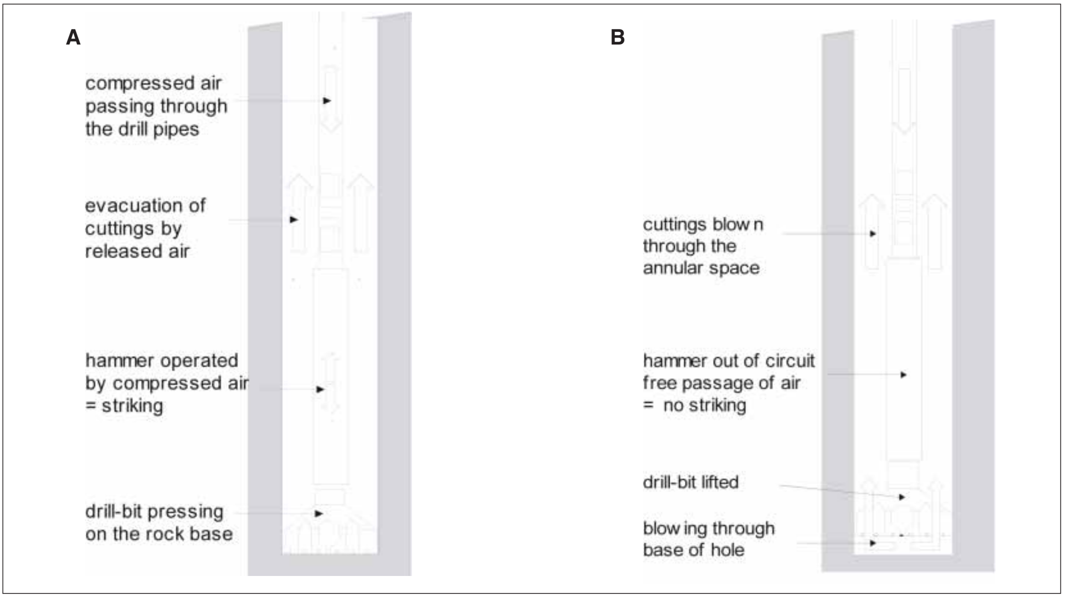


Figure 8.2: Working principle of DTH hammer drilling.
A: percussion: the compressed air operates the piston of the hammer, which strikes the drill bit pressed on the rock; part of the air then escapes into the annular space, carrying the cuttings with it.
B: blowing, or removal of the cuttings: the drill bit is withdrawn slightly, so that all the air flow passes around the hammer without operating it, and then escapes into the annular space.

2.3 Borehole parameters

The parameters that control drilling progress depend on the technique used (rotary or DTH): rotation and pressure on the drill bit (Box 8.1), and rising speed and pressure of the drilling mud or air – see box 8.2. These factors have varying influences on the rotary or DTH techniques, and it is essential to control them in order to achieve good working conditions: smooth progress, constant cutting removal, and stabilisation of the borehole sides (Figure 8.3).

In rotary drilling, for a given rotational speed, the essential parameter for progress of a borehole is the weight acting on the drill bit. Rotational speed is kept as regular as possible, depending on the drill-bit diameter and the nature of the formation. Generally, rotational speed will be lower for hard formations.

In DTH drilling, on the other hand, the determining factor is not weight, but the percussive action of the drill bit on the rock caused by the pressure of the compressed air acting on the hammer. However, insufficient weight can induce blind striking, which can cause serious damage to the hammer and drill bit. Too much weight, on the other hand, damages the drill-bit buttons. In practice, and with experience, the pressure on the drill bit is controlled by ear – a clear striking sound means that the hammer is working correctly – so as to obtain a regular rotational speed and to prevent excessive vibration.

Box 8.1
Calculation of pressure and rotational speed*.

Drill-bit loading
In rotary mode, the theoretical minimum pressure on a tricone bit is about 450 kg per inch of bit diameter and about 225 kg per inch for a three-bladed bit, i.e. a minimum downward force of 1 350 kg for a 6” three-bladed bit, and 2 700 kg for a tricone bit of the same size.

For a DTH hammer, the usual pressure is 100 to 200 kg per inch of drill-bit diameter, i.e. between 600 and 1 200 kg for a 6” drill bit.

Rotational speed
The calculated speed is that of a point situated at the periphery of the drill bit (tangential speed), that is, the time the point takes to cover a given distance.

The following formula is used to calculate the number of revolutions per minute:

$$\text{revolutions per minute (rpm)} = \frac{\text{tangential speed (m/min)}}{\pi \cdot d(m)}$$

where $\pi = 3.14$ and d is the drill bit diameter (m).

In rotary mode, the minimum tangential speed must be 60 m/min, and for a DTH hammer it must be 10 m/min, that is, for a 150 mm drill bit:
– in rotary mode, 127 rpm;
– in DTH mode, 21 rpm.

Torque
For rotary and DTH drilling, the minimum advised torque is 2 000 N-m per inch of diameter of drill bit used.

A safety factor of 1.33 is applied; that is, for a 6” drill bit, a torque of 16 kN-m.

* Raymond Rowles, *Drilling for Water, a Practical Manual*, Avebury/Cranfield University, 1995.

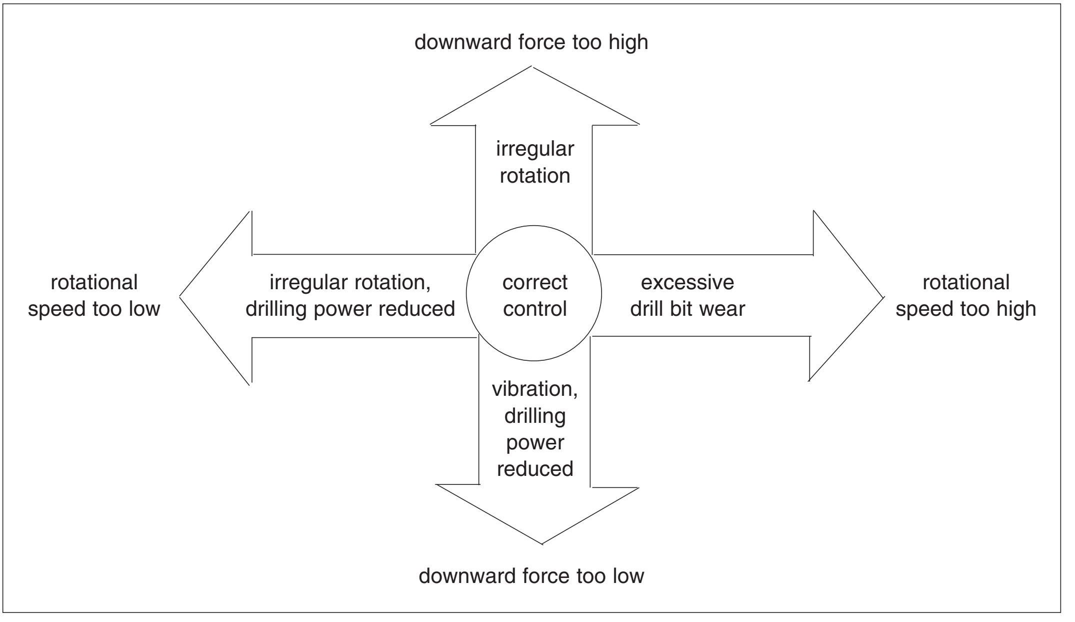


Figure 8.3: Control of downward force and rotation.

2.3.1 ROTATION, PRESSURE AND LIFTING FORCE

The rotation is transmitted mechanically (motor, gearbox, clutch or kelly on large machines) to the drill string by the drive head. It is calculated by simply counting the number of revolutions per minute.

The torque of the machine is expressed in Newton-metre and plays a fundamental role in rotary rigs working in hard sedimentary formations, and at great depths. It plays a secondary role in lightweight rigs, since the rotary technique has a limited application in hard formations. The values expressed are well within the recommended ranges.

The pressure depends on the power of the rig itself and the weight of the drill string above the drill bit. Consequently, the deeper the borehole, the heavier the weight on the drill bit induced by the weight of the drill pipes. When the borehole is started, the pressure on the drill bit is therefore sometimes low, particularly with lightweight rigs. On the other hand, at great depths, the drill string must be supported so as not to apply excessive pressure on the drill bit (Figure 8.4). The pressure to be applied on a tricone bit (rotary) is much higher than that applied on a DTH bit, but rotational speed is reduced (Box 8.1).

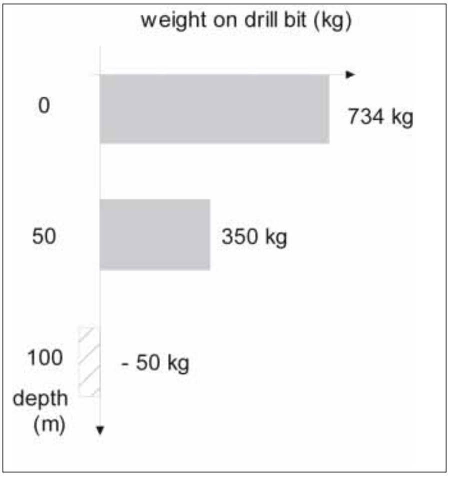


Figure 8.4: Downward force applied as a function of depth and weight of drill pipes.
The drill bit is 150 mm diameter, and the downward force on the hammer is about 800 kg. The weight of standard drill pipes is about 7 – 8 kg/m. The downward force of the drilling rig (in addition to the drill string) has to be increased at the start of drilling; after a certain depth is reached, the drill string may have to be supported as the weight of drill pipes increases.

The lifting force is provided by the machine power. Its value is given by the manufacturer and is generally expressed in tonnes. Obviously, it lifts the drill string, but can also be used to free the drill bit if the borehole sides collapse.

2.3.2 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, summarised in Table 8.I.

Table 8.I: Drilling fluids.

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

DTH drilling is often done without foam but this practice must be avoided. The use of foam really improves the efficiency of drilling (cuttings removal) and strongly decreases the risk of getting the hammer stuck.

Rotary drilling can be carried out using only air, without drilling mud. This technique allows quicker drilling and can sometimes get to a good depth in dry and stable formations. This allows the absence of water to be established without having to install any casing. 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 metres of the borehole (10-20 m), as it avoids the need for drilling mud if drilling is to be continued with a DTH hammer (bedrock near the surface). However, if the surface layers are not stabilised by the cake, the risk of the sides collapsing is higher (erosion by the air flow). Furthermore, the wet cuttings tend to agglomerate and, being too heavy to rise to the surface, they remain in suspension in the borehole until they form a plug in the annular space.

2.3.3 ROTARY DRILLING MUD

Drilling mud plays an essential role in the drilling process: it brings the cuttings to the surface, stabilises the sides, and lubricates the drill bit. The intrinsic characteristics of drilling mud (density, viscosity) are regularly checked and modified during the drilling process, thinning or thickening as necessary:

– density influences the transport of the cuttings to the surface and the stabilisation of the bore hole sides. Heavy drilling mud has better transport properties, and the cuttings float better;

– low temperature cools the drill bit;

– viscosity influences the lubrication of the drill bit as well as the transport of the cuttings (thrusting effect).

Note. – Polycol is a polymer which gives a spiral movement when circulating in the hole, and this improves the rise of the cuttings.

Hydrodynamic parameters (flow, pressure) also have an effect:
– the flow of the pump influences the circulation rate of the drilling mud (rate of rise), and directly influences the removal of the cuttings (Box 8.2). For the cuttings to pass within the annular space, it is necessary to maintain a minimum speed suitable to the density of the fluid. For constant flow, the velocity of the fluid (m/s) decreases as the annular space increases;
– the pressure of the drilling mud offsets head-losses in the drill string, since the circuit is balanced (open U circuit at atmospheric pressure at the surface). In theory, no pressure is necessary to ensure the return of the drilling mud. Nevertheless, high pressure is very useful in the event of a blockage in the annular space.

2.3.4 AIR IN DTH DRILLING

Air has two different functions: to operate the hammer, and to bring the cuttings to the surface. Therefore, several essential parameters must be checked.

The minimum air supply necessary to operate the hammer (several litres per second) and also to provide air flow high enough to carry medium-size cuttings (several millimetres – Figure 8.5 and Table 8.II) must be determined. The addition of foam to create an air/foam emulsion increases the transport capacity, and the emulsion can carry cuttings with diameters of about one centimetre, for low rise rates of about 10 to 15 m/s. By lubricating the rocky sides of the hole, the foam decreases the risk of getting the hammer stuck and it must be systematically used in deep boreholes.

The pressure of the air injected has a direct effect on the ability of the hammer to crush the rock, and therefore on the drilling advance speed (Table 8.III). The lubrication of the air must be permanent, because it lubricates the hammer piston liner.

Table 8.II: Air velocity necessary in DTH drilling, without the addition of foam, to bring spherical cuttings of a specific gravity of 2.8 to the surface.

Cuttings diameter (mm)	Air velocity (m/s)
0.1	1
0.5	5
1	8
5	18
10	24

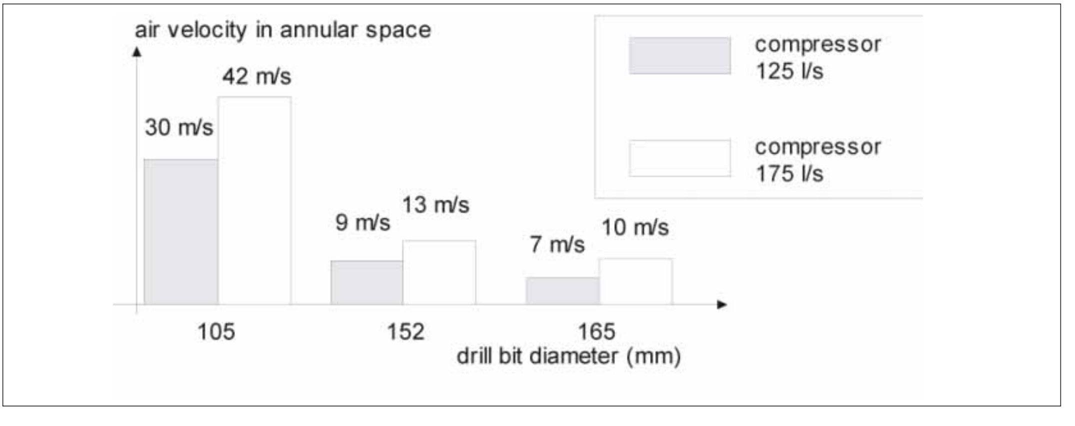


Figure 8.5: Air velocity as a function of compressor flow and drill bit diameter.

Table 8.III: Drill advance speed at a site in northern Uganda in gneiss formations with an ACF-PAT 301 rig equipped with a 150 mm drill bit and a 8 or 12 bar compressor.

Compressor	8 bars – 175 l/s			12 bars – 125 l/s		
Borehole number	10 825	10 823	10 829	10 828	10 832	10 836
Average time per 2 m drill pipe (min)	44	52	69	23	18	36

Box 8.2
Calculation of rise rate of the fluid.

To calculate the fluid velocity in the annular space, pump flow is divided by passage cross-sectional area, e.g., for a flow of 19 l/s, a 150 mm borehole, and 76 mm drill pipes:

$$\frac{Q}{\pi id^2/4 - \pi iD^2/4} = V$$

$$\frac{0.019}{3.14 \times (0.15)^2/4 - 3.14 \times (0.076)^2/4} = 1.4 \text{ m/s}$$

where d is the external diameter of the drill pipes (m), D the diameter of the borehole (m), Q the flow (m^3/s) and V the speed (m/s).

Raymond Bowles (1995) gives minimum annular flow speeds required for various fluids: 0.6 m/s for water, 0.35 m/s for drilling mud (water + bentonite) and 15 m/s for pure air (without foam).

He also gives maximum permissible flow speeds: 1.5 m/s for water and 25 m/s for air. At speeds above this, erosion of the sides of the borehole may occur, which could lead to loss of the borehole.

2.3.5 DRILLING GUIDELINES

The values of these parameters are merely indicative (Table 8.IV) and correspond to recommendations for standard drilling rigs; they are therefore much larger than the values used with lightweight rigs.

Table 8.IV: Drilling parameters (guidelines).

	Rotary	DTH
Pressure on the drill bit	Per inch of drill bit	
– three-bladed bit	225 kg	
– tricone bit	450 kg	
– DTH-hammer bit		100-200 kg
Rotation	10-150 rpm	25-50 rpm
Torque	2 000 N-m per inch of drill bit Coefficient of 1.33 in addition to be applied	
Fluid flow speed	Drilling mud	Air (pure)
– minimum	0.35 m/s	15 m/s
– maximum	1.5 m/s	25 m/s
Minimum pressure of the fluid (in bars)	Drilling mud	Air
for a 4” borehole	1 bar	12 bars
	Depends on diameter	Depends on diameter

The characteristics of the ACF-PAT rigs do not meet the specifications given in Table 8.IV (pressure, torque) in rotary technique, which simply means that these drills have very precise limitations in application, and that it is necessary to adapt the technique to the formations encountered. A rotary technique with light drilling machinery is not applicable in hard formations, where DTH hammers are required.

3 Lightweight drilling rigs

The three drilling rigs described below have been developed by the firm PAT, based in Thailand. ACF has adapted these machines (originally designed for working in Asian contexts, i.e. sedimentary formations) to the context of African bedrock zones. Three drilling kits have been manufactured: ACF-PAT201, ACF-PAT 301 and ACF-PAT 401 PTO.

3.1 ACF-PAT 201 kit

This very simple machine is a rotary rig composed of a frame and a rotary motor (Figure 8.6 and Annex 11A), a mud pump, and a small light compressor for borehole development.

The main advantages of this machine come from its light and mobile structure, which enables drilling to be carried out in isolated zones without needing to transport a complete site kit, which is very heavy*. A standard pick-up is enough to transport it from site to site with the rest of the equipment. The whole kit can be transported by light aircraft, which is an asset in many inaccessible places with humanitarian crises. The very simple operation of this type of machine allows local teams to become technically independent very quickly.

Boreholes are equipped with handpumps, or sometimes 4” submersible pumps, depending on demand and available flow. Maximum exploration depth is about 45-60 m in all unconsolidated formations (sand, clay, and fine gravel). For depths greater than 60 m, the machine is limited by the configuration of its drill string in its standard version (60 m), by its manual lifting winch, and by the capacity of the mud pump. However, it is possible to use some optional equipment which allows drilling to a depth of 80 m.

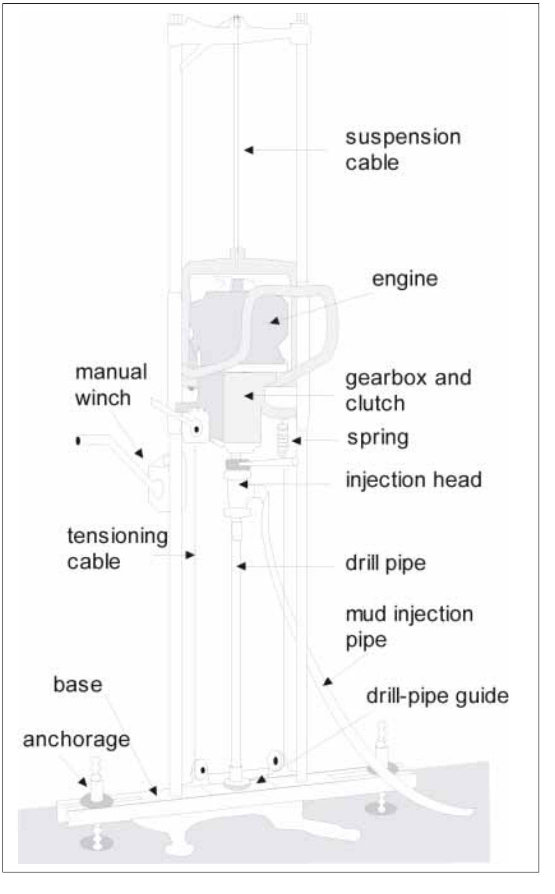


Figure 8.6: The ACF-PAT 201 drilling rig.

* Net weight of the complete site kit: 787 kg. Gross weight of the complete kit: 949 kg. Packed volume (8 boxes): 5.5 m^3.

Table 8.V: Characteristics of the ACF-PAT 201 kit (1998 version).

Frame	Total height of crossbar: 2.9 m Manual lifting winch equipped with 5 pulleys (cable length 11.5 m, ratio 4:1) Installation chassis for a pick-up
Drive head	Engine: Honda GXV-140 petrol 5 HP, 3 600 rpm + gearbox + clutch Rotational speed 80-120 rpm
Drill pipe, standard drill bits and accessories	Length 1.5 m x 40 units –thread 2” 3/8 API reg. Exterior dia. of the drill pipes 54 mm – 4 mm pitch – weight 16 kg – total 45 m Three-bladed bits: 1 pcs 8” (103 mm) – 2 pcs 6” 1/2 (165 mm) – 2 pcs 3” 1/2 (89 mm) 1 three-bladed bit 165 mm for clay Adaptor: 2 pcs 201 A – 2” 3/8 API female 2 pcs 201 A – 3”1/2 API female Complete toolbox
Pressure torque lifting force	Manual winch 196 Nm Manual winch max. 400 kg
Mud pump	Pump: Taki – TGH max. 42 m – max. flow 19 l/s Engine: Honda GX 390 – 13 HP petrol Suction pipe 3” x 4 m Delivery pipe 1”$^{1/2}$ x 6 m
Development compressor	Engine: Honda GX 390 – 13 HP – 3 600 rpm Compressor: FUSHENG model TA 80 – 3 compression cylinders – max. flow 7.5 l/s – max. pressure 100 m 80 m air hose on reel

The drilling power is given by the weight of the drill pipes above the drill bit, and is limited by the surface formation encountered (a cap of laterite, for example).

Its configuration and cost also make it very suitable for exploration to optimise a well-digging programme, thus avoiding expensive dry wells.

Numerous borehole programmes have been carried out by humanitarian organisations with this machine in South-East Asia, in Africa by ACF, in very isolated areas such as Southern Sudan, Liberia, Sierra Leone, Mozambique or Angola.

The speed of implementation depends essentially on the geological context and the conditions of access to the site. In a very favourable context (shallow water table), it is possible to drill one borehole per day. However, during a drilling programme, the time invested in transport, installation and packing up, choice of site, construction of boreholes, and maintenance must also be taken into account. Normally, in a difficult context, it is possible to drill one borehole per week.

The technical specifications of the ACF-PAT 201 kit are given in Table 8.V.

3.2 ACF-PAT 301 kit

The ACF-PAT 301 rig (Figure 8.7 & Annex 11A) is a combined rotary and percussion (DTH) drill, developed to drill in all types of hard sedimentary formations. ACF has adapted it to much harder formations, such as bedrock.

In rotary mode, it can drill deeper than the ACF-PAT 201 in fairly hard formations. It can therefore be limited to rotary mode. Its investigation depth is about 100 m for 6” and up to 150 m for 4” holes (ACF, Myanmar, 1996). In percussion mode, it can be used for boreholes of 40 to 60 m depth and 150 mm diameter in rocks and weathered formations.

This rig has most of the advantages of the lighter ACF-PAT 201, but much wider application. It is available as an air-transportable kit, and can be used for emergencies; its technology is relatively

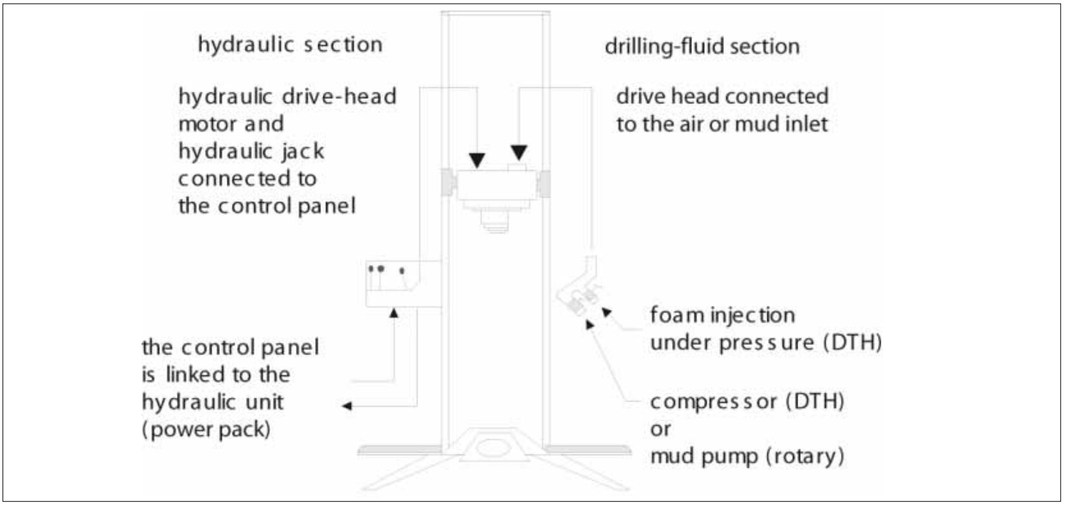


Figure 8.7: The ACF-PAT 301 drilling rig – working principle.

simple and accessible for a trained local team. The assembly can be fixed on a pick-up or a flat-bed truck, or mounted directly on the ground. The frame can also be towed (mounted on two wheels – not advisable in rough conditions).

The ACF kit includes a chassis adapted to the dimensions of the bed of a Land Cruiser pick-up, which allows the machine to be fixed. It is important to fit jacks to the back of the pick-up or truck in order to be able to drill vertically and stabilise the vehicle during the drilling process.

Installation of this rig directly on the ground is the simplest technique, and allows a very quick start while waiting for a possible mounting on a vehicle.

Since 2002, PAT has developed a new concept of the 301, the PAT 301T, by installing the rig on a trailer. The PAT 301T is easier to install and more stable (and efficient) than the standard 301. As the trailer is independent of the vehicle, the rig doesn't prevent use of the vehicle during drilling as with the 401, giving operational flexibility.

Table 8.VI: Site configuration depending on intervention contexts.

Context	Characteristics	Site configuration
Borehole in camps, in an urban area or near the base	Fairly short distances between drilling locations	Machine on the ground or on a pick-up Towed compressor
Village borehole in a scattered zone (Sahel type)	Long distances, Very bad roads	Machine and compressor on a truck
Only rotary drilling		Machine on pick-up, machine on ground

3.2.1 TECHNICAL CHARACTERISTICS

The machine is composed of a frame, a drive head and hydraulic power unit, a pumping unit (mud pump), a small compressor (for development), and an air compressor to work with a DTH hammer. The technical specifications of the standard kit are given in Table 8.VII and 8.VIII. The applications of the PAT in rotary mode are below the advised standards: the use of the tricone bit, which requires a high pressure, is not very advisable. In practice, for fairly hard sedimentary formations, the DTH is more suitable, because it needs much less pressure. The air-rise rate is limited by the flow of the compressor used and the drilling diameters.

Table 8.VII: Characteristics of the ACF-PAT 301 kit.

Frame	Height: 3.15 m, with crossbar of 2.25 m of useful run, equipped with 2 wheels Weight 320 kg – drilling table dia. 200 mm
Drive head	Hydraulic motor Rotational speed 0-40 rpm – torque 136.5 kgf.m (1 320 Nm)
Drill pipe & standard drill bits	Length of the drill pipes 2 m x 50 units – exterior dia. 76 mm Thickness 4 mm – weight 16 kg Screw thread: 2”3/8 API reg. Three-bladed bits: 2 pcs 9” (228 mm) – 1 pcs 8” (203 mm) – 2 pcs 6”1/2 (165 mm) – 2 pcs 4” (101 mm) 1 three-bladed bit 61/2” for clay 3 adaptors 2”3/8 x 2”3/8 API reg. (female – female) 2 adaptors 2”3/8 x 3”1/2 API reg. (female – female) Hammer: Stenuick Challenger 5 – drill bits: 1 x 150 mm – 2 x 165 mm
Hydraulic unit	Engine: Honda 13 HP petrol, 3 600 rpm (portable chassis) Hydraulic oil reservoir 60 l Hydraulic pump 250 bars
Feed system	Drive head raised and lowered by a hydraulic cylinder and heavy-duty transmission chain Lifting capacity: 1 590 kg, max. speed: 15 m/min
Mud pump R Standard	Engine: Honda GX 390 – 13 HP – 3 600 rpm – petrol (or Yanmar 10 HP diesel, hand-start, 3 600 rpm, air-cooled) Pump: Taki 65-33/2 (168 kg), 1 000 l/min at 30 m head, 600 l/min at 50 m head, pressure max. 4 bar
Screw compressor for drilling	ATLAS COPCO XAH 12 bar -175 l/s* Weight 1.5 T – 2 wheels – Diesel engine: DEUTZ 115 HP
Development compressor	Engine: GX 390 HONDA 13 HP – 3 600 rpm (Yanmar 10 HP diesel, hand-start, 3 600 rpm, air-cooled) Compressor: FUSHENG TA 80 (3 cylinders) – max. pressure 10 bar– max. flow 125 l/s 1/2” x 5 m flexible rubber hose with connections from reel stand to borehole development compressor 1/2” x 50 m (optional 80 m) flexible rubber hose with connections and attached air probe Tubular steel frame with detachable steel handle for rolling up and storing the hose after well development
Foam pump	Engine: Honda GX 120 petrol – 3.8 HP 3 600 rev/min (also available: 4.0 HP Yanmar diesel engine, hand-start , 3 600 rev/min, air-cooled) 3-cylinder piston pump (triplex piston pump) Max. pressure 35 bar – max. flow 20 l/min 25 mm x 6 m lift pipe 25 mm x 2 m suction pipe

* Other compressors are now available:
– XAS-186 7 bar, 186 l/s
– XAHS-186 12 bar, 186 l/s
– XAHS-236 12 bar, 236 l/s

3.2.2 WORKING PRINCIPLE

A hydraulic circuit drives a motor for rotating the drill string, and a hydraulic jack for raising or lowering the drill pipes and providing pressure on the drill bit (Figure 8.7). This jack moves the drive head up or down the pillar by means of a chain. The machine is operated from a control panel (Figure 8.8).

Table 8.VIII: Characteristics of the PAT 301T.

Frame	Height: 3.15 m, with crossbar of 2.25 m of useful run, equipped with 2 wheels Weight 320 kg – drilling table dia. 200 mm Mast raised hydraulically to vertical from storage position Mast equipped with 2 floodlights for night-time operations
Drive head	Hydraulic motor Rotational speed 0-45 rpm – torque 205 kgf.m (1 980 Nm) Able to swing aside for easy casing installation
Drill pipe & standard drill bits	Length of the drill pipes 2 m x 50 units – exterior dia. 76 mm Thickness 4 mm – weight 16 kg Screw thread: 2"3/8 API reg. Three-bladed bits: 2 pcs 9" (228 mm) – 1 pcs 8" (203 mm) – 2 pcs 6"1/2 (165 mm) – 2 pcs 4" (101 mm) 1 three-bladed bit 6"1/2 for clay 3 adaptors 2"3/8 x 2"3/8 API reg. (female – female) 2 adaptors 2"3/8 x 3"1/2 API reg. (female – female) Hammer: Stenuick Challenger 5"
Feed system	Drive head raised and lowered by a hydraulic cylinder and heavy-duty transmission chain Lifting capacity: 2 300 kg, max. speed: 19.5 m/min Drive-down capacity: 3 480 kg, max. speed: 14.5 m/min
Hydraulic unit	Engine: Yanmar 20 HP diesel, 2 800 rpm (portable chassis), 3 cylinders, water cooled, electric start Hydraulic oil reservoir 70 l Hydraulic pump 250 bars max.
Mud pump R Standard	Engine: Honda GX 390 – 13 HP – 3 600 rpm - petrol (or Yanmar 10 HP diesel, hand-start, 3 600 rpm, air-cooled) Pump: Taki 65-33/2 (168 kg), 1 000 l/min at 30 m head, 600 l/min at 50 m head, pressure max. 4 bar
Screw compressor for drilling	ATLAS COPCO XAH 12 bar -175 l/s* Weight 1.5 T – 2 wheels – Diesel engine: DEUTZ 115 HP
Development compressor	Engine: GX 390 HONDA 13 HP – 3 600 rpm (or Yanmar 10 HP diesel, hand-start, 3 600 rpm, air-cooled) Compressor: FUSHENG TA 80 (3 cylinders) – max. pressure 10 bar– max. flow 125 l/s 1/2" x 5 m flexible rubber hose with connections from reel stand to borehole development compressor 1/2" x 50 m (optional 80 m) flexible rubber hose with connections and attached an air probe Tubular steel frame with detachable steel handle for rolling up and storing the hose after well development
Foam pump	Engine: Honda GX 120 petrol – 3.8 HP 3 600 rpm (also available: 4.0 HP Yanmar diesel engine, hand-start, 3 600 rpm, air-cooled) 3-cylinder piston pump (triplex piston pump) Max. pressure 35 bar – max. flow 20 l/min 25 mm x 6 m lift pipe 25 mm x 2 m suction pipe

* Other compressors are now available:
– XAS-186 7 bar, 186 l/s
– XAHS-186 12 bar, 186 l/s
– XAHS-236 12 bar, 236 l/s

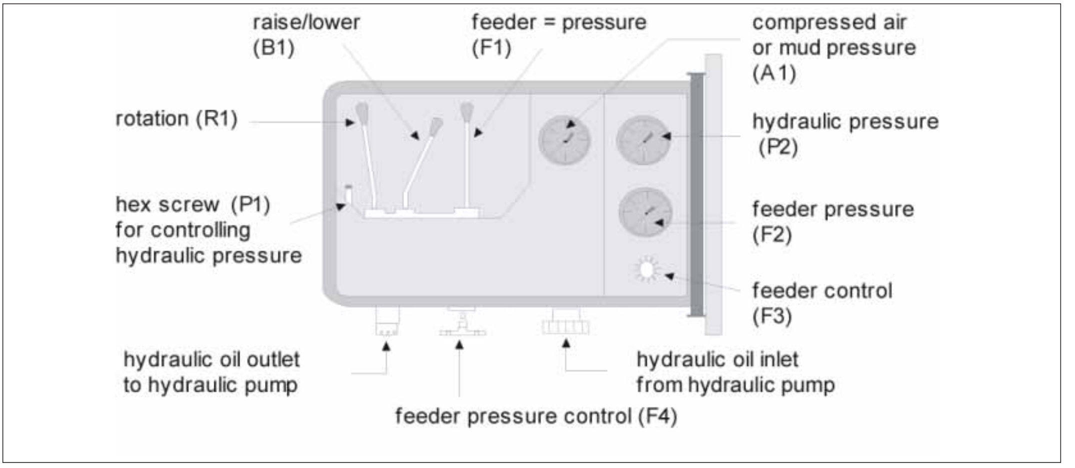


Figure 8.8: Control panel functions on the ACF-PAT 301 (1996 model).
The hydraulic pressure provided by the hydraulic pump is 210 – 220 bars maximum, and is controlled at the inlet to the control panel by the hex-head control screw P1. If the chain breaks too often, it may be that this screw is incorrectly set.
Pressure on the feeder F3: this imparts correct rotation in automatic setting. The control range of screw F3 is adjusted as follows: – turn the control screw for feeder F3 to minimum; – adjust the hydraulic pressure to 400 psi (manometer F2) using valve F4.

The pneumatic hammer is driven by a compressor (235 to 283 l/s, 12 bars). The compressed air used for the hammer must be permanently fed with oil (lubricator placed between the compressor and the air admission valve). A foam pump allows a foaming agent to be injected in addition, to facilitate the transport of cuttings to the surface.

3.3 ACF-PAT 401 PTO kit

The ACF-PAT 401 PTO rig is a development of the 301. Its applications are the same as those of the 301, but it offers easier drilling conditions, because it is more powerful. Its characteristics are given in Table 8.IX.

The rig is powered by the engine of the vehicle which transports it: in the standard version, a Toyota Land-Cruiser or a Dyna truck. A power take-off drives the hydraulic pumps: lifting/lowering/rotation pump, mud pump, stabilising jack pump and foam pump.

The equipment is therefore powered by a single engine, totally controlled from the board situated at the back of the vehicle (see Annex 11A). Getting on the road, installing the rig and starting work are simple jobs: the vehicle is positioned, and the platform stabilised. The whole kit is air-transportable (1 vehicle + 1 compressor). The drilling platform can be mounted on the vehicle by a team of mechanics in a few days. The total weight of the kit is 4.5 tonnes.

3.4 Other lightweight drilling rigs

There are other drilling rigs on the market similar to the ACF-PAT. Table 8.X compares the characteristics of the main lightweight rigs used in drinking-water supply programmes. The Eureka and Dando machines are British. The Stenuick (BB) is not very widely used in drilling for water, but has some useful characteristics for DTH-hammer drilling; its special feature is the fact that it is entirely pneumatic, which simplifies maintenance. Table 8.XI compares the range of Pat drilling rigs with other similar models.

Table 8.IX: Characteristics of the ACF-PAT 401 kit.

Drilling platform (to be installed on a Land-Cruiser*)	Composed of a hydraulic unit, a control panel, oil reservoirs, 35 drill pipes, a mud pump and a foam pump, lighting and electrical system 12 volts DC Total weight of the kit with 70 m of drill pipes: 2 t
Drive head	Rotational speed 0-60 rpm Torque 2 460 Nm max Able to swing aside for easy casing installation
Drill pipe & standard drill bits	Length of the drill pipes 2 m x 35 units – exterior dia. 76 mm Screw thread: 2”3/8 API reg. Weight of each drill pipe: 15.2 kg Three-bladed bits: 2 pcs 9” (228 mm) – 1 pcs 8” (203 mm) – 2 pcs 6”1/2 (165 mm) 2 pcs 4” (101 mm) 1 tricone bit 6”1/2 1 three-bladed bit 6”1/2 for clay Adaptors 2”3/8 API reg. female x 2”3/8 API reg. female 2 adaptors 2”3/8 API reg. female x 3”1/2 API reg. female Toolbox, spares, lubricants Hammer 4” and 5”, bits 165 mm
Hydraulic unit	Deck engine: Yanmar diesel, 4 cylinders, 30 HP, 2 800 rpm, water cooled, electric start, driving hydraulic pumps System pressure 250 bar max. Reservoir capacity 125 l
Feed system	Drive head raised and lowered by a hydraulic cylinder and heavy-duty transmission chain Pull-up capacity: 3 500 kg, max. speed: 25.5 m/min Drive-down capacity: 2 560 kg, max. speed: 34.5 m/min
Stabilising jacks	2 front / 2 rear Lifting power of 6 t per jack
Mud pump	Engine: Honda GX 390 – 13 HP – 3 600 rpm – petrol (or Yanmar 10 HP diesel, hand-start, 3 600 rpm, air-cooled) Pump: Taki 65-33/2 (168 kg), 1 000 l/min at 30 m head, 600 l/min at 50 m head, pressure max. 4 bar
Foam pump	Engine: Honda GX 120 petrol – 3.8 HP 3 600 rpm (also available: 4.0 HP Yanmar diesel engine, hand-start, 3 600 rpm, air-cooled) Triplex piston pump driven by a hydraulic motor, 450 rpm, 10 l/min max., 30 bar max.
Compressor (as 301)	ATLAS COPCO XAH 12 bar – 175 l/s Weight 1.5 t Other compressors are available as for the 301
Development compressor	Engine: Honda GX 390 – 13 HP – 3 600 rpm (or Yanmar 10 HP diesel, hand-start, 3 600 rpm, air-cooled) Compressor: FUSHENG TA 80 (3 cylinders) – max. pressure 10 bar– max. flow 125 l/s 1/2” x 5 m flexible rubber hose with connections from reel stand to borehole development compressor 1/2” x 50 m (optional 80 m) flexible rubber hose with connections and attached an air probe Tubular steel frame with detachable steel handle for rolling up and storing the hose after well development

* The complete kit can also be assembled on a trailer.

Table 8.X: Comparison of several lightweight drilling machines.
P: service pressure. Q: air flow. W: power.

	Weight of rig only or kit (t)	Lifting force (kg)	Lifting speed (m/min)	Rotation speed (rpm)	Torque (Nm)	Drilling mud pump	Compressor (DTH)	Comments
Eureka drill system	1.5	750		40-75	1 000	No	Rotary	
Dando Buffalo 3 000	1.85 1.71	7 000 Motor 20 hp + winch 3 000				No	No	Options: rotary DTH cable-tool machine
Stenuick* BB		2 600		70	1 800		Q: 250 l/s P: 12 bar	Rotary + DTH pneumatic
ACF-PAT 201	1 (kit)	400 Manual	Manual	80-120	196	Q: 19 l/s P: 4.2 bar	No –	Kit Rotary
ACF-PAT 301	3.5 (kit)	1 590 Intermittent	Max: 15 Nor: 10	0-40	1 320	Q: 19 l/s P: 4.2 bar	Q : 125-236 l/s P : 12 bar	Kit W: 13 HP Rotary + DTH
PAT 301T	3.5 (kit)	2 300 Intermittent	Max:19.3	0-45	1 980	Q: 19 l/s P: 4.2 bar	Q: 125-236 l/s P: 12 bar	
ACF-PAT 401 Land Cruiser PTO	4.5 (kit)	3 500 Intermittent	Max: 25.5 Min: 1.2	0-60	2 460	Q: 15.5 l/s P: 4 bar	Q: 175-236 l/s P: 12 bar Rotary + DTH	PTO kit W: 40 HP
ACF-PAT 401 Dyna PTO	4.5 (kit)	3 500	Max: 25..5 Min: 1.2	0-60	2 460		Q: 125-236 l/s P: 12 bar Rotary + DTH	PTO kit W: 40 HP
PAT 501	5.5 (kit)	4 350 Intermittent	Max: 25.5	0-50	4 840	Q: 19 l/s P: 4 bar	Q: 175-236 l/s P: 12 bar	Trailer

* BB drill, equipped with a F624 pneumatic motor for rotation and two F575 motors for raising and lowering.

Table 8.XI: Comparison of PAT drilling rigs.

Description	PAT-Drill 201	PAT-Drill 301	PAT-Drill 301T	PAT-Drill 401	PAT-Drill 501
Physical formation	Alluvial, soil, clay	All kinds	All kinds	All kinds	All kinds
Drill system and operation	Manual	Hydraulic	Hydraulic	Hydraulic	Hydraulic
Rig assembly	Separate kits, 3 engines driven	Separate kits, 3 engines driven	1 complete unit, main engine driven	1 complete unit, main engine driven	1 complete unit, main engine driven
Mobility	No	2 -wheel trailer	2- wheel trailer	2 -wheel trailer Mounted on Toyota Land Cruiser	4- wheel tandem trailer Mounted on 3-t truck
Transport	Load on/off pick- up	Load on/off pick- up	Towed by pick -up	Towed by pick- up Mounted on Toyota Land Cruiser	Towed by pick- up Mounted on 3-t truck
Drill depth*	0-60 m	0-100 m	0-100 m	0-120 m	0-150 m
Drill pipe (diameter x length)	50 mm x 1.5 m	76 mm x 2 m	76 mm x 2 m	76 mm x 2 m	76 mm x 3 m
Borehole diameter in alluvia, rotary drilling, mud flushing*	3 1/2” – 6 1/2”	4” – 8”	4” – 8”	4” – 9”	4” – 9”
Borehole diameter in hard rock, DTH-hammer drilling, air flushing*	Not recommended	4 1/2” – 6”	4 1/2” – 6”	4 1/2” – 6”	4 1/2” – 6”
Air drilling, DTH-hammer	—	3”– 4” hammer	3”– 4” hammer	4”– 5” hammer	4” –5” hammer
Button-bit diameter	—	90-150 mm	90-150 mm	115-165 mm	115-165 mm
Air compressor		250-400 cfm, 7-12 bar	250-400 cfm, 7-12 bar	300-400 cfm, 7-12 bar	300-400 cfm, 7-12 bar
Foam pump	—	Engine driven, separate kit	Hydraulic driven, mounted on rig	Hydraulic driven, mounted on rig	Hydraulic driven, mounted on rig
Weight (without compressor)	250 kg	700 kg	1 450 kg	1 860 kg	3 080 kg
Shipping information for a complete set	1.1 t, 3 m^3	Mud and air drilling, one 20 ft container	Mud and air drilling, one 40 ft container	Mud and air drilling, one 20 ft container	Mud and air drilling, one 40 ft container

* Depends on geological conditions and skills of operators.

4 Borehole design

4.1 Choice of casing

The depth and diameter of the casing and location of the screen depend on the hydrogeological context (depth of the aquifer, exploitation flow) and the type of pump to be installed (handpump or submersible pump). The choice of casing diameter depends on the size (diameter) of the pump, which in turn depends on the flow it can provide (Table 8.XII).

A 4” pump normally passes through a casing of 100 mm diameter. However, it is advisable to leave one inch between the pump and casing and it is therefore advisable to use casing of 113 mm internal diameter for an 4” pump. This clearance must be carefully considered when an electrical submersible pump is installed. It must be large enough to limit the head-losses (especially for large head-

Table 8.XII: Flows and diameters of submersible pumps.

External diameter of the pump (inches)	Usual flow range (m^3/h)
3”	1 – 3
4”	3 – 10
6”	10 – 50
8”	50 – 150

losses flows), but narrow enough to allow for a sufficient flow across the sides of the motor to cool it. When a motorised pump is placed below (or in) the screen a shroud must be installed in order to direct the flow across the motor to ensure cooling.

Logically, the external diameter, and therefore the thickness, of the casing depends on mechanical forces to be resisted (horizontal pressure of the ground and weight of the suspended casing). PVC casing, the most widely used for water boreholes of medium depth (no corrosion, easy to handle and install etc.), will be considered later.

The borehole diameter selected (Table 8.XIII) must allow the casing to pass freely, without force, and leave a space for the gravel pack around the screen.

Table 8.XIII: Corresponding diameters of PVC casing and drill bits in order to ensure good working conditions.

External diameter of the casing	Minimum diameter of the drill bit to be used
4” – 110 mm	6” – 152 mm
4”1/2 – 125 mm	6”1/2 – 165 mm
6” – 165 mm	8” – 203 mm
6”1/2 – 180 mm	8”1/2 – 215 mm
7” – 195 mm	9”5/8 – 245 mm

The quality of a borehole (sustainability, quality and turbidity of the water, exploitation flow) depends greatly on the installation of the equipment, the location of the screen relative to incoming water, the placing of the gravel pack, and finally the cementing of the annular space to avoid surface infiltration.

The size of the screen slots determines their maximum hydraulic discharge capacity. Table 8.XIV gives an example of this information for PVC screens. The table gives the upper theoretical limits although slot size is initially determined by the nature of the formation encountered during the drilling operations (see Section 6.1.1).

Table 8.XIV: Maximum yield (m^3/h) per metre of screen pipe.

Screen diameter (mm)	Slot size					
	0.5 mm	0.75 mm	1.0 mm	1.5 mm	2.0 mm	3 mm
110	2	2.8	3.4	3.7	4.2	
125	2.2	3	3.9	4.2	5	5.7
160	3	4.1	5.4	5.8	6.5	7.5
180	3.2	4.6	5.8	6.1	7.2	8.1
200		5	6	6.4	7.6	8.6

Note. – Increasing the borehole diameter does not lead to much of an increase in its capacity. A series of tests was established in the USA to illustrate this, and results are shown in Table 8.XV.

Table 8. XV: Yield versus borehole diameter.

Diameter of borehole	D	2D	3D	4D	6D	8D
Yield*	Q	1.12Q	1.19Q	1.25Q	1.35Q	1.43Q

* Increasing the diameter has the same influence (same coefficient) on the specific capacity ($m^3/h/m$) of the borehole as on the yield (m^3/h).

4.2 Pre-casing

Pre-casing is not normally required, but it may be necessary if the sides of the borehole are unstable: surface formations are not usually very consolidated, and pre-casing stabilises them for subsequent drilling. It is advisable to fix the pre-casing base with a layer of cement in the case of significant erosion and collapse problems (e.g., in granitic sands, the flow of air can create a cavity at the base of the pre-casing), or in the case of infiltration of surface pollution (e.g. a contaminated surface aquifer which needs to be isolated).

In DTH mode, it is quite likely that the sides of the borehole in the first few meters of soil will collapse (before the rocky layer is reached), especially when using foam, because of the water. As a result, the risk of getting the hammer stuck is very high. Consequently, considering the price of a hammer, it is highly advisable to install pre-casing when drilling with DTH.

In rotary mode, the risk of erosion of the borehole sides and collapsing is reduced, even at great depths (50 to 80 m), because the drilling mud stabilises the sides by caking. Also, the circulation rate of the drilling mud is not very high.

The surface formation may be loose (sand, soil), which may require several metres of pre-casing.

Non-cemented 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). Lightweight drilling machines such as the ACF-PAT range are not powerful enough to carry out this kind of operation beyond 20 m.

The internal diameter of the pre-casing must be several millimetres larger than the diameter of the drill bit used to drill through the underlying terrain. For example, to pass a 165 mm (6"1/2) drill bit, the pre-casing will need to have an internal diameter of 178 mm. Pre-casing of 167 mm internal diameter can also be used with care and in shallow boreholes.

4.3 Usual configurations

These examples are taken from boreholes intended to take 4" handpumps or electrical submersible pumps (Figures 8.9 and 8.10).

Normally, handpumps pass through casing with a 100 mm internal diameter. Kardia K 65 pumps are an exception, with their 96-mm external diameter cylinder and centralisers: casing of 113 mm internal diameter must therefore be used. Pre-casing, if necessary, will then be of 178-195 mm or 167-180 mm.

It is strongly advisable to case boreholes throughout their depth to increase life of the screen, and ensure filtering of fine particles by the gravel pack.

Sometimes some boreholes in bedrock are not cased in their lower sections (especially boreholes equipped with handpumps). The borehole is then only partially cased, to protect the less consolidated upper part, with a casing of 125 mm diameter or more. The lower, fractured section is not cased.

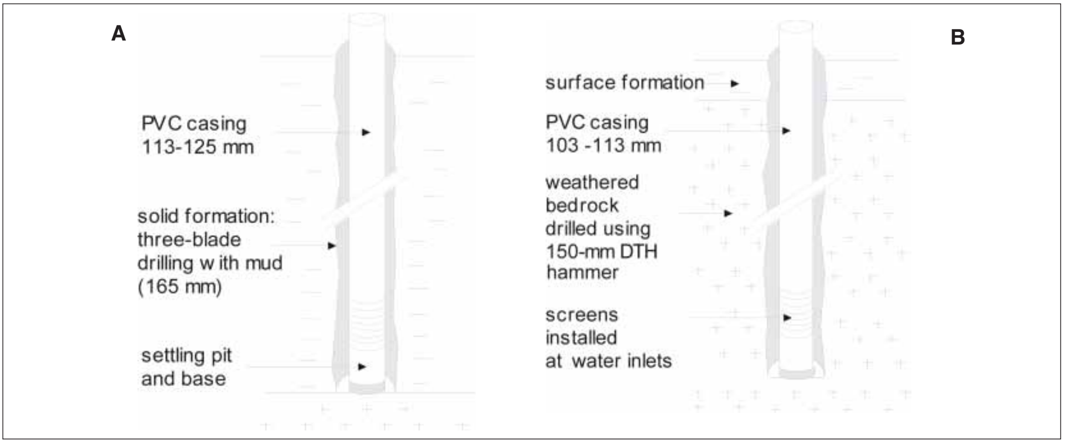


Figure 8.9: Rotary drilling (A) and DTH hammer (B).

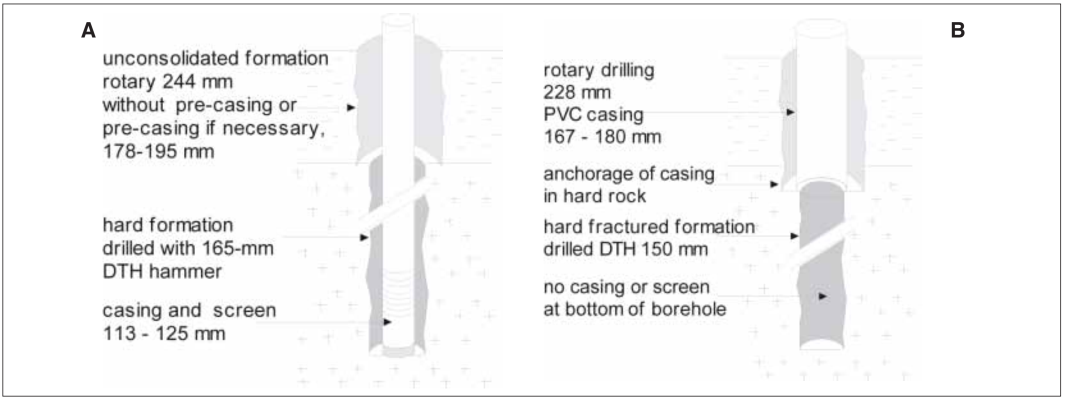


Figure 8.10: Mixed drilling using both rotary and DTH techniques.
A: complete equipment. B: partial equipment for partly consolidated formations.

This technique is not advisable, because it affects the longevity of the borehole, even if the fractures are clean and the pumped water appears to be clear at first.

Exceptionally, when using a lightweight drilling rig in very hard formations, where drilling is very slow, the only solution is to drill to a smaller diameter borehole (100 mm) and leave it uncased.

The most usual diameters are shown in Table 8.XVI.

Table 8.XVI: Choice of drilling diameters and equipment.

Geological context	Technique	Pre-casing (mm)	3-bladed bit (mm)	Piping (mm)	3-bladed bit (mm)	DTH bit (mm)
Sedimentary	Rotary	167 – 180 (DN 165, 6”1/2)(9”)	228	103 – 113 (6”1/2)	165	
Sedimentary	Rotary	178 – 195 (DN 175, 7”)	245 (9”5/8)	113 -125	165	
Consolidated	DTH	167 – 180	228	103 – 113 (ND 100, 4”)		150 (5”7/8)
Consolidated	DTH	178 – 195	244	113 – 125 (ND 115, 4”1/2)		165 (6”1/2)

5 Borehole drilling

The examples and tips mentioned below refer especially to drilling boreholes with the ACF-PAT 301 machine, but the technique is applicable to other machines with similar characteristics.

5.1 Choice of technique

The behaviour of the formations to be drilled will depend, obviously, on their nature, but also on their water content (Figure 8.11). Only experience allows cuttings removal and drilling progress to be correctly evaluated, depending on the method used. Beyond a certain depth, the air rotary method is of no further use, because it is difficult to control (poor cuttings removal). In relatively unconsolidated sedimentary formations, the best technique is rotary drilling using drilling mud.

5.2 Site preparation

5.2.1 INSTALLATION

The organisation of the site (Figure 8.12) must allow the driller to see the overall picture, and therefore act quickly if problems arise. Practical measures taken must include:

– a safety barrier around the site;
– access for vehicles;
– water supply (water tanks);
– easy access for filling the pits;
– a sheltered area for writing work;
– an area for spoil (cuttings);
– a levelled area to facilitate setting the machine vertical;
– location and digging of drilling mud pits;
– 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;
– clearly delimited work zone, with a fence if necessary.

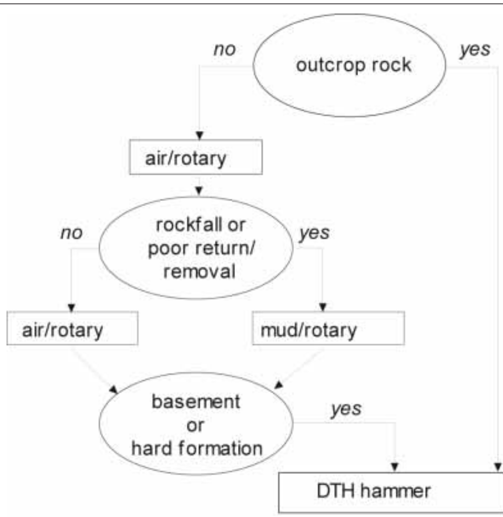


Figure 8.11: Flow chart for selection of drilling technique.

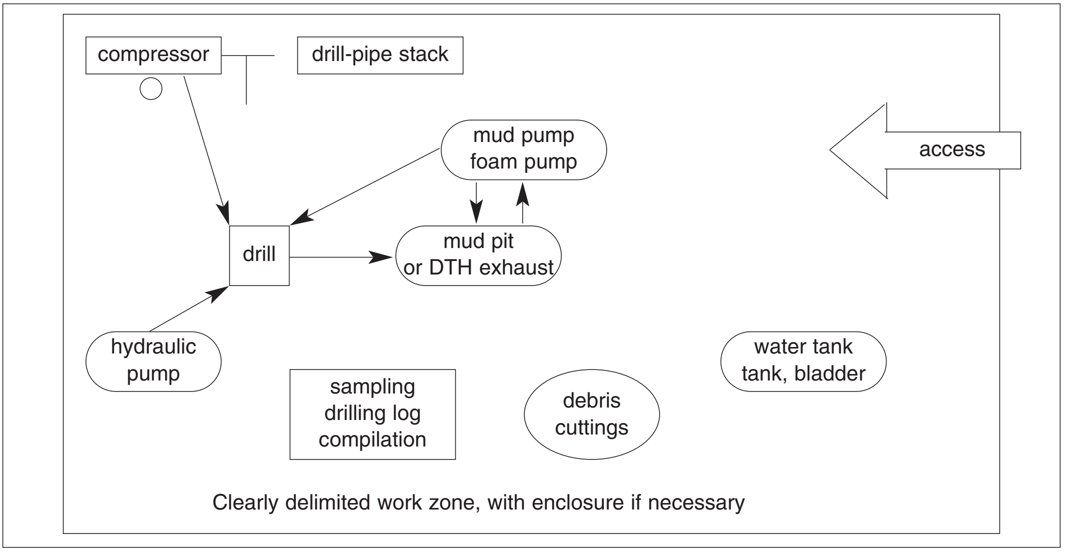


Figure 8.12: Site organisation.

To ensure better stability of the machine on the ground, it is advisable to fix 6-mm steel cables to the upper corners of the pole frame and to pegs firmly anchored in the ground. It is also advisable to place sandbags on the anchor arms of the machine.

The hydraulic pump unit (power pack) must be protected from the sun and placed in a well-ventilated area in order to avoid overheating, which could mean a power loss (critical oil temperature 60 °C).

The ACF-PAT 301 and the hydraulic pump are linked by two pipes which carry the hydraulic oil. The male and female connectors for these pipes cannot be wrongly connected to the pump or the control panel. The hydraulic unit must not be started before having made the connections, because that would pressurise the links and block the circulation.

Pipes must be connected during prolonged storage (a closed-circuit pipe on the hydraulic pump and one on the control panel).

The pipe storage rack divides the drill pipes into in two groups, which helps to avoid counting errors, and therefore errors of depth drilled. It is always advisable to number them so as to differentiate them. The threads must be protected by plugs/caps and systematically greased (drill pipes and drive head) with copper grease every time they are used, to ensure the drill string is watertight and to prevent seizing.

If the machine is mounted on a vehicle, the site should be set out in the same way. On a light vehicle such as the Land-Cruiser 4x4, the hydraulic pressure unit and drill pipes are on the back, and the compressor is towed by another vehicle which transports the rest of the equipment. On 5-t trucks, it is possible to mount the compressor as well.

Setting up a site with a machine fixed on a vehicle is quicker. The jacks are used to stabilise the rig in the vertical plane, and lift and the vehicle. Beams must be placed under the jacks to distribute the weight over a larger ground area.

5.2.2 MUD PITS

Mud pits form a reservoir of drilling fluid, and allow recycling after settling of the cuttings. For shallow boreholes (20-30 m) in unconsolidated formations, the dimensions given in Figure 8.13 and Box 8.3 can be used.

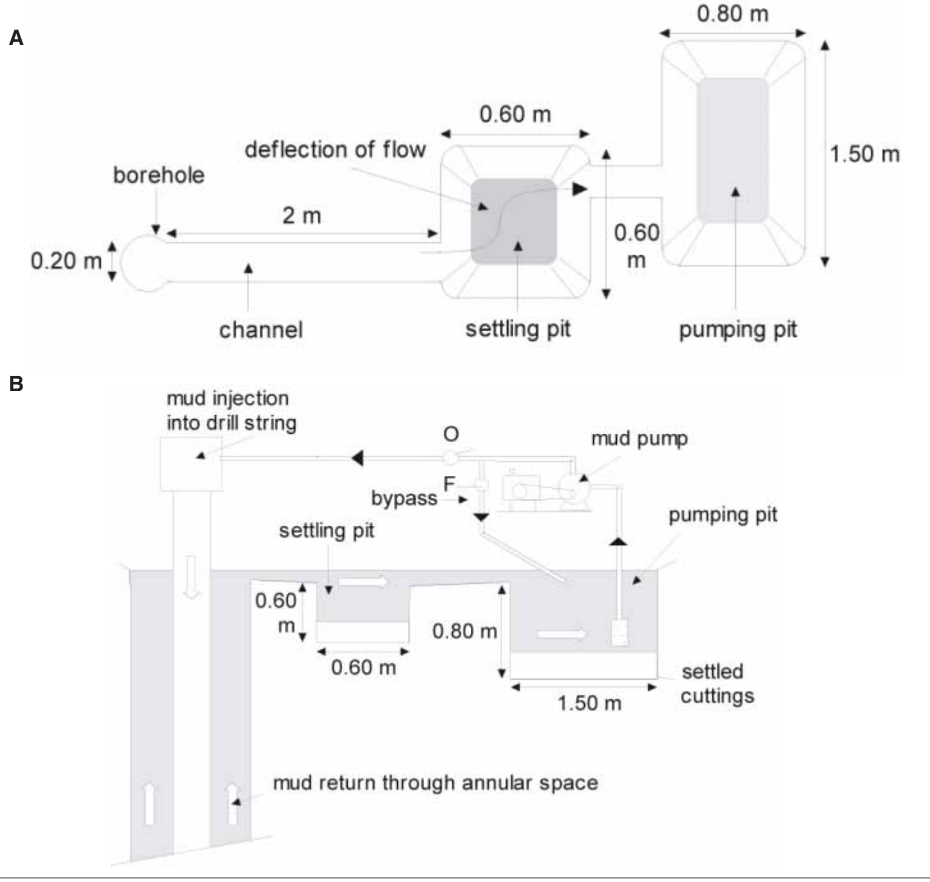


Figure 8.13: Mud circulation.
A: plan view; B: section view.

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.

Box 8.3
Mud pit design.

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):

– for the settling pit:
  width = $\sqrt[3]{\text{volume borehole in litres} \times 0.57}$
  length = 1.25 x width
  depth = 0.85 x width
– for the pumping pit:
  width = as for the settling pit
  length = 2.5 x width
  depth = 0.85 x width

The first pit (settling pit) facilitates the sedimentation that is started in the channel. Its volume is 0.2 m^3 (0.6 x 0.6 x 0.6 m).

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; its volume is about 1 m^3 (1.5 x 0.8 x 0.8 m). The pits and channels are regularly scraped out and cleaned of sediments formed in the course of the drilling process.

5.2.3 PREPARATION OF DRILLING MUD

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 polycol to increase its density and to prepare drilling mud which can be thickened or thinned, as follows:

– polycol is a polymer which is very widely used in rotary drilling. It must be mixed in a proportion of 2.5 to 5 kg per m^3 of water. The water-polycol mixture is more homogenous than the mixture of water and bentonite, and it needs less attention in its use. There are many types of polycol with different characteristics, suitable for different contexts (biodegradable, anti-colloidal, suitable for a saline environment, suitable for different climates etc.);

– bentonite is a powdered clay which must be mixed in a proportion of 15-30 kg per m^3 of water. It risks sealing the aquifer, but this sealing property makes it better for very permeable formations (gravels, sands), where the losses of drilling mud and the risk of collapse can be significant.

Clean water should be used for drilling mud. It is essential to have a 5 – 10 m^3 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. With experience, and depending on the formation being drilled, the driller adjusts the density according to the feel of the mud. Clay has the effect of thickening the mud, therefore it is necessary to thin it by adding water. In loose or sandy formations, it is necessary to use quite dense mud, as ingress of groundwater can thin it excessively.

To obtain a homogenous mixture, the polycol or bentonite must be sprinkled over the water jet while filling the pit. A mixer can be made with some fittings: a venturi tube is made, and then connected to the bypass on the discharge side of the mud pumps (Figure 8.14).

The drilling mud is circulated from pit to pit so that it remains homogenous before the effective start of drilling.

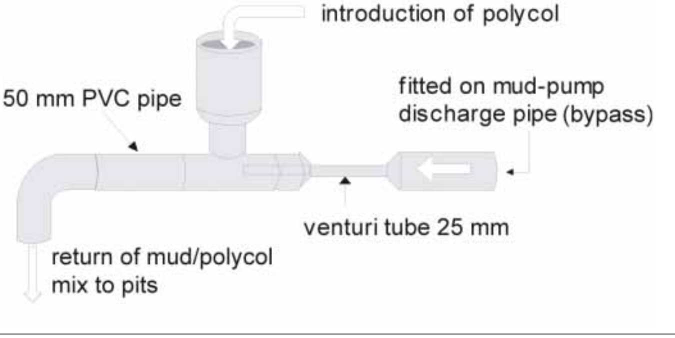


Figure 8.14: Venturi mixer made from PVC fittings.

5.2.4 REMOVAL OF CUTTINGS IN THE DTH TECHNIQUE

The cuttings (and the water with foam) are raised to the surface by blowing compressed air, and then channelled to allow sampling (and the estimation of the flow).

When the machine is installed on a vehicle, the mixture of water and cuttings strikes the underside of the deck. It is necessary to create a circular area on the ground which directs the flow towards a drain. In practice, the most effective means of channelling the cuttings and avoiding splashing is to place 1-2 m of casing (Figure 8.15) under the drilling table. A bucket is placed under the shower of cuttings.

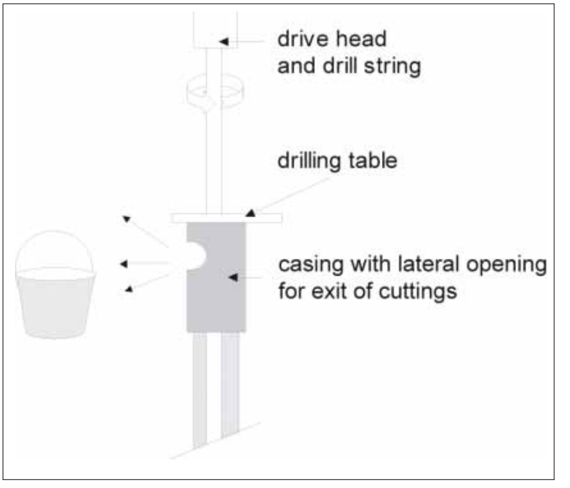


Figure 8.15: Collection of cuttings.

5.3 Rotary drilling

5.3.1 STARTING

It is absolutely essential to follow the procedures given in Figure 8.16.

5.3.2 ADVANCE: ADDING A DRILL PIPE

Drilling progress is regulated by the rotational torque and pressure on the drill bit controlled from the control panel. The possible solutions to drilling problems are explained in detail in paragraph 5.3.4.

The borehole must be drilled down to the end of the drill pipe passage in order to create a space between the bottom of the hole and the drill bit when the drill pipe has to be changed. When the end of a drill pipe is reached, it is raised and lowered by its full length in order to check the hole and clear the borehole sides. A drill pipe can be added as long as the drilling mud is not too full of cuttings (Figure 8.17).

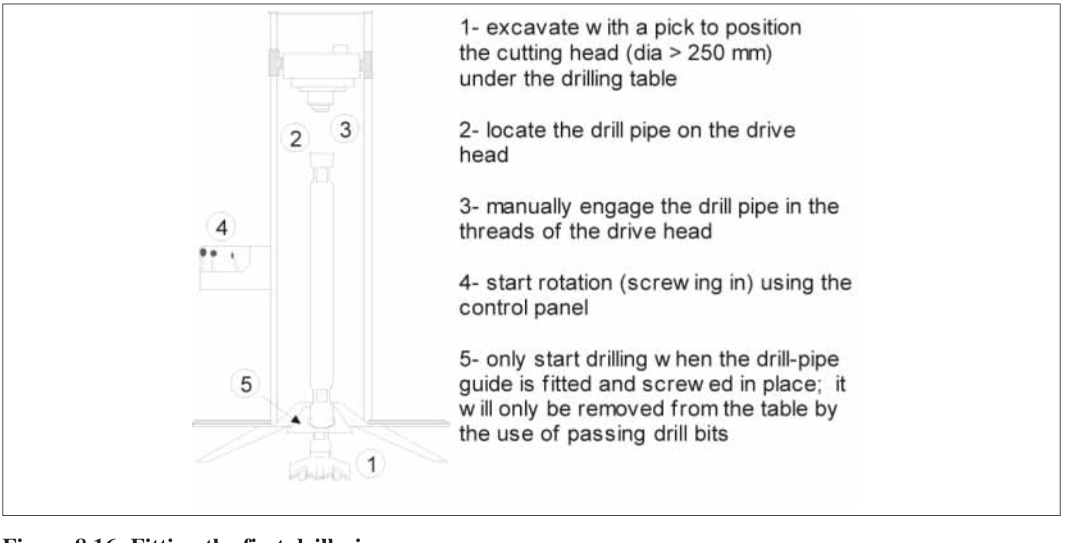


Figure 8.16: Fitting the first drill-pipe.

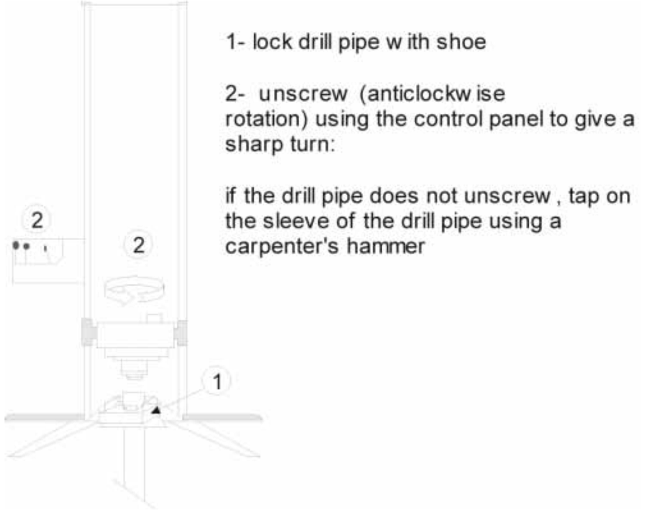


Figure 8.17: Unscrewing a drill pipe.

After switching over the mud-pump outlet to circulate mud from pit to pit (slowing the motor), it is possible to change the drill pipe. Stopping and restarting the flow of mud must be done as smoothly as possible in order to avoid any destabilisation of the borehole sides.

The locking shoe holds the drill pipes suspended in the borehole during the addition or removal of drill pipes: it engages at the level of the drill pipe flats (Figure 8.18).

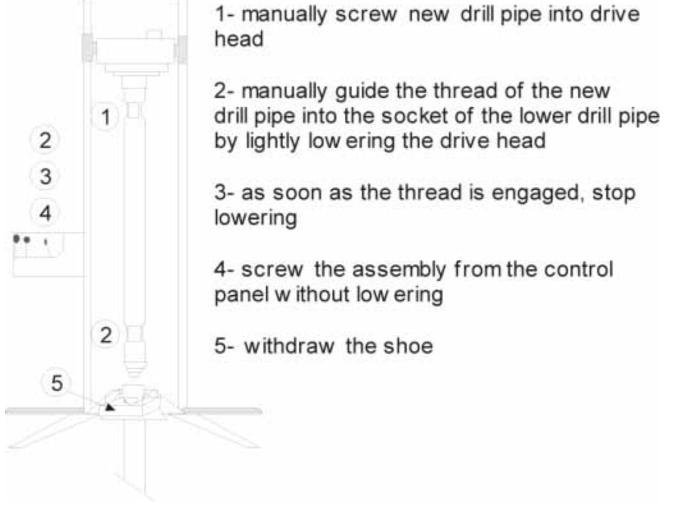
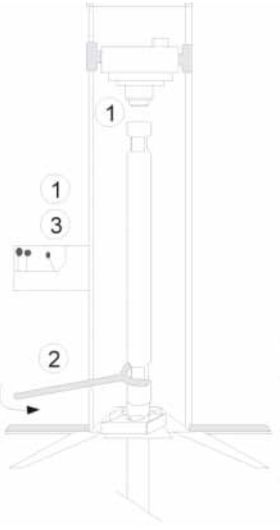


Figure 8.18: Locking drill pipes in suspension.

5.3.3 REMOVAL OF A DRILL PIPE

The drive head is lifted into the high position and the shoe engaged on the flat of the lower drill pipe. To remove a drill pipe, it is necessary to unscrew the upper thread using the drive head first, then the spanner, and then to unscrew the lower thread (Figure 8.19).



1- unscrew the drill pipe using the motor; if necessary tap with carpenter's hammer

2- finish unscrewing drill pipe completely manually w ith the spanner

3- remove the drill pipe, low er the drive head, and move on to the next rod (screw onto the drive head and pull the drill string up)

The shoe is always positioned on the flat of the low er drill pipe; the spanner can be used as a lever w ith the motor, but care should be taken not to make rapid movements so as to avoid injury

Figure 8.19: Removing a drill pipe.

5.3.4 COMMON PROBLEMS

Many difficulties may appear in the course of the drilling process, but most of them are simple to overcome with a little experience (Table 8.XVII). Success depends on constant monitoring of all the factors which may influence the progress of the operations, on precise observation of the cuttings, and on 'listening' to the machine: experienced drillers are very attentive during the key phases of the drilling process, to detect the slightest problem.

Table 8.XVII: Frequently-encountered problems in rotary drilling and recommended solutions.

Observations – difficulties	Recommended solutions
Significant losses and/or dilution of drilling mud	Increase the density of the drilling mud Use bentonite rather than polycol Install pre-casing
Thickening of drilling mud	Empty and clean pits Add clean water
Sides of borehole not stabilised and collapsing, erosion of sides	Increase density of drilling mud Reduce fluid circulation rate Reduce cleaning and circulation time Case immediately Install pre-casing
Sides collapsing, circulation stopped, rotation blockage	Increase pressure and flow of drilling mud Lift drill string until circulation returns to normal Install pre-casing
Sealing of aquifer	Clean with water to break the cake Use polycol rather than bentonite

5.3.5 ANALYSIS OF CUTTINGS AND SIGNS OF WATER

The geological section of the ground being drilled is established by the hydrogeologists or their assistants as the borehole goes along, and described in detail in the borehole report. The cuttings which come to the surface with the drilling mud 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. Samples are taken with each change of drill pipe and formation, by hand, just at the borehole outlet, and placed in a box with different compartments in order to visualise the geological section. They are then preserved in plastic bags marked with the name of the borehole and the depth at which the sample was taken. The samples are always covered in drilling mud, which makes them difficult to interpret, so they have to be rinsed with clean water.

In rotary drilling, there is nothing that clearly indicates the presence or absence of water during the drilling process: only water tests (direct blowing) and pumping tests, carried out once the borehole has been equipped, allow the presence of water to be confirmed, and the exploitation flow to be evaluated. Nevertheless, during the drilling process, there are several signs of water that allow an aquifer area to be located:

- analysis of the cuttings, as noted before, indicates the presence of an aquifer by revealing layers of permeable material (sands, gravels), supported by cross-checking with the information gathered in other boreholes drilled in the same area and which have turned out to be positive;
- loss of drilling mud, which means leakage of drilling mud into the surrounding ground, becomes evident from rapid decrease in the levels in the pits during circulation, or in the borehole after the circulation has stopped (for example, while a drill pipe is being changed). These phenomena indicate that the borehole is passing through layers of permeable material;
- traces of oxidation and visible alterations on the grains of quartz and feldspar (ochre/rusty aspect) are signs of groundwater movement. However, these may be old signs, relating to water movements in the past, and they may not reflect the current situation (e.g. if the static level has dropped);
- thinning (i.e. dilution) of drilling mud indicates groundwater ingress. But this phenomenon is rarely detected, because the pressure of the drilling mud is usually higher than that of the aquifer, and the aquifer is usually plugged by the cake.

5.4 DTH percussion drilling

5.4.1 ADJUSTMENT AND LUBRICATION OF THE DTH HAMMER

The DTH hammer is a precision tool, consisting of a piston which slides in a cylinder due to the passage of compressed air through a set of cavities. The piston strikes the drill bit during the percussion phase and releases compressed air during the blowing phase (Figure 8.20).

It is essential to keep the hammer lubricated, and so the injected air must itself be lubricated throughout the length of the drilling. A lubricator is located between the compressor and the air-admission valve of the drilling rig, injecting biodegradable drilling oil. The operation is checked by blowing the lubricated air onto a small board placed under a suspended drill pipe. Optimum flow (0.2 l/h) occurs when the board is lightly and evenly sprayed. Adjustment is carried out with the screw situated on the lubricator: the screw at the base is turned fully to the right (closed), then unscrewed a quarter turn to the left. If foam is added, the quantity of oil used must be higher. Every time a drill pipe is changed, it is essential to check the presence of oil in the air coming out of the drill head. Finally, when the hammer is completely dismantled, it is necessary to oil it (by direct introduction of hydraulic oil) and to grease all the threads (with copper grease).

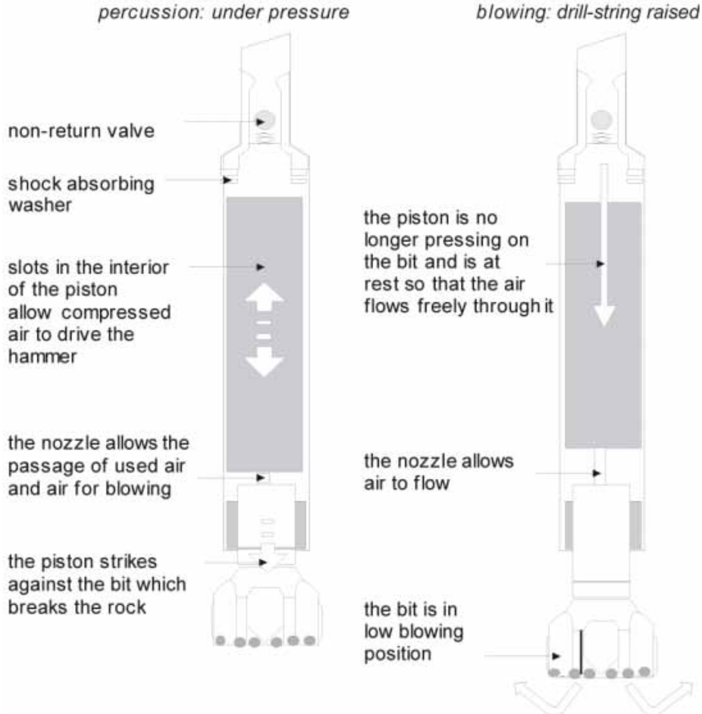


Figure 8.20: Hammer function.

5.4.2 INSTALLATION OF THE HAMMER

In bedrock areas, weathered layers are drilled in rotary mode using either air or drilling mud until the bedrock is reached, when drilling continues using a hammer (Figures 8.21 and 8.10).

Certain precautions must be taken for the installation and lowering of the hammer to the bottom of the borehole:

– all drill pipes must be cleaned with air from the compressor to remove all drilling mud residue before the hammer is connected (to avoid damage to the hammer);

– before storage, all dry drilling-mud residue must be cleaned from the drill pipes used for rotary drilling, with water from with the foam pump in high-pressure washer position;

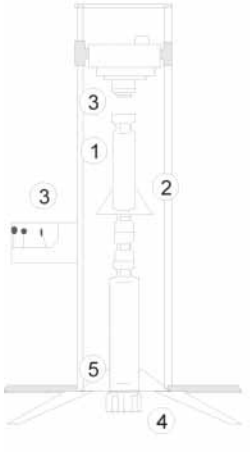
– before lowering the DTH hammer, the depth of the borehole must be measured (with a dipper) in order to check for possible collapse;

– when each drill pipe is added, it is cleaned after being screwed to the drive head and before being connected to the drill string (place a board on the drill pipe locked in the shoe and blast with air to flush out contaminants);

– drilling mud contained in the borehole is regularly flushed (by air blowing) as the hammer descends. If the hole is pre-cased and the space between the casing and the drill bit is small (just a few millimetres), there is always a risk of putting the hammer into percussion mode if it rubs against the sides of the casing, which would damage it.

5.4.3 DRILLING PROCESS

Before starting percussion, clockwise rotation is commenced and then maintained during raising or lowering of the drill string. It is only stopped when all other operations cease.



1- fit the hammer w ith a 1-m drill pipe provided for this purpose

2- pass the drill-pipe guide around the 1-m drill pipe

3- manually locate the 1-m drill pipe under the drive head and screw up (clockw ise)

4- test the percussion of the hammer on a plank of wood by supplying air and supporting it lightly; check the lubrication is correct (oil spray on the wood)

5- screw the drill-pipe guide onto the table as soon as the hammer is engaged in the borehole

Figure 8.21: Fitting the hammer.

Any anticlockwise rotation can unscrew the drill string or the hammer completely, causing them to fall to the bottom of the borehole; this can be aggravated by the vibrations caused by percussion. The recovery of a drill bit or part of the drill string requires specific tools and is a delicate operation. Anticlockwise rotation during percussion is therefore to be avoided at all costs.

5.4.3.1 Starting the hole

With the air flow shut off, the drill bit is placed several centimetres above the ground to be drilled, and clockwise rotation is started. The air is turned on, and the hammer is gradually pressed onto the ground until percussion starts.

Initially, air flow is opened half way, percussion is relatively weak, and rotation slow, until the drill bit penetrates the ground. The air valves are progressively opened to increase percussion.

Pressure and rotation are then controlled to give regular advance.

5.4.3.2 Advance

Good drilling involves a balance between pressure and rotation, giving constant penetration speed and regular, smooth rotation (Figure 8.3).

The borehole is regularly purged (every 50 cm) by blowing in order to remove cuttings and avoid blockage. Large cuttings tend to remain in suspension above the DTH hammer during the drilling process. If air circulation stops, cuttings can fall back onto the hammer and block it.

To purge the borehole, the hammer is slightly withdrawn (stopping percussion) and set to the blowing position. The total air flow provided by the compressor must allow the borehole to be purged of all cuttings. It may be necessary to sweep up the height of the drill pipe to purge the borehole thoroughly.

5.4.3.3 Addition and removal of drill pipes

The procedure explained in Sections 5.3.2 and 5.3.3 for rotary drilling can also be consulted.

Before unscrewing the drill pipes, the residual pressure in the drill string is checked with a manometer. This pressure remains high if a plug of cuttings is formed in the annular space (see Section 5.4.4 for precautions to be taken to avoid this): in this case the drill pipes must be unscrewed carefully to release pressure gradually.

Air lubrication is checked with the addition of each drill pipe.

5.4.4 DIFFICULTIES AND POSSIBLE SOLUTIONS

Air drilling of formations covered by unconsolidated material that has not been pre-cased can present difficulties:

– in the first stages of drilling, the pressurised air can erode and undermine the soil around the borehole, thus endangering the stability of the drilling rig;

– during the drilling process, the movement of cuttings to the surface erodes the sides of the borehole, which may cause collapse and block the drill string;

– air losses in very loose formations can lower the rise-rate of the cuttings.

If the surface formation does not have a minimum of stability, and if the cuttings do not rise to the surface correctly and so create a blockage, the rotary technique, using drilling mud rather than air must be used. If the surface formation collapses, pre-casing is essential before continuing drilling with the hammer.

For the problems usually encountered during the drilling process, there are several solutions, as recommended in Table 8.XVIII. The addition of foam (polymer) appreciably modifies the characteristics of the circulating air, and solves a certain number of problems (return of cuttings, filling and air losses in the ground).

Table 8.XVIII: Frequently-encountered problems in DTH-hammer drilling and recommended solutions.

Observations – difficulties	Recommended solutions
Poor rise of cuttings to the surface	Longer blowing time Injection of foam and water
Decrease in air flow at the borehole exit – blockage of cuttings High residual pressure in drill pipes	Injection of foam and water Care while unscrewing drill pipes
Air losses in surface formations	Injection of foam Pre-casing if necessary
Blockage with dry or slightly damp cuttings Formation of small balls	Injection of water and foam if necessary Frequent high-pressure blowing Pulling up drill string
Erosion of the borehole sides due to air flow and return of cuttings to surface	Decrease in air flow Use of foam Pre-casing
Formation of a large cavity	Stop drilling Immediate casing, or pre-casing
Drill bit blockage by falling debris	Sharp rotation, raising and lowering to crush the debris High-pressure blowing with water and foam
Blockage of rotation	Percussion and sharp restart of rotation Light anticlockwise unscrewing to increase amplitude of jolts
Drilling in a cavity	Left to the drillers' judgement

5.4.5 ANALYSIS OF CUTTINGS, SIGNS OF WATER AND FLOW CALCULATION

As the fluid used in DTH drilling is air, the cuttings will be clean and not mixed with drilling mud, facilitating analysis. Even the use of foam doesn't hamper the observation of the cuttings. 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).

In drilling with air, ingress of water is visible and quantifiable in most cases (return of a mixture of water and cuttings when blowing). However, some water ingress may not be noticed because it is blocked by the cuttings that form a cake on the sides of the borehole.

It is easy to estimate water flow during the drilling process to decide when it should be stopped, and the borehole equipped. Flow measurements are taken at each significant water ingress (blowing). In addition, all water emerging from the borehole is channelled to an outlet equipped with a pipe to facilitate measurement using a bucket.

Ingress of water in the finished borehole must be regular and continuous. The measured flow is generally less than the borehole capacity, because the cuttings block some supply zones, and the borehole is still not fully developed. Nevertheless, ingress of water is generally progressive: it appears first in the form of traces of dampness, and then, as the borehole advances, in the form of a cumulative flow coming from various fissures or fractures. In some cases, crossing a well-supplied major fracture causes a sharp increase in flow.

6 Borehole equipping

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. The aquifer must be protected from surface pollution which can enter down the side of the casing by the surface works and the cement plug (Figure 8.22).

6.1 Permanent casing

6.1.1 CHOICE OF CASING AND SCREEN

PVC is the most suitable material for shallow boreholes. It is preferable to use proper reinforced casing with screw joints. The mechanical strength of the casing can be calculated (Box 8.4). It 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.

Strictly speaking, the screen slot size depends on the grain size of the aquifer (Table 8.XIX). Before drilling starts this is not always known, but usually the slots should be between 0.5 and 2 mm wide.

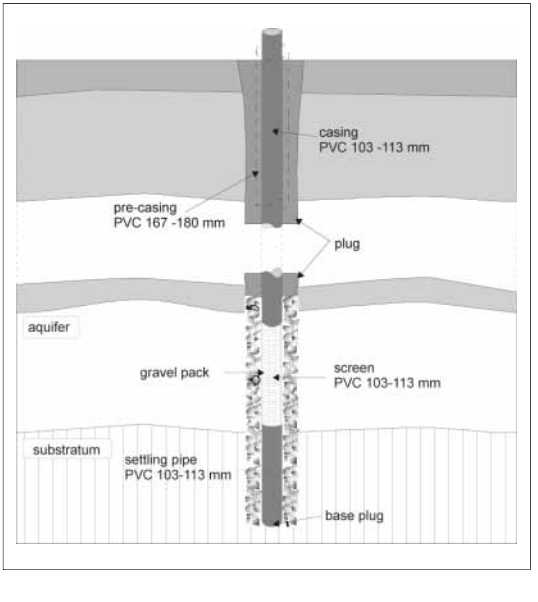


Figure 8.22: Borehole equipment (based on ACF, Uganda, 1997).

Box 8.4
Resistance of the casing to crushing.

For water boreholes, an important mechanical characteristic of the casing is its crush resistance. Sometimes this information is provided by the suppliers, but it can be calculated using the following simplified formula:

$$Re = K \cdot E \cdot (e/D)^3$$

where Re is the crushing resistance (bar), K a non-dimensional coefficient (for PVC K = 2.43 (Tubafor®), for steel K = 2.2), E the modulus of elasticity (bar) of the material at 20°C (for PVC 3 x 10^4, for steel 2 x 10^6), e the thickness of the casing wall, and D its external diameter.

For slotted casing (screen), calculated values should be multiplied by the coefficient (1 – F), where F is the fraction of voids. For particular cases, consult the supplier.

The forces, i.e. the lateral pressure on the casing, are generally calculated from:
– the specific weight of the ground, with the lateral forces equal to half the vertical forces, which are themselves equal to the weight of the unconsolidated, dry or saturated ground above (specific weight of 2 to 2.5). Therefore, it is usually considered that hard formations do not exert any lateral pressure;
– the pressure due to the presence of water or drilling mud in the borehole (hydrostatic pressure in bar P = H d/10).

For example, if the static level is near the surface and the formation is unconsolidated, the horizontal pressure is then 20 bars for each 100 m of depth (weight of the ground divided by 2 + 10 bars of hydrostatic pressure).

However, bearing in mind the small cross-sectional area of the boreholes, the vault effect of their sides protects the casing from lateral ground pressure. In practice, only the static and dynamic hydrostatic pressures are taken into account. These pressures are increased during pouring of cement grout, lowering the casing, and sharp reduction of water level during development.

For shallow boreholes in hard bedrock, experience has shown that it is enough to consider a horizontal pressure of 0.75 bars per 10 m section. Therefore, casing with a strength of 7.5 bars can be installed in a 100 m borehole.

During drilling of the first boreholes, the grain size of the aquifer can be easily identified by analysing the cuttings with a sieve. Table 8.XIX gives the grain size of gravel pack and the screen slot size recommended for different aquifer grain sizes encountered underground.

Table 8.XIX: 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

6.1.2 CASING FITTING

The risk of collapse could be high, and the casing is therefore fitted as quickly as possible. 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's tests (electrical resistance, gamma ray, neutron) can be carried out before casing to improve the casing plan, especially in sedimentary formations, with the use of rotary drilling, where it is sometimes difficult to identify the aquifer horizons (see Chapter 5).

The screen is placed so that its bottom is level with the bottom of the aquifer or zone of water ingress, with its length chosen according the following rules:

– confined aquifer: 80 to 90% of the thickness of the aquifer

– unconfined aquifer: 30 to 60% of the thickness of the aquifer

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 destabilised 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).

The de-watering of the screen presents several risks; oxygenation of the aquifer can favour the precipitation of metals (Fe, Mg etc.) that clogs up the screens and encourages the development of bacteria (see Chapter 8B). It also accelerates the compaction of the aquifer.

These rules have to be strictly applied for a motorised borehole (the pump should be installed above the screen or should have a shroud if installed below it). For handpumps the velocity of the water is lower and the longevity of the borehole is not so affected by having the pump within the screen (in this case, centralisers around the pipe of the pump must be used to avoid the pump cylinder hitting the screen during pumping).

Moreover:

– the bottom section of the casing must be a length of unslotted casing of about 0.5 m, plugged at the bottom (settling pipe);

– since the casing does not always reach the bottom of the borehole (cuttings suspended in the drilling mud falling back when circulation stops, or collapse of the material from the borehole sides), it is necessary to reduce the length of the casing by 0.5 to 1 m in relation to the actual

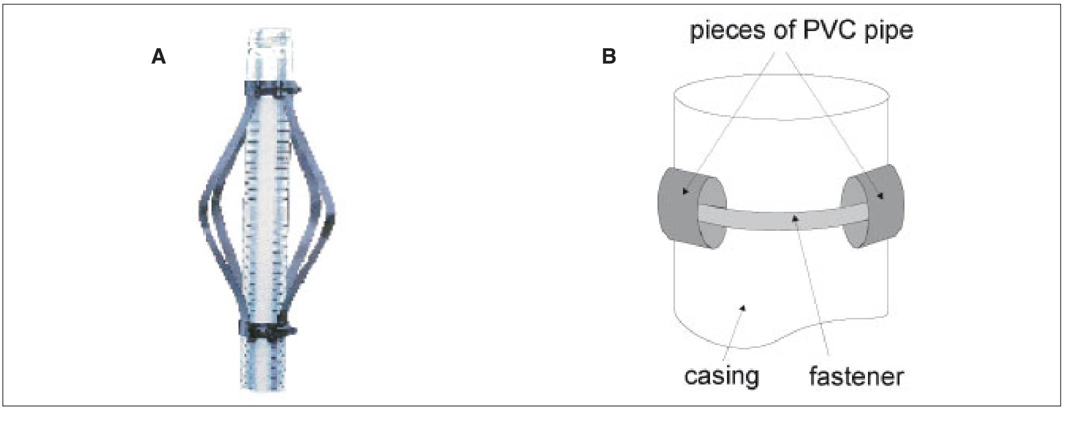


Figure 8.23 Centralisers.
A: commercial model. B: in Angola, centralisers were made by fixing small pieces of PVC pipe secured with fasteners around the casing. One centraliser was installed on each screen section, and one per two or three casing sections.

depth drilled (after drilling several boreholes in the same area, the driller should be able to estimate the height lost during drilling and adapt accordingly);

– the top of the casing must extend to about 0.5 m above the surface of the ground.

The lengths of casing could vary with the joint threading, so it is advisable to measure each length.

The casing must pass freely down the borehole under its own weight. If the borehole is not vertical, friction between the casing and the borehole sides can block the installation. Light pressure on the casing can facilitate its descent, otherwise it is necessary to return it to the surface and rebore the hole.

An alternative method consists of lowering the casing without a bottom plug so that it can scrape down the sides. In this case, it is recommended to seal the bottom of the borehole with cement grout pumped down from the surface once the casing is in place.

In order to guarantee correct positioning of the casing in the borehole and an even gravel pack around the screen, it is recommended to install centralisers. Various suppliers produce centralisers, but they can be easily made in the field (Figure 8.23).

6.2 Gravel pack and grouting

6.2.1 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 stabilisation of the surrounding aquifer.

The gravel pack must be reasonably uniform, calibrated, clean, round and preferably siliceous, to guarantee good porosity and longevity. It must not be calcareous, lateritic or crushed.

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 (Table 8.XIX).

The gravel is passed down through the annular space between the casing and the sides of the borehole. The use of a funnel (sheet metal, plastic sheet or pipe) facilitates its introduction.

If the falling gravel blocks the annular space, circulation of water can clear it.

Mud 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. The gravel filter must then go on a few metres beyond the height of the screen (compaction may occur after installation). This level can be checked with a dipper in shallow boreholes.

The volume of gravel required can be defined theoretically (volume of the borehole minus volume of the casing) or empirically (Box 8.5), but in practice, more gravel is always needed than is estimated (non-rectilinear hole, formation of cavities etc.). Table 8.XX gives some approximate volumes of gravel required for various borehole and casing diameters, in litres per metre height of gravel pack.

Tab 8.XX: Volume of gravel in relation to borehole and casing diameter.

Borehole diameter	Casing diameter	Volume of gravel (l/m)	
		Theoretical volume (empirical formula)	Likely real volume
3”3/4	1”1/2	6	10.16
3”3/4	2”	5.1	9.5
5”3/4	4”	8.65	12.67
6”1/2	4”	13.3	19
6”1/2	4”1/2	11.15	15.83

Box 8.5
Volume of gravel.

Empirical calculation of the volume of the gravel filter:

$$V = h \times \pi \times (D^2 - d^2) \times 0.16$$

where V is the volume of gravel (l), h the height of the gravel filter (m), D the diameter of the borehole (inches) and d the diameter of the casing (inches), $\pi = 3.14$. The factor 0.16 is here to correct the difference of units.

6.2.2 GROUTING

Grouting is an essential operation which protects the borehole from external pollution; even if a slab is cast around the casing, only proper grouting can prevent water filtering down the side of the casing. Grouting can be done with clay or with a mixture of bentonite and cement.

A clay plug must be placed on top of the gravel pack in order to stop the grout from plugging the gravel pack. The bentonite continues to swell over time, guaranteeing the seal even if the grout becomes damaged.

6.2.2.1 Preparation of the grout

The operation consists of filling the annular space above the gravel filter with a mixture of water and cement (grout) up to ground level. When the borehole is deep, one plug can be put above the gravel pack with another in the last two metres, the intermediate space being filled with clay (cuttings).

The proportion is about 50 l of water for 100 kg of cement, which gives 75 l of grout. If bentonite is available, the following mixture is used: 70 l of water, 4 kg of bentonite and 100 kg of cement. This second mixture stops the water from filtering out of the grout, but its setting time is slightly longer.

6.2.2.2 Placing the grout

The procedure involves filling the annular space up to ground level, and then leaving to set for a minimum of 12 h before starting development and pumping tests.

Generally, grouting must be carried out before pumping tests. Nevertheless, if it is not possible to wait for 12 h, it can take place after the development operations and pumping tests, as long as a clay plug has been placed above the gravel filter.

7 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.

Box 8.6
Self-development of the aquifer.

An aquifer put into production via a borehole is automatically developed by pumping.

Lowering of the water table is a maximum at the borehole, but decreases with distance from the borehole axis, forming a depression cone. The size of this cone depends on the nature of the ground and the supply of the aquifer or its limits, as well as on pumping time and flow.

It has been demonstrated that the speed of the water decreases with distance from the borehole (according to Darcy's law) and therefore that the materials around the borehole are sorted under the influence of the pumping. The coarser materials settle around the screen, and the finer ones settle at the limit of the area affected. Fine particles are therefore drawn into the screen over time by a slow process which causes pumps to deteriorate.

'Sand bridges' are also formed, fine materials which accumulate under the effect of the flow. To break them, it is necessary to reverse the flow, through the development operation, which involves causing suction followed by pressure (Figure 8.25B).

7.1 Borehole cleaning

In rotary drilling using mud, cleaning consists of washing the sides of the borehole with clear water to eliminate the cake. It is best to make the drilling mud as thin as possible without risking a collapse of the borehole, at the end of the drilling phase, before casing. Once the casing has been introduced, the injection of clean water from the surface thoroughly rinses the screen and the gravel pack blocked with drilling mud. The phases of rinsing and air-lift pumping are alternated in the borehole until clear water emerges.

DTH-hammer drilling does not seal the aquifer. On the contrary, the borehole is developed by successive blowing while it is being drilled. However, it is still possible to suck in a great deal of sand, damaging the pumping equipment and causing the ground around the screen to sink. It is therefore necessary to carry out the development of the borehole.

7.2 Development processes

7.2.1 AIR-LIFT DEVELOPMENT

Air-lift development is the most effective and widely used process of development. Its main advantage is avoiding damaging pumps with sand. At the intake level, quite strong pressure and suction forces are created by the introduction of large volumes of air. Through alternate phases of air-lift pumping and direct blowing of air at the screen level, sand bridges are destroyed. Air lift is the most effective development technique for destroying sand bridges.

In practice, two pipes are introduced in the borehole (Figure 8.24):

– a $1^{1/2}$" PVC or G.I. pipe, called the water pipe, through which the pumped water returns to the surface;

– a polyethylene pipe with a smaller diameter, mounted on a drum and called the air pipe, introduced into the water pipe, which allows compressed air to be injected. Depending on its position inside the water pipe, it pumps water out of the borehole water, or blows on the inside the casing.

The different phases of development are given in Table 8.XXI. The method consists of blowing from the base of the borehole, in successive phases, to just above the screen. 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 centre of the bucket. If the circle created is as big as a coin then the development must be continued.

Table 8.XXI: Air-lift development process.

Pumping	Lower the water pipe foot to about 0.6 m from the borehole bottom Introduce the air pipe into the water pipe, locking with a self-grip wrench when its bottom end is about 0.3 m above the bottom of the water pipe (pumping position) Install a tee at the exit of the water pipe to channel the jet Ensure a seal between the two pipes with a rag or a piece of rubber compressed by the weight of the air pipe Open the air valve and let the pumped water flow until it is clear
Blowing	Shut off the air and lower the bottom end of the air pipe to about 0.3 m below the bottom end of the water pipe, i.e. 0.6 m lower than previously (air-cleaning position) Open the air valve, which expels the water contained in the casing Close and reopen the air valve sharply and repeatedly
Pumping	Raise the air pipe 0.3 m inside the water pipe: eject very cloudy water (reversal of flow with consequent turbulence around the screen)
Renewal	Clarify the water, raise water pipe by 1 m and restart operations (alternating pumping and blowing) up all the height of the screen Restart from the base, and continue the process until the water is totally clear
Cleaning the casing	Once above the screen, lower the device to the bottom of the borehole and pump out the sand deposited there
Borehole plugged by clay or bentonite	Position the pipes at the bottom of the borehole, in blowing position (air pipe below water pipe) Connect the mud-pump delivery pipe to the water pipe Pump air and clean water into the borehole at the same time that the air is being blown The flow created rinses the borehole: the water descends through the water pipe and returns through the casing

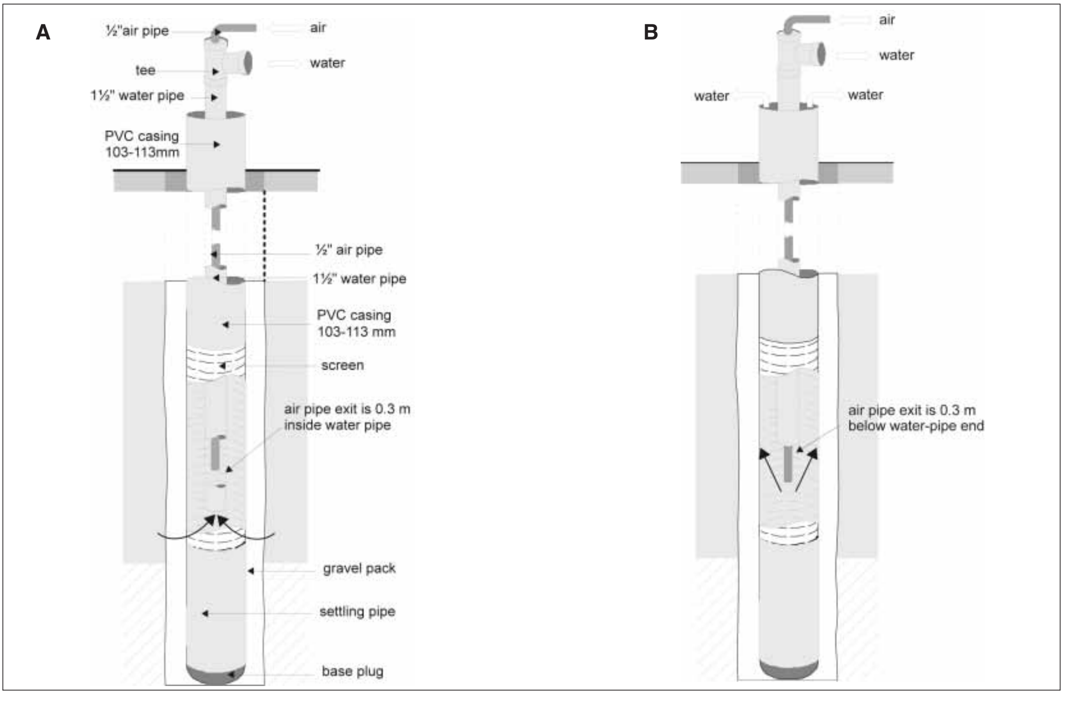


Figure 8.24: Air-lift development.
A: pumping phase. B: blowing phase.

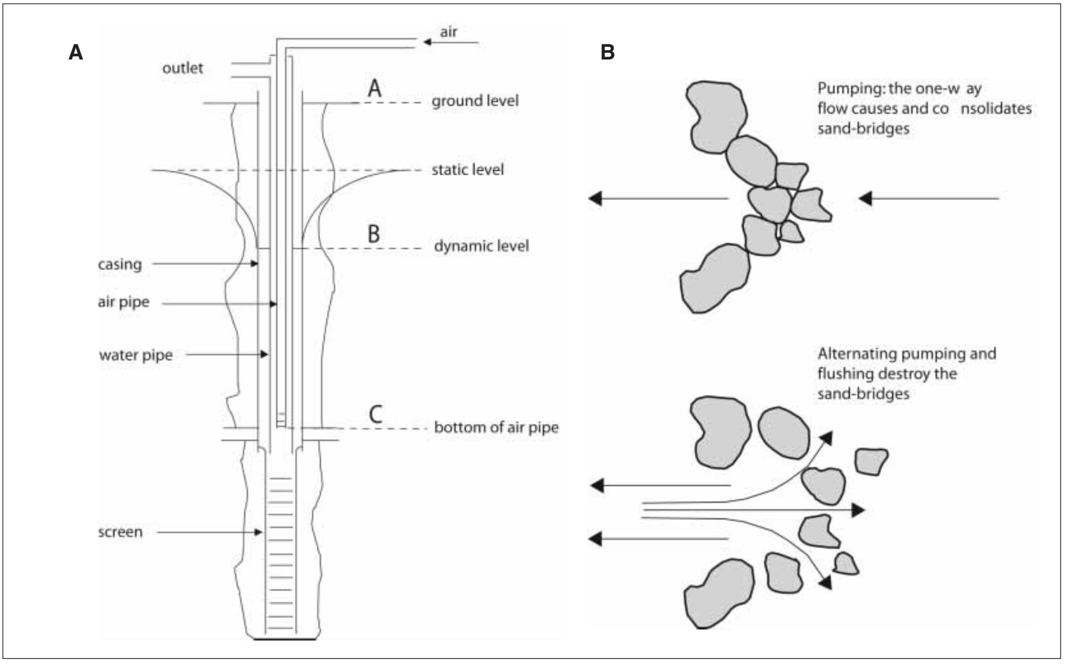


Figure 8.25: Air-lift.
A: design. B: sand-bridge destruction.

For small-diameter boreholes ($1^{1/2}$" or 2"), a simple blowing test allows the presence or absence of water to be confirmed.

Note. – If the water column isn't high enough then the air-lift won't be able to elevate the water, for physical reasons. Approximately, the system will function efficiently if BC ≥ 0.60 x AC (Figure 8.25A).

7.2.2 OTHER DEVELOPMENT TECHNIQUES

Other development techniques can be used, depending on the characteristics of the boreholes and the equipment available. These different methods can be also combined with each other:

– *Over-pumping*: this is the easiest method and consists of pumping at a higher rate than the planned exploitation yield. It complements the air-lift method and is necessary when the planned abstraction rate is greater than the one obtained by air-lift. This method can also be coupled with the 'alternating pumping' or 'pistoning' (surging) methods. Used alone, it has no effect on sand-bridges.

– *Alternating pumping*: the objective is to create pressure variations within the installation by alternating phases of pumping and resting. A high pressure is created by the water column falling down in the rising main when the pumping stops.

– *Pistoning*: this consists of moving a piston vertically within the casing to create, alternately, suction (water and fines move from the aquifer to inside the casing) and compression (water and fines are pushed out of the casing); this destroys sand-bridges. The borehole can be emptied with a bailer or scoop.

– *Pressurised washing*: this consists of injecting pressurised water within the borehole. It can be useful and fast especially in sandstone formations where the drilling operation often obstructs the porosity. This cheap method can be coupled with the action of chemicals for cleaning the borehole and its surroundings (see Chapter 8B).

7.2.3 PUMPING

Carrying out pumping tests (see Chapter 6) after development with air lift generally allows the development of the borehole to be completed, through alternating pumping (see Section 7.2.2).

Note. – The yield of the pumping test must be higher than the planned exploitation yield.

7.3 Instantaneous flow

The characteristics of the aquifer are defined by long-term pumping tests, which are usually difficult to carry out. When equipped with non-motorised pumps, the characteristics of the borehole are determined by pumping tests in flow steps, which are easier to carry out in ACF programmes (see Chapter 6).

In order to prepare the pumping test steps, the instantaneous flow of the borehole and corresponding drop in water level are measured at the end of development:

– the flow is estimated when the air-lift device is in pumping position (note: the size of the device influences the flow of water blown);

– then the water level is lowered (avoiding de-watering the borehole), and a fairly long period is allowed for the flow to stabilise;

– finally, the flow (time to fill a 20 l bucket) and the corresponding lowering of water level are measured.

8 Monitoring and borehole report

Monitoring borehole construction does not necessarily have to be carried out by a hydrogeologist. Experience has shown that a rigorous site manager can very well be in charge of this job after a training period with the hydrogeologist responsible for the borehole programme. Afterwards, the site manager technician will regularly (daily, by radio if necessary) provide the hydrogeologist with all the major information and important decisions taken during the drilling process. The monitoring cards and borehole report are given in Annexes 11B to D.

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;

– 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, clay and cement plugs.

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, machinery maintenance, mechanical problems encountered, and their solutions.

When the borehole is completed, essential information is summarised in the borehole report, whether the borehole is dry or wet. The hydrogeologist 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 centralised at project level and also delivered to the relevant local authorities, who may, in certain cases, recommend a common approach for all organisations involved in the same area.

These reports are filed with all the technical information on the water point: field surveys, data and interpretations of geophysical exploration tests, pumping-test data, site plan etc.

9 Surface works

An example of a borehole equipped with a handpump is given in Figure 8.26. Construction details are given in Annex 14.

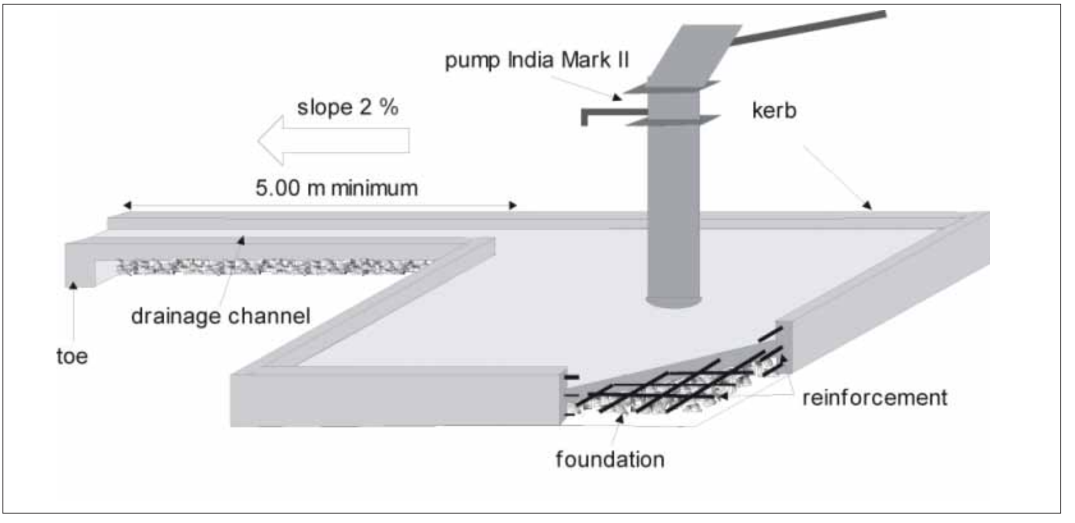


Figure 8.26: Borehole surface works (ACF, Kampala, Uganda, 1996).

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