Cranfield UNIVERSITY
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Private Sector Participation in Low Cost Water Well Drilling

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Investigation into the Effective Use of a Low-Cost Water Well Drilling Rig. Unpublished MSc Thesis

Chris Wardle
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Investigation into the Effective Use of a Low-Cost Water Well Drilling Rig

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Abstract

The private sector is a resource that is much under-utilised by the water industry in rural Africa. The initial investment required for a conventional drilling rig is large and this in turn makes borehole construction very expensive. A low-cost drilling rig is being developed in an attempt to overcome this problem. It is based on the Asian Sludging technique; a hand operated percussion drill where cuttings are removed by being drawn up the drill string under suction. The eventual goal is to create an effective drilling rig that can be operated and transported by human power alone.

This thesis investigates the drilling rig proto-type by considering aspects of the drilling operation including stroke length, stroke type and fluid viscosity. The relationship between these variables with both fluid discharge and drill penetration are discussed. The effect of using a funnelled cutting shoe on the end of the drill string is also studied.

The thesis shows that the penetration of the drilling rig in soft material directly corresponds with the fluid discharge that it achieves. A high solid load in the drilling fluid and a high pumping head are both identified as prime causes for a loss in potential fluid discharge. The cutting shoe greatly enhances the performance of the drilling rig.

Contents

List of Plates

Tables

List of Figures

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Chapter 1. Introduction

The demand for low-cost drilling.

A drilling method known as 'Sludging' is used extensively in many parts of Asia to bore holes for both drinking water and irrigation. Depths of up to 60m can be achieved, with borehole diameters of between 25mm and 150mm (Whiteside and Trace, 1993).

The technique traditionally requires the operator to move a bamboo pipe up and down inside the water-filled borehole. More recently, iron pipes have been adopted as a drilling tool. A settling pit to the side of the hole maintains a constant head of water at the top of the hole (Anon, 1995). On the up-stroke a hand is placed over the top of the pipe. This acts as a valve so that water and cuttings from the hole are held within the pipe as it rises. On the down-stroke the hand is removed and both water and cuttings are dispelled from the open end, allowing the pipe to penetrate downwards. The sludging drilling method is limited to soft alluvial deposits (Whiteside and Trace, 1993) due to the relatively fragile nature of the equipment. Penetration rates have been measured in India, and can range from 16.5 to 45m/hr (Danert & Ball, 1999).

A project based at Cranfield University and funded by DFID (Department For International Development) has the objective of modifying the Sludging technique so that it can be introduced into Africa, initially Uganda, as a low-cost drilling rig. By reducing costs and keeping technology to a minimum it is intended that the drilling rig will be adopted by the private sector, a much under-utilized resource in the African drilling industry (Carter, 1998).

There are several practical issues that will need to be addressed. This thesis investigates the processes that take place when the drill is being operated. There are a range of variables involved in the drilling rig's operation. These include the head to which the drilling fluid is pumped, the length of the stroke used to move the pipe up and down, and the solid load in the drilling fluid. An understanding of these factors identifies a more effective way to operate the drilling rig. The material into which a borehole is drilled determines what is understood by the term 'effective.' If the drilling rig is operating in very hard rock then the strength of the drill pipe and the ability of the drilling rig to break through the rock will largely govern the downward penetration of the drill. Where softer material is dominant, the effectiveness of the drill to penetrate downwards is dominated by its ability to remove cuttings thus cleaning the hole and providing a fresh surface onto which the drilling rig can impact. In this case the discharge from the top of the drilling rig will control the effectiveness of the operation. This investigation is primarily concerned with the latter of these two scenarios, and therefore optimizing discharge is synonymous with an 'effective' operation.

Initial tests were carried out with the drilling rig to understand the processes involved in operation. The rig was positioned above a 'sealed borehole.' The full length of this borehole is screened and the base is sealed so that when filled with water the only outlet is a small hole near the top. This allows a constant head of water to be maintained in the borehole during experimentation. General observations found that a fast cycle time (one complete up and down stroke) increases discharge. Shorter stroke lengths (0.2m, 0.3m) seem to produce a higher discharge than long strokes (0.6m, 0.7m). The majority of the discharge occurs during the down-stroke, and the water does not appear to achieve a height greater than that reached by the top of the drill string at the end of the up-stroke. An increase in the head to which the water is pumped decreases the discharge, and a fast down-stroke appears to increase discharge. Measurements of cycle times, discharge and stroke length were taken to provide the parameters within which a mathematical model of discharge could be developed.

Aim

The aim of this thesis is to identify ways in which the Sludging drilling technique can be most effective in soft material.

Objectives

1. To develop a mathematical model of discharge from the drill pipe. From this, hypotheses regarding the discharge and penetration of the drill pipe for different stroke lengths, pumping heads, and stroke rates will be developed.

2. To compare the hypotheses to results from field tests of the drill.

3. To evaluate, and if necessary modify the model.

Chapter 2. Theory behind the process

The low-cost rig operates in a similar manner to a percussion drill. A percussion drill sharply strikes the bottom of the borehole which fractures the rock into fragments (Clark, 1988). Cuttings are then removed with a bailer. The low-cost drilling rig also cuts downwards using a sharp cutting shoe on the end of the drill string which penetrates the ground as it impacts on the base of the borehole. The method of cutting removal is very different to the percussion method. Throughout drilling the hole is filled with water which acts as drilling fluid. A constant head of water at the top of the hole is maintained by a settling pit (see figure 2.1). Water carrying the cuttings is drawn up the inside of the drill string, as with reverse circulation drilling. The fluid is then expelled from the top of the drill string and directed towards the settling pit. The same hydraulic principles of a reciprocating displacement pump apply here. The reciprocating pump uses a piston that creates a vacuum behind it as it moves up the cylinder. Water is displaced into the vacuum by atmospheric pressure pressing on its external surface (Fraenkel, 1997). Suction is created in the drilling rig by a flap valve at the top of the drill string. As the drill pipe is raised, water and cuttings are drawn up the pipe due to the vacuum created behind the flap valve. At the end of the up-stroke the drill string stops but the water and cuttings push the valve open and continue upwards. This is because there is only limited friction between the pipe and the fluid, and so momentum in the fluid is retained after the up-stroke has ended.

Figure 2.1. The low cost drilling rig.

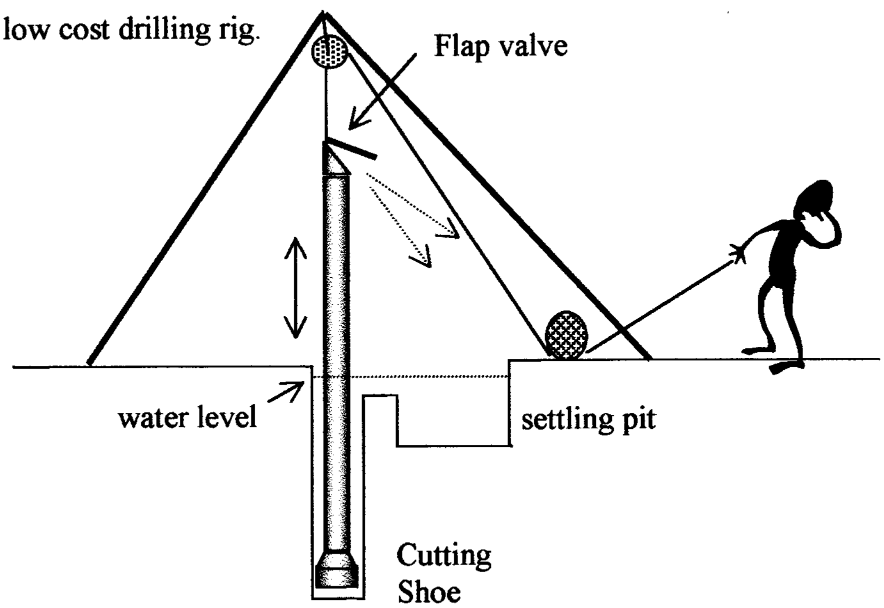


Figure 2.2. Photograph of Flap valve.

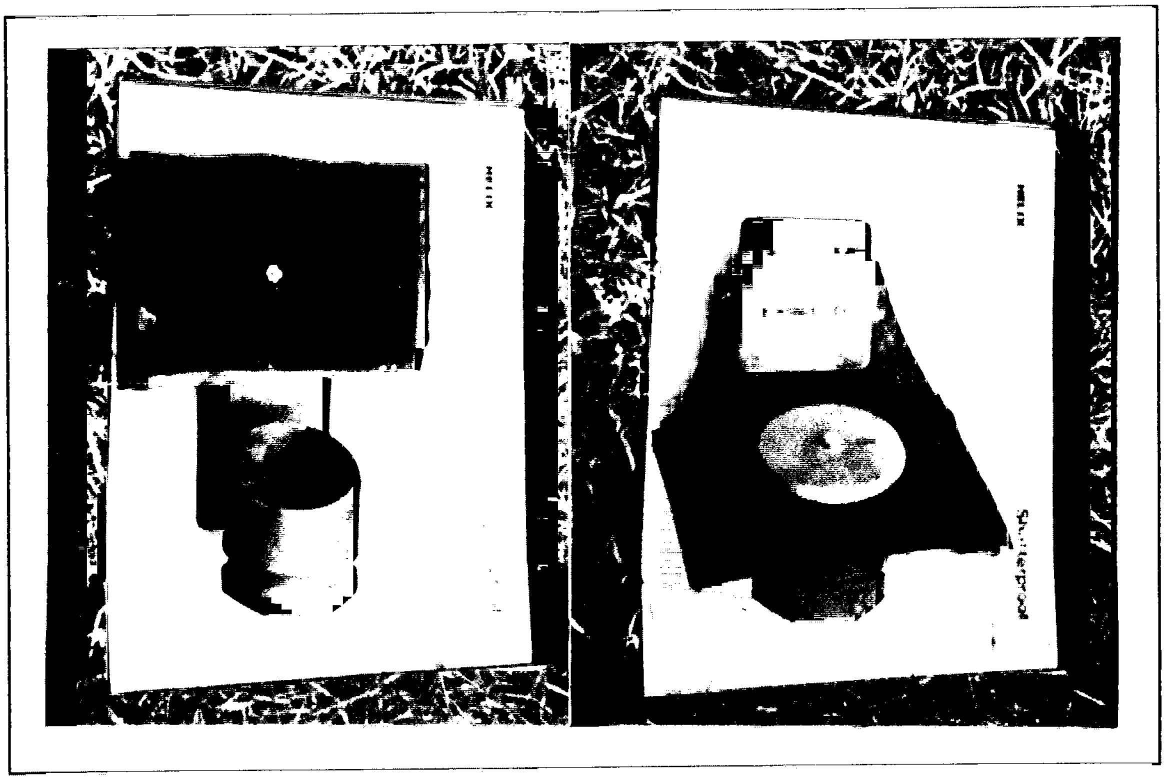


Figure 2.3. Photograph of the flap valve during operation.

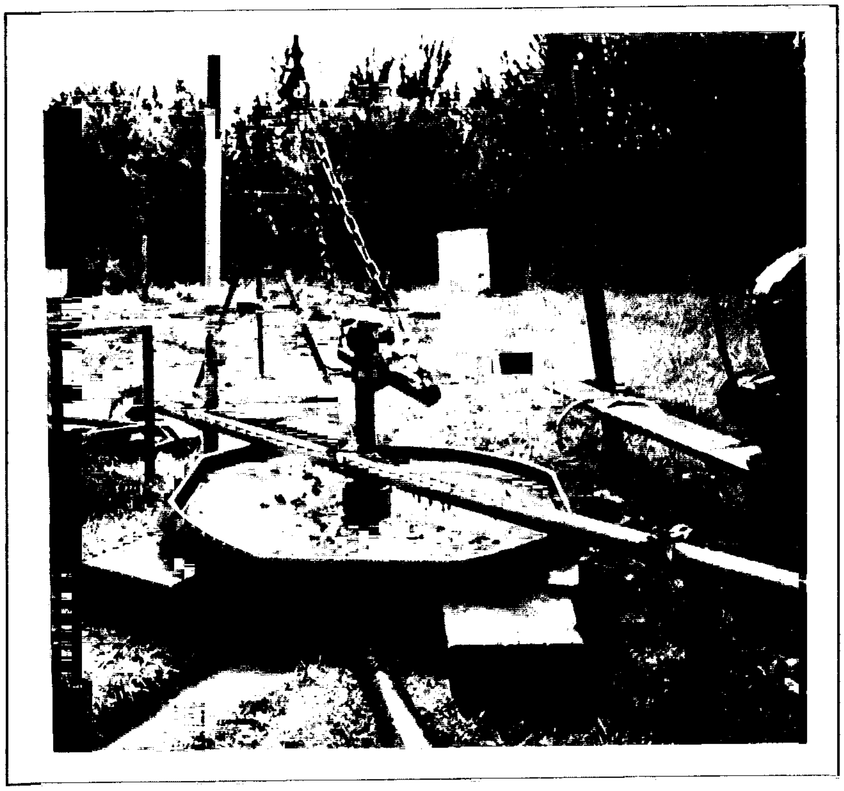
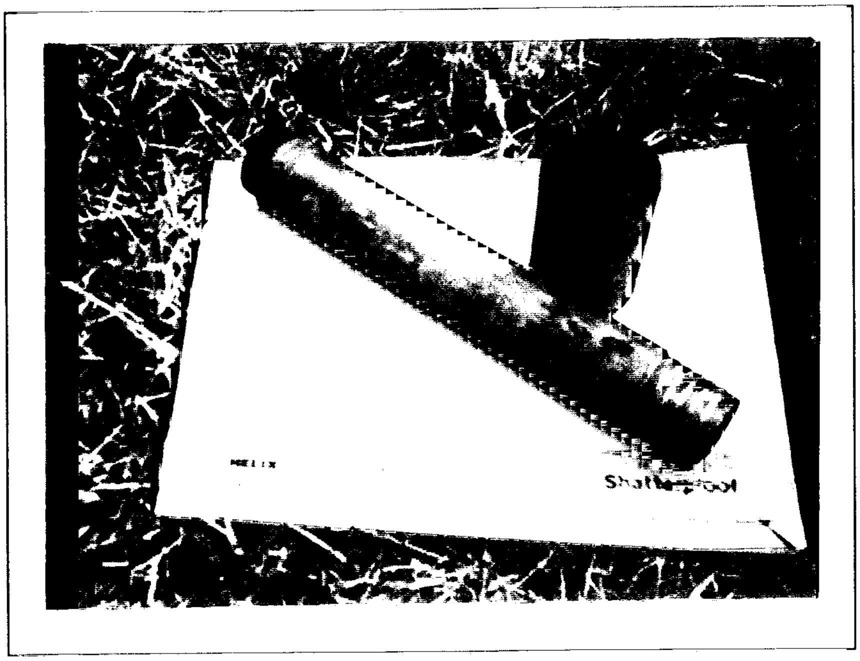


Figure 2.4. Photograph of a 0.06m diameter cutting shoe.



In order for a mathematical model of the drilling rig to be developed (see chapter 3), simplifications of the processes that are involved need to be made. Some important assumptions include:

a. There is no friction between the drilling fluid and the inside of the drill string, or between the drill string and the borehole wall.

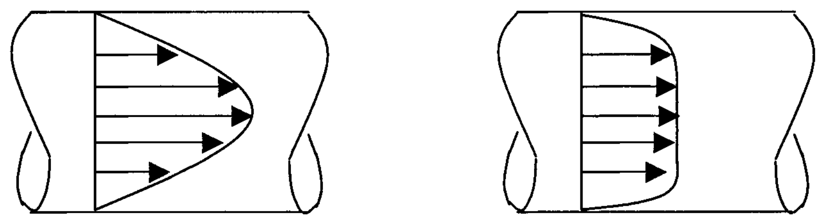
b. There is instantaneous deceleration of the drill string at the end of the up-stroke, and no 'dead time' between the up and the down-stroke. i.e. the down-stroke follows the immediate completion of the up-stroke.

a) Friction in the drill pipe.

There will inevitably be some friction between the water and the inside of the pipe. When fluid flows over a surface there will be shear stress between the surface and the fluid, which will act to retard the fluid (Douglas *et al,* 1995). However, it must be questioned whether this will be of significance during in the relatively short stroke length of the drill pipe, and if this friction increases greatly as cuttings and soil particles become suspended in the water.

Water travelling in a pipe is often treated as an 'ideal' fluid. This means that it is assumed to have no viscosity. Viscous shearing stresses are therefore absent and so all frictional effects are overlooked (Benedict, 1980). The water used in drilling rapidly becomes a mud. This could give the fluid a higher viscosity than water, and it may no longer be classified as 'ideal.' The assumption that there is no friction must then be reconsidered. If friction occurs between the internal pipe wall and the fluid then a boundary layer where flow is restricted will exist (Douglas *et al,* 1995). This effect is far more pronounced if flow becomes turbulent, where progression of the fluid particles is irregular with a seemingly random interchange of position (Webber ,1974).

Figure 2.5. Relationship between pipe wall and drilling fluid velocity.



(a) (b)

Velocity profiles. (a) laminar flow. (b) Turbulent flow. (Bober & Kenyon, 1980)

In order to discuss the extent of the retarding influence of the pipe wall it must be established whether the flow of the fluid in the drill string is turbulent. Turbulent flow exists if a fluid has a Reynolds number of greater than 4000 (Webber, 1974).

Reynolds Number: $R = pvd / \mu$

(where R = Reynolds number; p = fluid density; d = pipe diameter; and μ = viscosity).

Using a typical stroke length of 0.3m (from initial tests) the Reynolds number for the flow in the drill string at the end of the upstroke is as follows:

$R = pvd / \mu$

$R = 1000 \times 0.6 \times 0.03 / 0.00114$

$R = 15789.$

(viscosity of water = 0.00114 kg/ms at 15 ^{0}C, (Kay, 1998)).

This high number suggests that flow is indeed turbulent. A velocity of only 0.15m/s would give the discharge a Reynolds number of 4000, the threshold for turbulent flow. This would require a cycle time of four seconds which is very slow and impractical. Therefore turbulent flow can be assumed.

The Darcy-Weisbach equation can be used to determine the head loss in a pipe during turbulent flow (Kay, 1998).

$h_f = \lambda l v^2/2gd.$

Where h_f = head loss, λ = friction factor, v = velocity, g = gravity, and d = pipe diameter.

For the low cost rig, head loss =

$h_f = \lambda l v^2/2gd.$

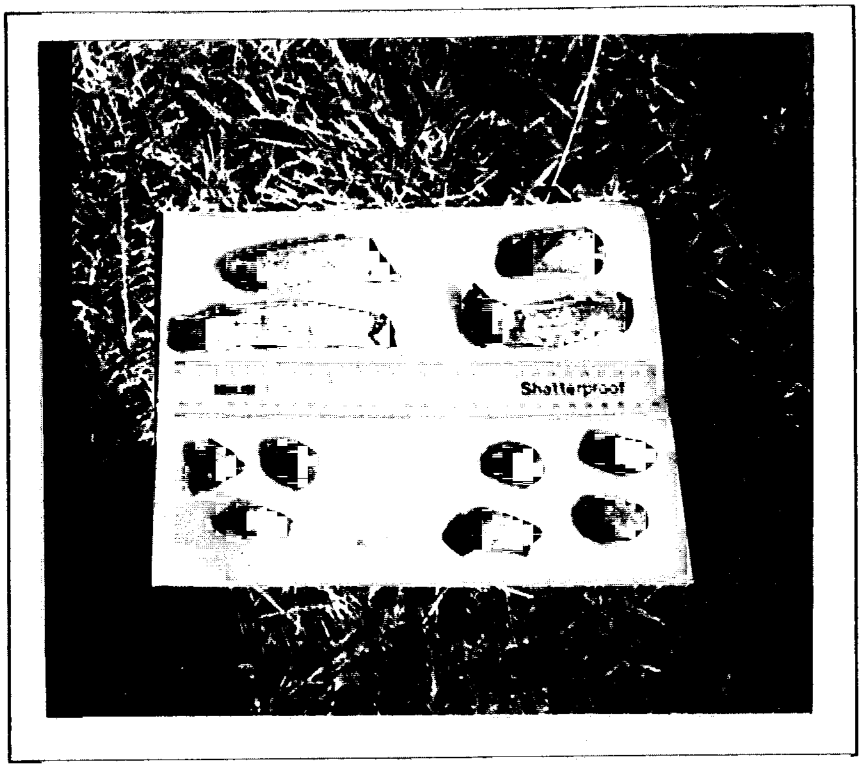
$h_f = 0.03 \times 0.3 \times (0.6)^2 / 2 \times 9.81 \times 0.025$

$h_f = 0.0066m$

Using a typical λ value of 0.03 (Hydraulic Research, 1983); a stroke length of 0.3m; and an initial velocity of 0.6m/s. (taken from initial test measurements).

This head loss (less than 1cm) is sufficiently small for internal pipe friction to be disregarded. In addition, the fluid is held in and is travelling at the same speed as the pipe until the end of the up-stroke. There will only be potential up-stroke friction

Figure 2.6. Photograph showing cuttings from the low-cost drill.



(The cuttings above the ruler are clay, bottom right are rocks, and bottom left are brick)

It can be concluded that internal pipe friction will be disregarded in the design of an initial discharge model, but later modifications may be required following an investigation into the influence of viscosity on head loss.

Friction between the borehole wall and the drill string will create a loss of energy from the system. In practice, the effects of friction between the external pipe wall, the fluid in the annulus, and the borehole wall can not be separated from the friction between the fluid and the internal pipe surface when measuring in the field. It should therefore not be treated as an individual function within the mathematical model. It is possible that comparison between the model and the field test data will produce an overall coefficient of friction for the drill.

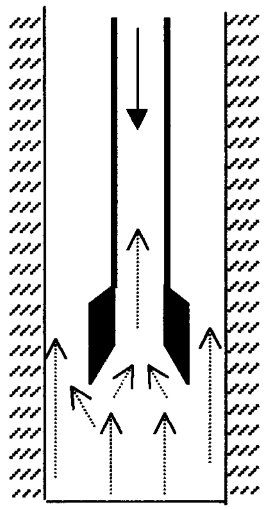
Paradoxically, the proximity of the external pipe wall to the borehole wall could increase discharge despite the possibility of increasing friction. The pipe end has a cutting shoe (see figure 2.4) which may act in a similar way to a pipe reducer and increase the velocity of the water inside the drill during the down-stroke. This is for a fraction of the 0.3m stroke length, between the flap valve being pushed open and the drill string stopping. This will further decrease the loss in head.

An important consideration is presented by Azouz and Shirazi (1997) who state that 'better cleaning of the borehole can be achieved with a drilling fluid circulated in turbulent rather that laminar flow, since better mixing of the drilled cuttings with the bulk of the flow takes place.' This suggests that the effectiveness of cutting removal and therefore drilling is in fact a good trade off against the marginal head loss due to friction from turbulence within the drill string. Large cuttings similar to the size of the pipe diameter (35mm) have been collected during initial drilling tests (see figure 2.3). These including stones with widths as great as 30mm. Holland (1973) states that turbulence must exist in a slurry (a liquid containing suspended particles) to prevent solid particles from settling. However, If the suspended particles are clays then it is the electrostatic repulsion of the clay platelets that keep them in stable suspension (Jones & Hughes, 1996). In this case, turbulence is not a necessity in achieving particle suspension.

The Darcy-Weisbach equation does not account for the effect that particles held in suspension will have on flow at the boundary layer, or the possible increase in viscosity of the water once drilling commences. Solid particles hydraulically conveyed in a vertical pipe can be subject to forces which cause them to rotate and move inwards towards the axis of the pipe (Holland, 1973). This process called the Magnus effect should limit the additional friction between the internal pipe surface and suspended cuttings. However, this factor still does not consider the relationship between the potentially increasing fluid viscosity and the internal pipe surface. There is no literature available to allow the effect of viscosity on pipe flow to be quantified (Kay, 1999) and so initial experiments in a controlled environment will be required to establish if viscosity significantly reduces discharge.

because it will capture additional water on its descent by covering a larger area than that of the drill pipe alone. However, this effect will be damped if the shoe is not flush with the borehole on the down-stroke, as fluid may also be pushed in between the outside of the shoe and the borehole wall (see figure 2.7).

Figure 2.7. The effect of the cutting shoe.



Possible Outcomes resulting from the cutting shoe:

a) Additional fluid forced up the drill string during the down-stroke, increasing the discharge.
b) The reduction in diameter from the cutting shoe to the drill string will increase fluid velocity and the ability to remove and hold larger cuttings.
c) Friction between the shoe and the borehole wall reduces the down-stroke velocity and decreases discharge.
d) Water is displaced to the side of the shoe, possibly enlarging the borehole diameter.
e) A large diameter shoe may produce cuttings greater in diameter than that of the drill string, preventing fluid and cutting movement up the pipe.

b) Instantaneous deceleration of the drill string at the end of the up-stroke.

Initial experiments with the drilling rig have shown that the period of time used to complete one stroke averages between half a second and one and a half seconds. To measure the deceleration rate at the end of the up-stroke would be very difficult during field testing of the drill because such small periods of time are involved. In the mathematical model (chapter 3), this deceleration must also be absent as its influence on discharge can not be verified during field tests.

The effect of pipe deceleration on discharge will relate to pipe friction. As the operator reduces the drill string velocity at the end of the up-stroke, the momentum of the water will give it a higher velocity than the slowing pipe. The fluid will therefore be moving past the internal pipe surface which will create friction. The internal pipe friction has already been assumed to be negligible and this is a second reason why the effect of the decelerating pipe should also be disregarded.

Chapter 3. The Mathematical model

3.1. Model 1

It is necessary to develop a theoretical model of water movement during the drilling process. Actual measurements from the drilling rig can be compared with the model. This may allow the effectiveness of the rig to be assessed. The influence that cuttings within the fluid have on the process can also be considered in relation to the model. Model 1 has been derived by using the equations of motion shown in Figure 3.1.1.

Figure 3.1.1. Equations of motion.

1) $v = u + a.t$	where:
2) $s = u.t + \frac{1}{2}.a.t^2$	u = initial velocity
3) $v^2 = u^2 + 2a.s$	v = final velocity
	s = distance
	t = time
	a = acceleration

Different periods during the drilling cycle must be isolated, and the resulting discharge must be quantified. The selection of these periods relates to changes in the fluid's motion within the drilling cycle. The model developed here identifies three different sections of a column of discharge that can be achieved (see figure 3.1.5).

The first section is created directly by the up-stroke of the drill string. The fluid velocity at the end of the up-stroke is equal to the final velocity of the drill string. After the up-stroke has ended, the fluid will continue to travel upwards with this initial velocity. The height that the fluid achieves as a result of the up-stroke is described by equation 1.

Equation 1: $H_1 = s/gt_1$

Figure 3.1.2. Height of water column H_1

(v =final velocity; u =initial velocity =2s/t_1 (the final velocity of the drill string on the up-stroke); s = stroke length; t_1 = time of the upstroke; a = deceleration due to gravity: g;)

$v^2 = u^2 + 2aH_1.$
$v^2 - u^2 = 2a.H_1$
$v^2 - u^2 /2a = H_1$
$H_1 = -u_1^2/-2g$ (i.e. velocity head)
$H_1 = u^2/2g$
$H_1 = 2s/t_1/2g$
$H_1 = 2s/2gt_1$
$H_1 = s/gt_1$

The second section of the column of fluid is achieved at the same time as H_1. While the column of fluid still has upward velocity following the upstroke, the down-stroke has begun. There will be a section of the column of water located below the highest point reached by the drill string that is exposed by the down-stroke during the time between the up-stroke finishing and the fluid achieving zero velocity. The height of this section is described in equation 2.

Equation 2: $H_2 = ½ (2s/t_4^2) (2/gt_1)^2$

(where 's' is the stroke length, and 't_4' is the time taken for the whole of the down stroke)

Figure 3.1.3. Height of water column H_2

(v =final velocity of water column; u =initial velocity of water column =2s/t; s =stroke length , a =deceleration due to gravity: -g)
Time taken for water to stop:
$t_2 = v - u / a$
$t_2 = 0 - 2s/t_1 / -g$
$t_2 = 2/gt_1$

Downward pipe acceleration (using = $s = u.t + ½.a.t^2$): $a = 2s/t_4^2$
(where t_4 is the time taken for the whole of the down-stroke)
$H_2 = u.t + ½\, a.t^2$
$H_2 = ½\,(2s/t_4^2)\,(t_2)^2$
$H_2 = ½\,(2s/t_4^2)\,(2/gt_1)^2$

The third section of the column of fluid (H_3) describes the fluid exposed by the drill pipe between the point where the fluid starts to achieve downward acceleration and the end of the down-stroke. At the beginning of this section the drill pipe already has downward acceleration, as the down-stroke began at the start of t_2. It might be assumed that the drill pipe and fluid are both falling under gravity and therefore H_2 plus H_3 should equal the stroke length. However, the drill string's downward acceleration is restricted by the friction in the borehole and the pulley at the top of the drilling rig. The t_4 component and stroke length define the drill string acceleration.

Equation 3: $H_3 = (s - H_2) - g\, t_3^2 /2$

Figure 3.1.4 Height of water column H_3

Distance pipe moves during t_3
$= s - H_2$

Distance water moves downward during t_3
$= ut + ½\, a\, t^2$
$= g\,(t^3)^2 / 2$ (where $t_3 = t_4 - t_2$)

Difference between the distance the pipe has moved and the distance the water as fallen downwards is the height of the water column gained.

$H_3 = (s - H_2) - g\, t_3^2 /2$

Figure 3.1.5 *Model for the 'sludging' method of drilling*

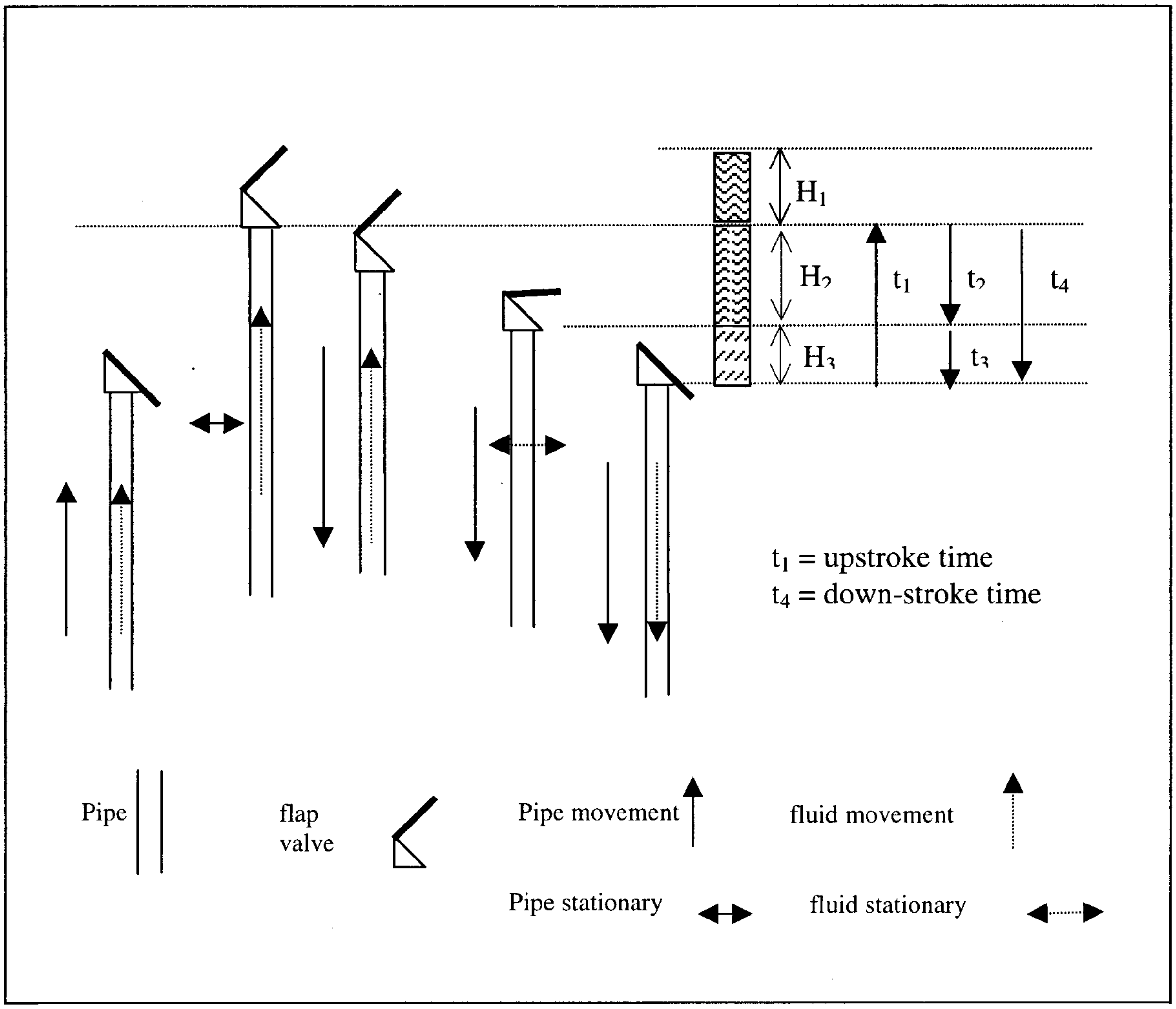


Figure 3.1.6 shows the proportion of discharge that each component (H_1, H_2, and H_3) contributes to the total fluid output of each cycle. The dominant section of the water column is H_2. During H_2 the period of time is t_2, and the cycle is in the down-stroke. The water velocity is decelerating from its maximum upward velocity to zero velocity. The time that this takes during faster cycles can be longer than the time of the down-stroke. The result is that a H_2 becomes the same as the stroke length. After this point H_2 decreases rapidly and H_3 becomes possible. H_3 makes a minor

contribution to discharge as the downward velocity of the water rapidly catches up with that of the drill pipe.

Figure 3.1.6 The components of discharge.

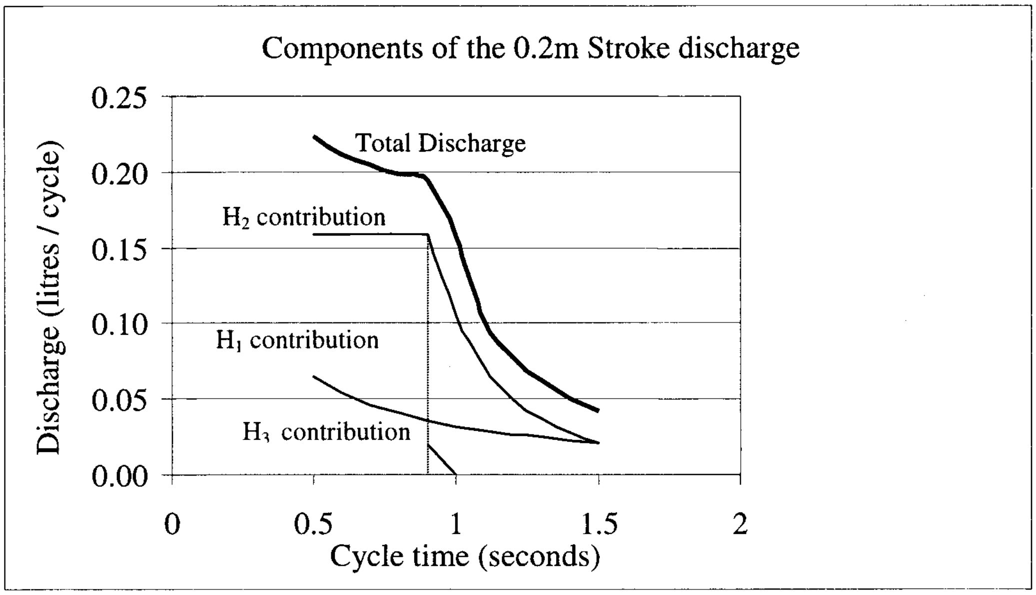
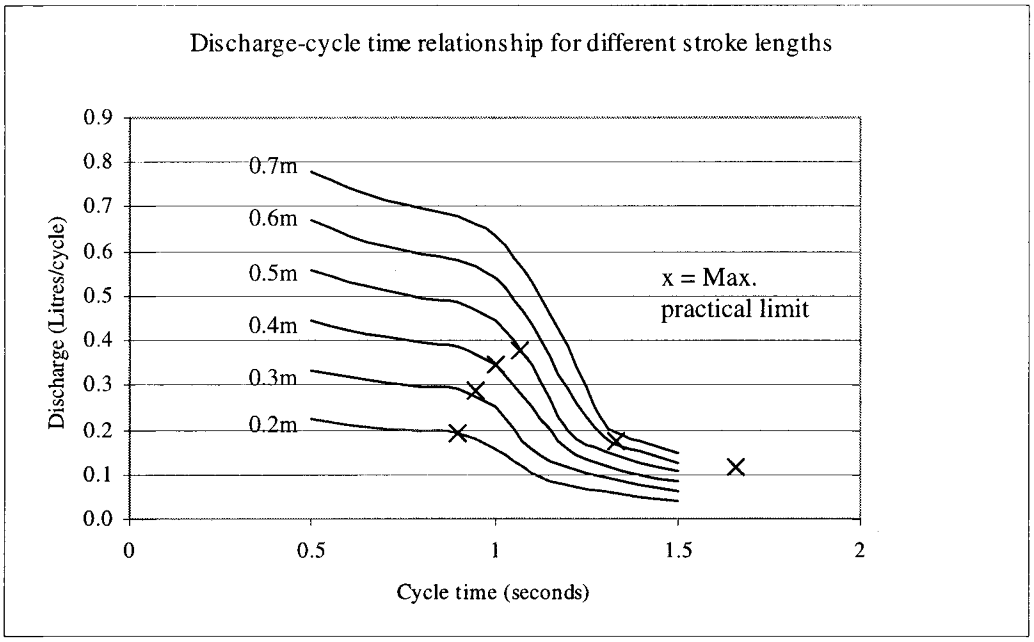


Figure 3.1.7 shows the predicted relationship between discharge and time taken to complete a drilling cycle for different stroke lengths, by applying the equations for H_1, H_2 and H_3.

Figure 3.1.7 Discharge-cycle time relationship for different discharges – Model 1.



The points of maximum practical limit (represented by a cross) show the fastest cycle times achievable for each stroke length (based on initial tests). The cycle times required to obtain the high discharges from the long stroke lengths are not physically achievable, demonstrating why the short to mid-range stroke lengths in initial tests produced higher discharges. The optimum cycle time is between 1 and 1.1 seconds. At a faster rate the increased effort of the operator only produces a marginally higher discharge. At slow cycle times the discharge drops dramatically. The graph shows that a discharge of 0.38 litres/second may be obtained using a 0.5 stroke length.

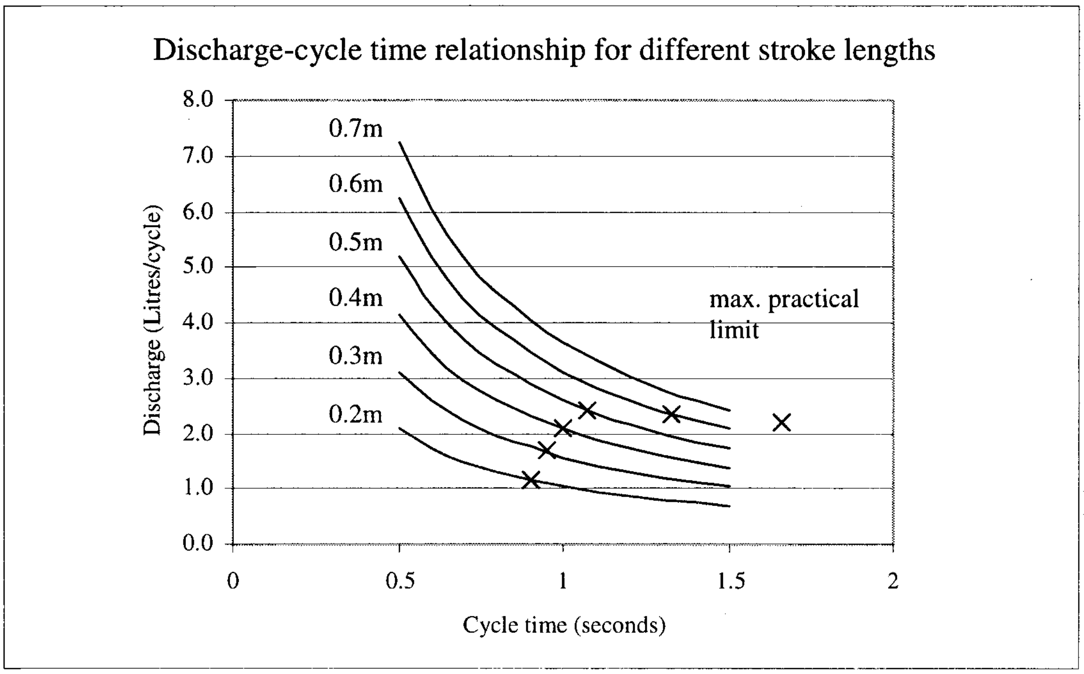
Model 1 suggest that:

1. The down-stroke time should be equal to or less than t_2 to maintain a high discharge.
2. A faster up-stroke marginally increases discharge.
3. Longer strokes theoretically give a higher discharge if a very high pumping rate can be achieved.
4. In practice, a maximum stroke rate of 0.5m should be used.
5. A discharge of 0.38 litres/second is obtainable.

3.2 A Mathematical Model including the effect of the cutting shoe.

Theoretically, the effect of the cutting shoe will be to funnel fluid up the pipe during the down-stroke. In an ideal situation, all of the water beneath the area covered by the shoe will be forced up the drill string as it moves down. The volume of fluid expelled is potentially the area of the shoe multiplied by the stroke length, assuming the process follows the law of continuity which states that discharge is equal to velocity multiplied by area (Kay, 1998). The H_3 component will no longer be present as the direction of fluid movement will be upward for the entire down-stroke. H_2 component will be equal to the stroke length multiplied by the cutting shoe area. The result of these changes to the model gives the graph in figure 3.2.1. The only two contributions to the discharge come from H_1 and the new H_2. The graph suggests that a discharge of as great as 2.5 litres/second could be achieved. This means that the new H_2 could theoretically dominate the entire discharge.

Figure 3.2.1. Discharge-cycle time relationship for different discharges including the effect of the cutting shoe.



The cutting shoe model suggests that:

1. The cutting shoe will increase discharge to a value greater than that predicted in model 1
2. Discharge is dominated by the down-stroke component.
3. Longer strokes theoretically give a higher discharge if a very high pumping rate can be achieved.
4. A discharge of 2.5 litres/second is obtainable.

3.3 Hypotheses

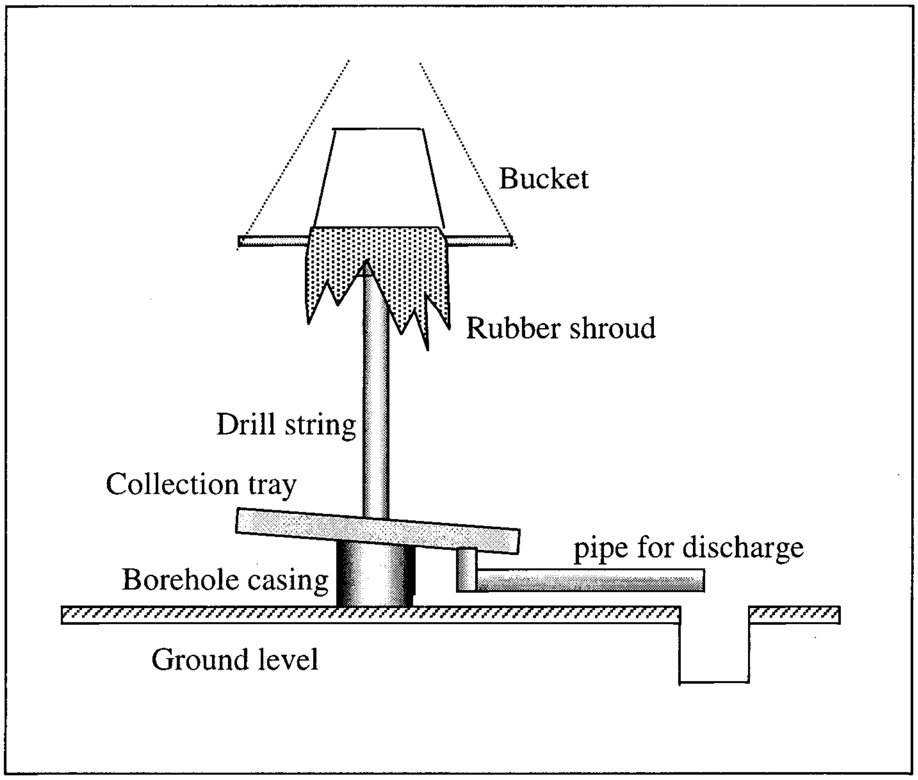
1. The cutting shoe will increase discharge to a value greater than that predicted in model 1
2. The drill will not achieve the discharge predicted by the cutting shoe model due to the effect of friction, head and viscosity.
3. The penetration of the drill will correlate with the discharge of the drill.
4. A mid-range stroke length of 0.5m will produce the highest discharges.

Chapter 4. Field testing

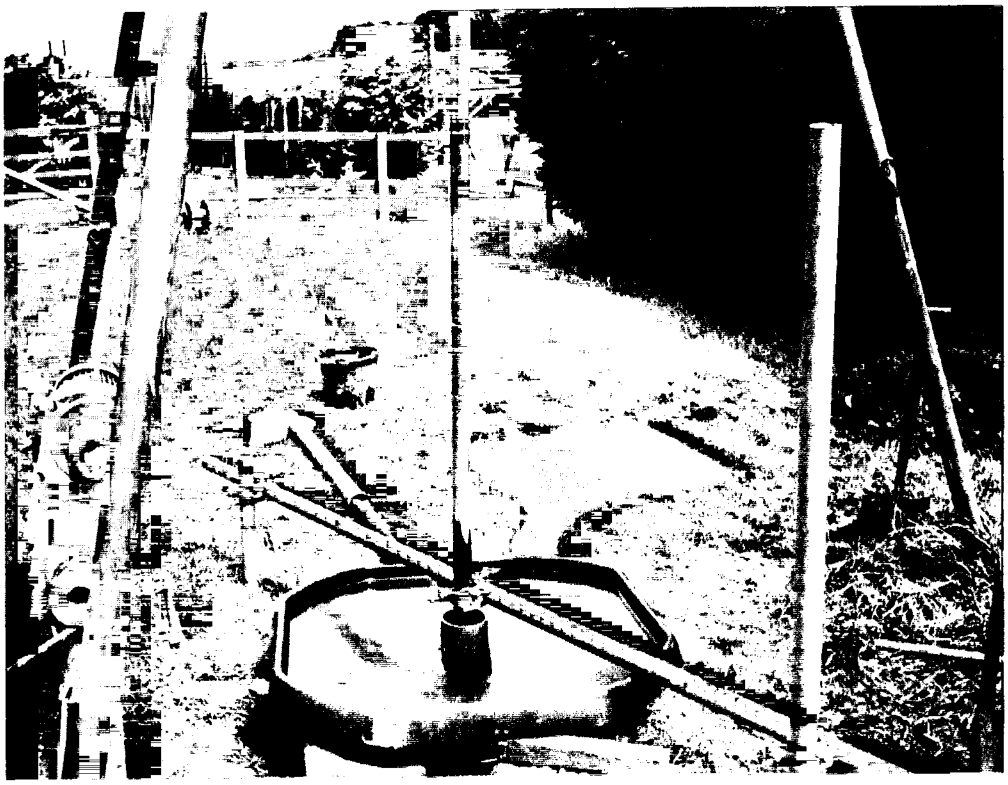
4.1 Stroke length, stroke rate, discharge and penetration

Investigation regarding the effect of stroke length on discharge was carried out in a borehole drilled by the low-cost rig. The geology of the site comprises four metres of Gault Clay overlying Woburn Sands. Measurements were taken whilst drilling through the sandstone, as clay can get trapped in the flap valve disrupting discharge. The discharge was measured by using a bucket and rubber shroud arrangement over the flap valve to direct the fluid downwards. A large plastic cement-mixing tray collected the water which then ran down a pipe connected underneath it. This could be directed to either a settling pit or collection bucket (see figures 4.1.1, 4.1.2). After each period of discharge measurement, the penetration was recorded by calculating the change in height of the drill string. The cutting shoe used for these experiments has an internal diameter of 0.08m.

Figure 4.1.1. Arrangements for discharge collection.



4.1.2. Photograph of the drilling rig, settling pit, and discharge collection pit.



Stroke lengths of 0.2m, 0.3m, and 0.4m were used. In addition, measurements were taken using different types of stroke cycle. A stroke cycle with an even speed (equal up and down stroke speeds), a cycle with a fast up-stroke, and a cycle with a fast down-stroke were used. The results are displayed in figures 4.1.3, 4.1.4, and 4.1.5. (Field test methodology can be found in appendix 1, and the raw data is available in appendix 2).

Figure 4.1.3. Variation in discharge and penetration using an 'even speed' stroke.

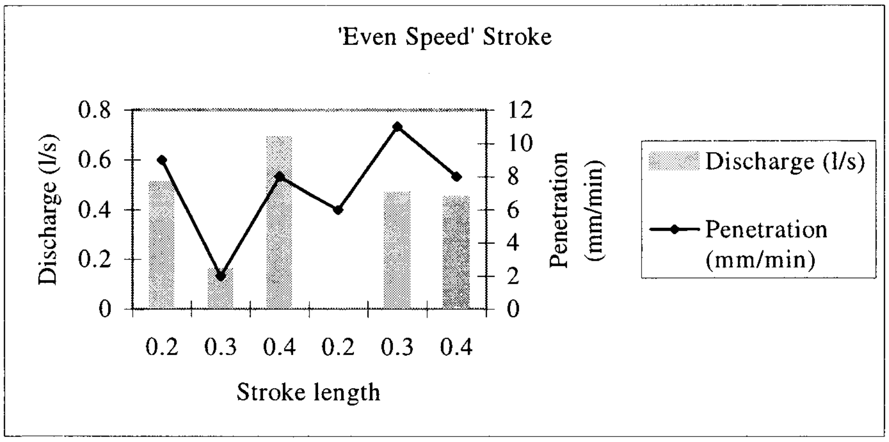


Figure 4.1.4. Variation in discharge and penetration using a fast up-stroke.

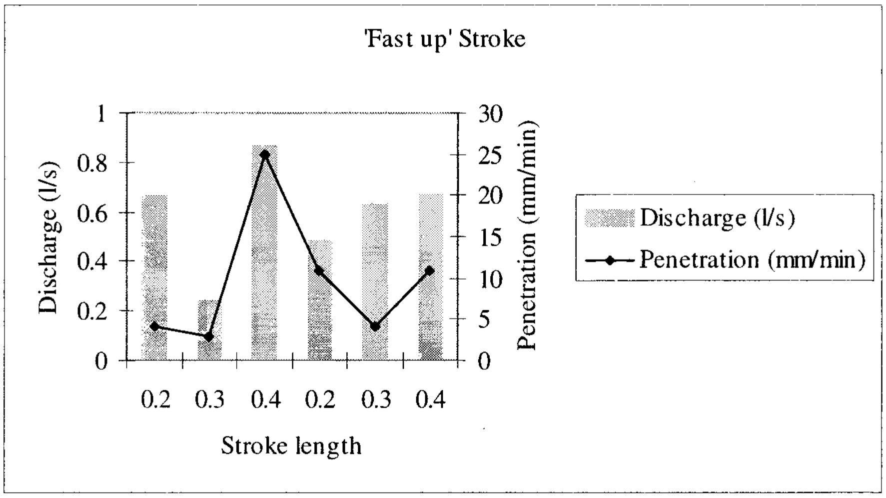
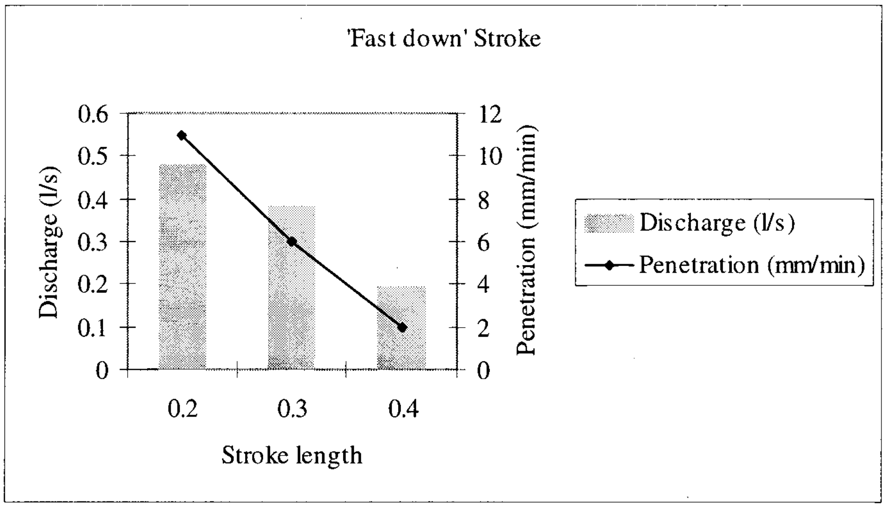


Figure 4.1.5. Variation in discharge and penetration using a fast down stroke.



The results show that the highest discharges are achieved with a fast up-stroke, and the lowest with a fast down-stroke. This is as the original discharge model predicts due to H_l increasing with a higher velocity up-stroke. However, the cutting shoe model should not be dismissed as most discharges are far greater than that predicted by model 1. Indeed, the highest discharge of 0.84 litres/second resulting from a 0.4m stroke with a cycle time of 0.94 seconds was predicted a discharge of only 0.36 litres/second by model 1.

The graphs all show correlation between penetration and discharge. The Spearman's Rank correlation values for each stroke type can be seen in table 4.1.1.

Table 4.1.1 Statistics for Stroke type, discharge and penetration

Stroke Type	Highest Discharge (l/s)	Highest Penetration rate (mm/min)	Rank Correlation for discharge and penetration
Even	0.69	11	0.71
Fast Up	0.86	25	0.55
Fast Down	0.48	11	1.00

The Spearman's Rank (Steel & Torie, 1980) results show a strong positive correlation between discharge and penetration. A value of 1 would show a complete positive correlation, and a value of –1 would represent a complete negative correlation between variables. The strongest correlation is found where there is a fast down-stroke. It may be that the extra energy in the down-stroke creates a greater impact on the base of the borehole, increasing penetration. The fast up-stroke, as the models suggest, will increase discharge but not necessarily have a harder impact on the hole base following the down-stroke. However, it should increase cutting removal and improve the ability of the cutting shoe to hit fresh material.

There are only moderate negative correlations between stroke cycle rate and discharge, and between stroke cycle rate and penetration (see table 4.1.2).

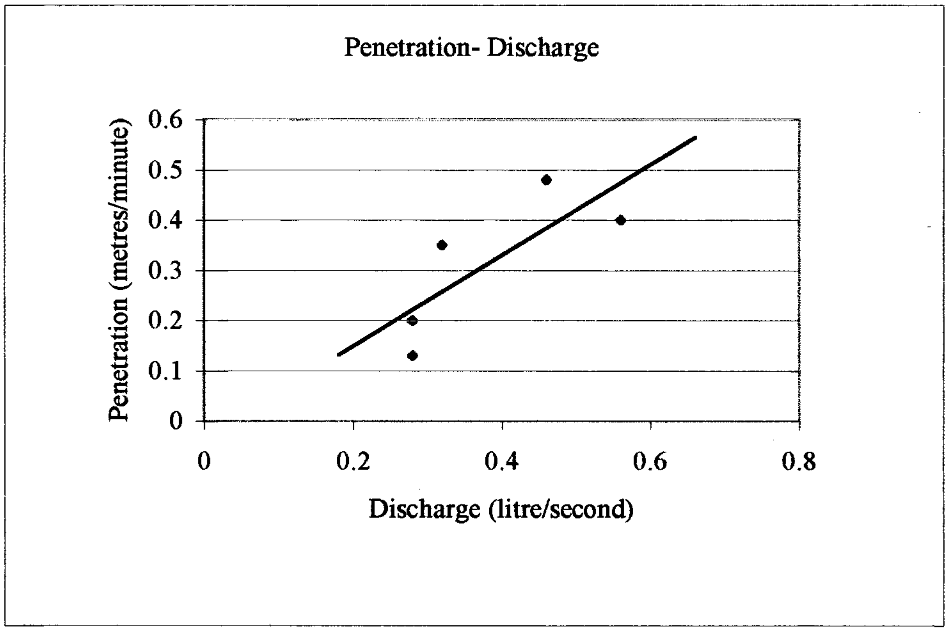
Table 4.1.2. Statistics for cycle rate, discharge and penetration

Stroke Type	Rank Correlation for penetration and cycle rate	Rank Correlation for discharge and cycle rate
Even Speed	-0.34	-0.6
Fast Up	0.11	0.23
Fast Down	-0.50	-0.50

A negative correlation would be expected as the longest cycle time should produce the least discharge, and therefore a low penetration. This is present for the 'even speed' and 'fast down' results but not in the 'fast up.' Unfortunately, the quantity of data (between three and six values for each variable) is limited for all of these results and this is a factor which must be considered when analyzing them. A value of +/- 0.886 is needed for the correlation to be significant at the 5% level (i.e. there is only a 5% probability that the relationship occurred by chance) if the sample size is six (Snedecor, 1962).

A second experiment was carried out to study the relationship between penetration and discharge. A new toughened steel shoe was developed at this time with a diameter of 0.06m. (This replaces a soft steel cutting shoe of 0.08m diameter). A stroke length of 0.3m was used. The graph of penetration and discharge can be seen in figure 4.1.6. Penetration rates are far greater than in previous results. This is largely due the new stronger sharper cutting shoe.

Figure 4.1.6. Penetration-discharge relationship with the toughened cutting shoe.



The Spearman's Rank value for figure 4.1.6 is 0.85 confirming the strong relationship between penetration and discharge discussed earlier in this section.

A Comparison between the field test results and the mathematical models demonstrates that the cutting shoe is of great importance. The results displayed in Figures 4.1.7, 4.1.8, and 4.1.9 show the measured discharges to lie in between the predicted values of model 1 and the shoe model. This suggests that the mathematical model that incorporates the potential discharge increase created by the cutting shoe is the more relevant. It follows that the factors discussed in previous chapters such as pipe friction, head and viscosity prevent the drill achieving similar discharges to those predicted by the shoe model. This is investigated in the following sections.

Figure 4.1.6. 0.2m Stroke length discharge-cycle time relationship for both mathematical models and the data collected.

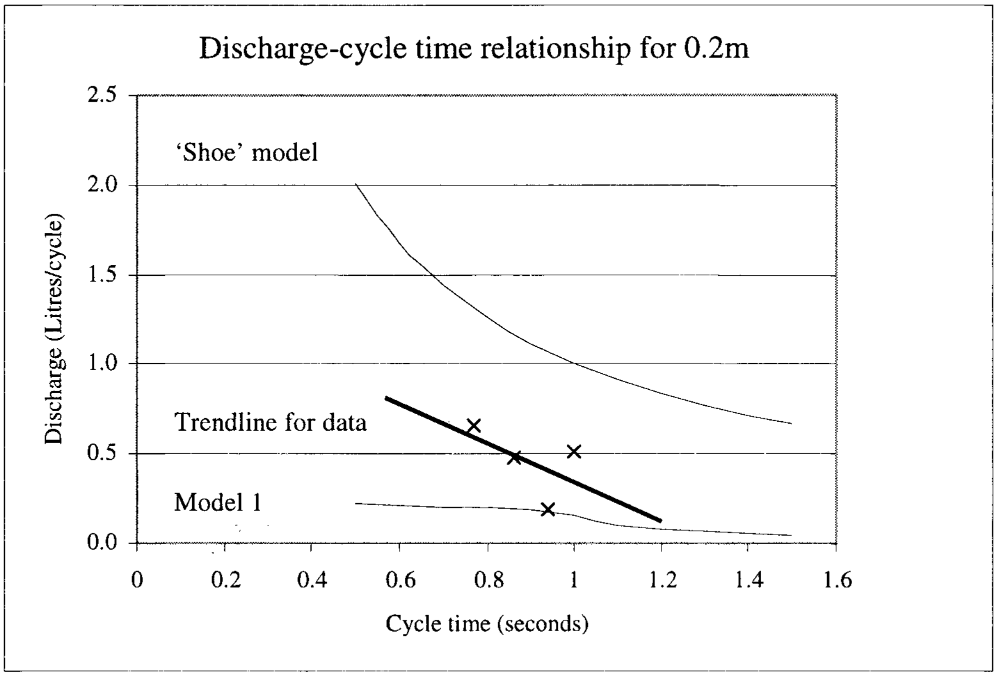


Figure 4.1.7. 0.3m Stroke length discharge-cycle time relationship for both mathematical models and the data collected.

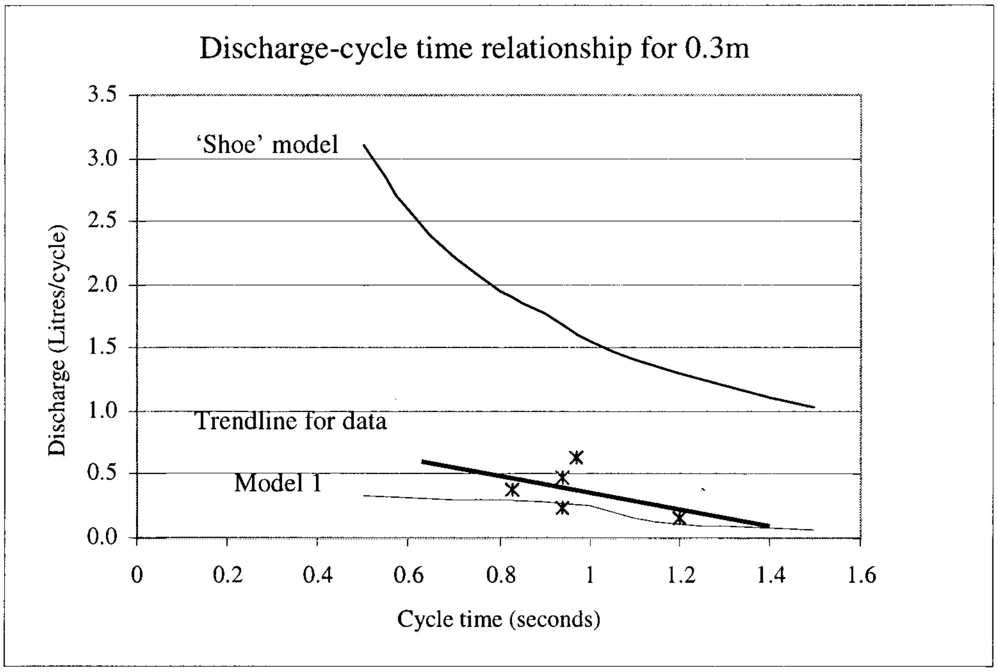
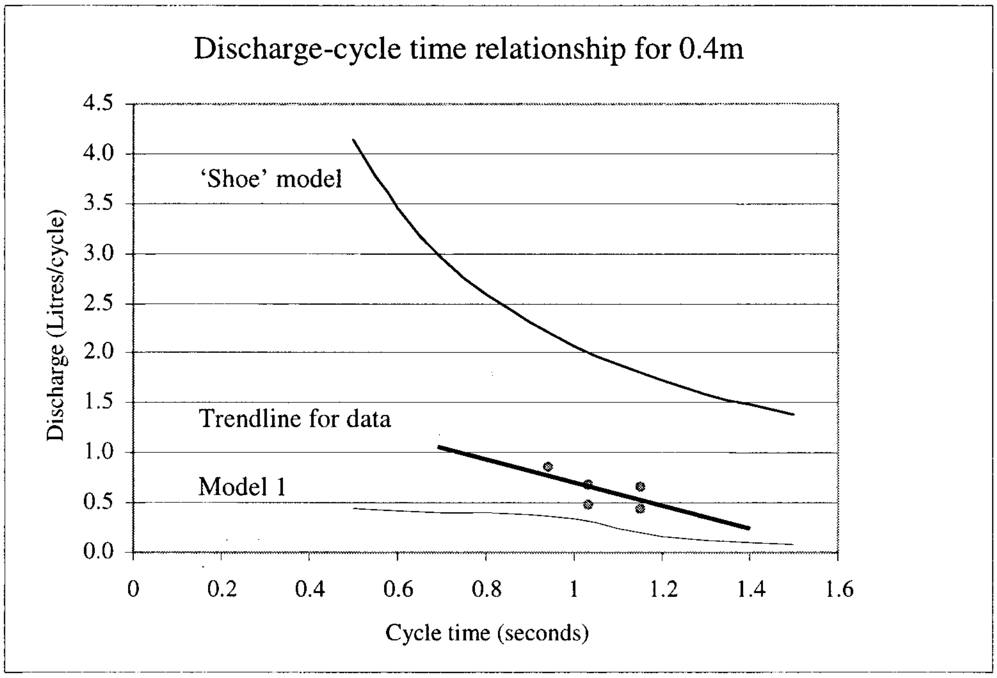


Figure 4.1.8. 0.4m Stroke length discharge-cycle time relationship for both mathematical models and the data collected.



Summary of Results for section 4.1

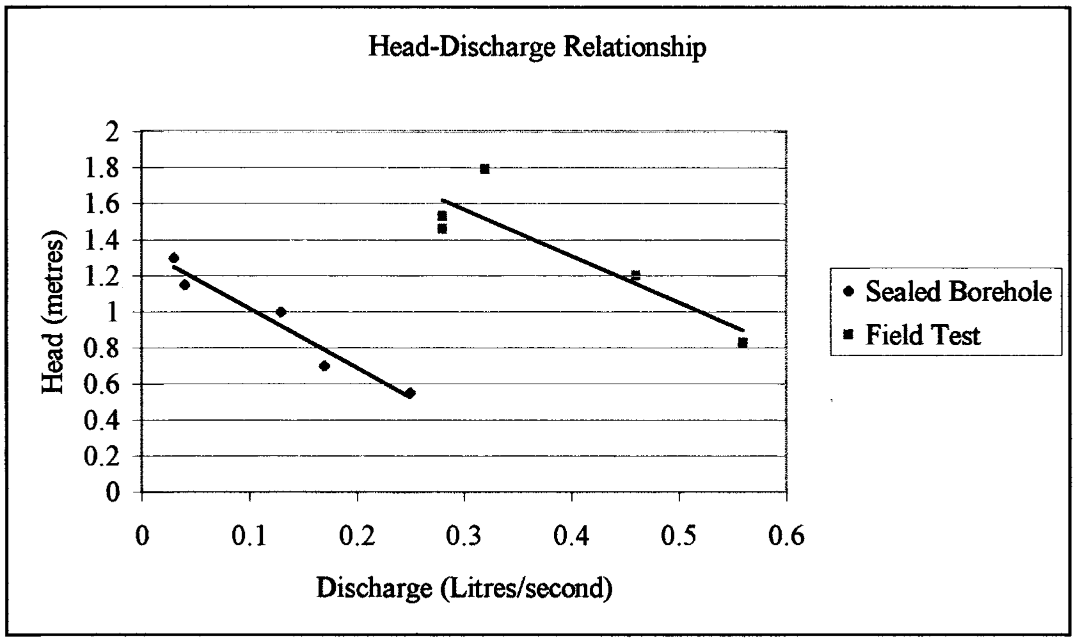
1. Penetration strongly correlates with discharge when drilling in soft material. Therefore an increase discharge increases the rate at which a borehole can be constructed.
2. Stroke length has not been shown to greatly influence either discharge or penetration.
3. The cutting shoe mathematical model is more relevant than model 1 as the measured discharges are higher than those predicted by model 1.
4. A cycle with a fast up-stroke achieves a higher discharge than either a cycle with a fast down-stroke or an even stroke.

4.2. Pumping head, viscosity, density and discharge.

Three experiments were conducted. The first considers the head-discharge relationship for the drill. A 0.3m stroke length was used to measure discharge at different heads. This was carried out in the sealed borehole and also in a field test (using the strengthened 0.06m diameter shoe for both experiments) to allow comparison. The second experiment considered viscosity. The sealed borehole was used, and an increasing amount of mud was added to the water. The stroke length was 0.3m, head was 0.85m, the strengthened cutting shoe was attached, and both discharge and viscosity were measured. In the third experiment the fluid density was considered instead of viscosity, and no cutting shoe was used.

Figure 4.2.1 shows the head-discharge curves for both the borehole and the field test.

Figure 4.2.1. Drilling rig head-discharge curves.



The Graphs show that the field test produces a higher discharge than in the wider sealed hole, confirming the advantage of having the cutting shoe flush with the borehole walls allowing fluid to be forced up the drill string.

The results of the stroke length, stroke rate, discharge and penetration in section 4.1 can now be considered in terms of head. The head-discharge experiments were carried out using a 0.3m stroke length. The lowest head measured was 0.83m and a discharge of 0.56 litres/second was achieved. The average head for the results in section 4.1 for the 0.3m stroke length was 1.68m. The discharge at this head using the equation for the line of best fit from the field test results in graph 4.2.1 is:

$y = -2.5801x + 2.3424$

$x = (1.68 - 2.3424) / -2.5801$

$x = 0.26$ litres/second.

(where y = head, and x = discharge)

Therefore the drilling rig in section 4.1 is operating with at least with a 46% reduction in potential discharge. The reduction could be even greater than this, but the shape of the head-discharge curve at lower head values is not known.

The results of the viscosity experiment can be seen in figures 4.2.2 and 4.2.3. The viscosity of the fluid remains fairly constant (only dropping from 26 to 27 seconds) as solid load is increased. This suggests that the internal pipe friction during drilling will not deviate dramatically from that of water, and treating the fluid as 'ideal' is acceptable. However this does not explain why the solid load within the fluid decreased the discharge by 0.2 litres/second, to 20% of its original value.

Figure 4.2.2. Viscosity-discharge relationship.

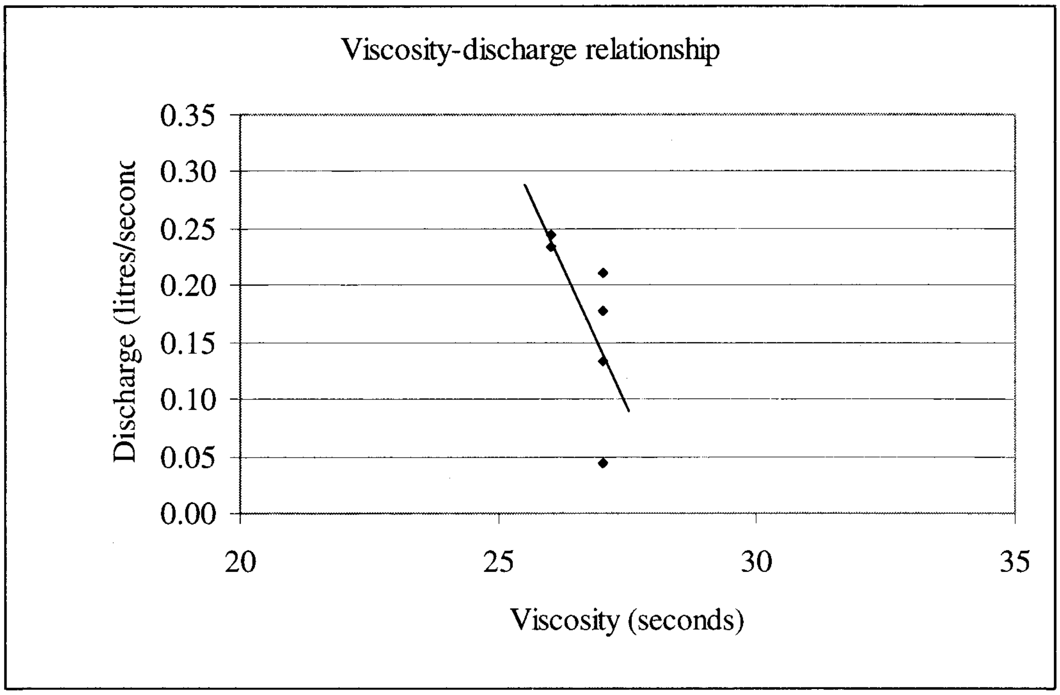
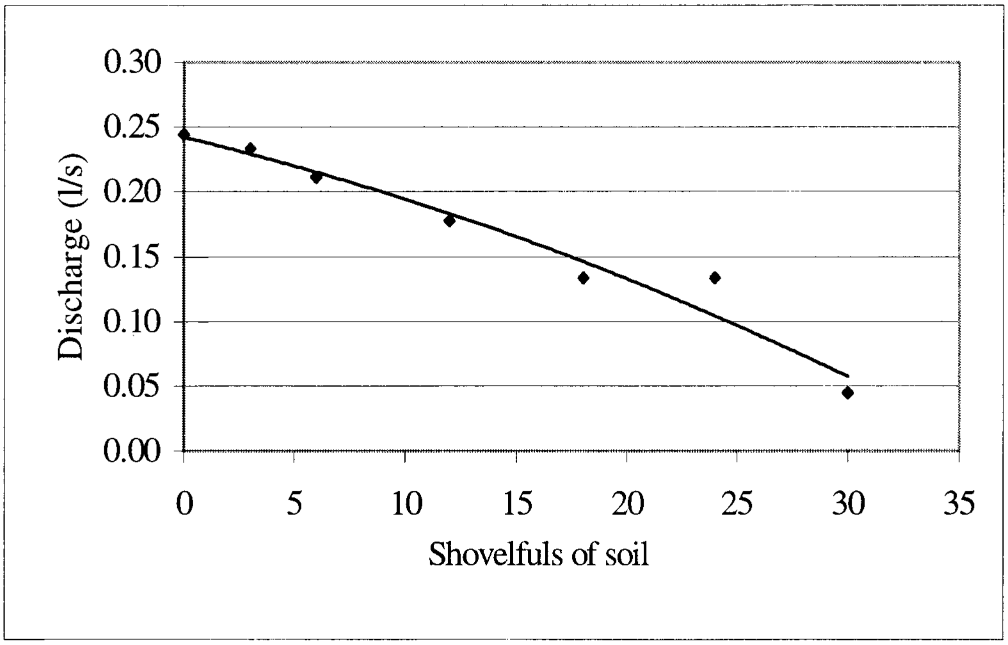
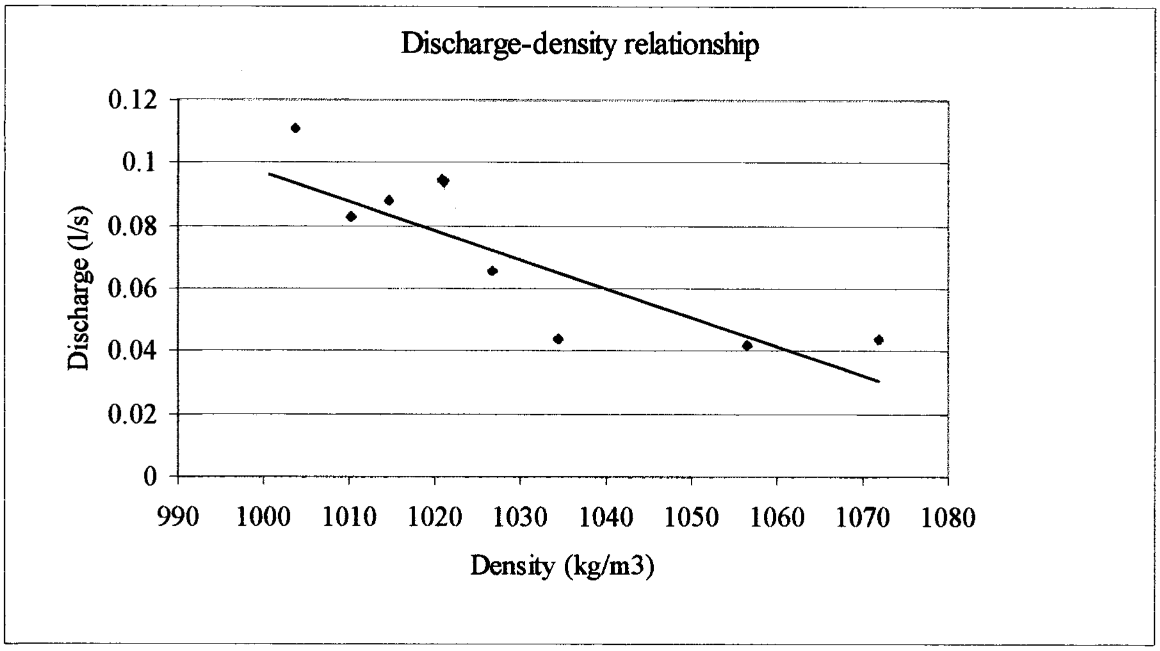


Figure 4.2.3. Solid load- discharge relationship.



The third experiment considered the relationship between the fluid density and head. The cutting shoe was not used. This allows comparison between the results for experiments two and three, and the effect of the shoe can also be studied. The results are displayed in figure 4.2.4.

Figure 4.2.4. Discharge- fluid density relationship

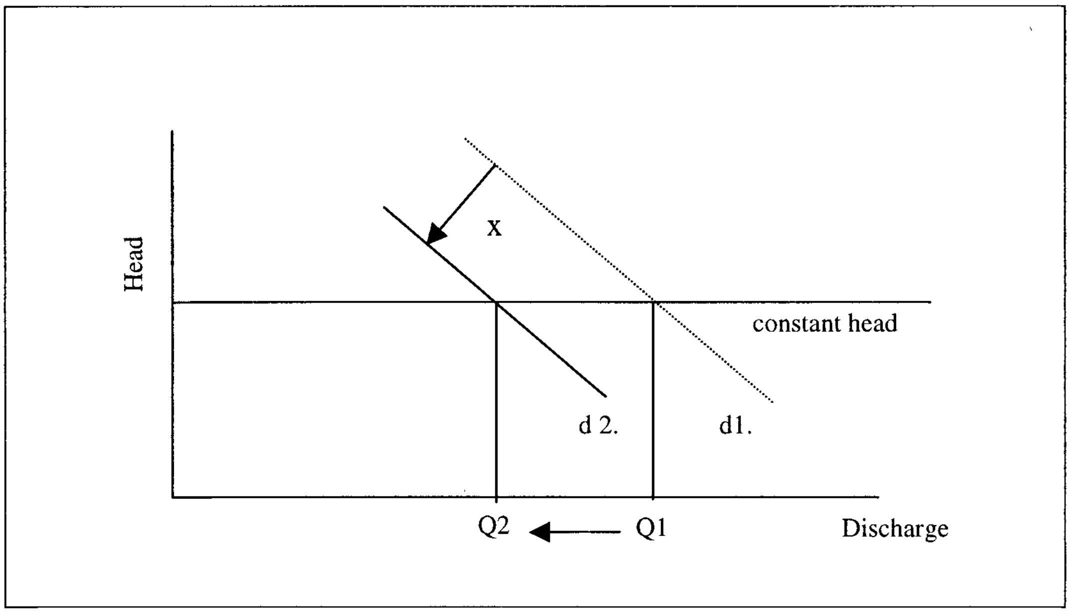


It can be seen that discharges without the cutting shoe are approximately 50% of those achieved with the shoe. In addition, these negative correlations between density and discharge suggest that an increase in fluid density has caused the loss in discharge seen in figure 4.2.2. The power used for both solid load experiments was kept fairly constant as the drilling rig was hand operated and the same cycle rate for each measurement was maintained.

Power $= p$ghQ
(where p = density; g = gravity; h = head; and Q = discharge).

It can be seen that if power, gravity and head are all constant, then discharge must decrease if density increases. A possible explanation is described in figure 4.2.5 . An increase in density reduces the entire discharge-head curve by a factor of 'x.' The head remains constant and so the discharge decreases.

Figure 4.2.5. Head-discharge curve for a change in fluid density.



The counter argument to this theory is that the fluid density has risen by only 7%, and yet an 80% reduction in discharge is being attributed to this small increase. The power equation ($P = \rho ghQ$) suggests that if density increases then discharge should decrease proportionally, and this is not the case. The power into the system may have changed slightly, but the operator was certainly not noticeably changing the amount of effort put into lifting the drill string, while keeping the stroke rate constant. There is obviously more to this issue than the results are showing, and further investigation is required to understand the processes that are taking place.

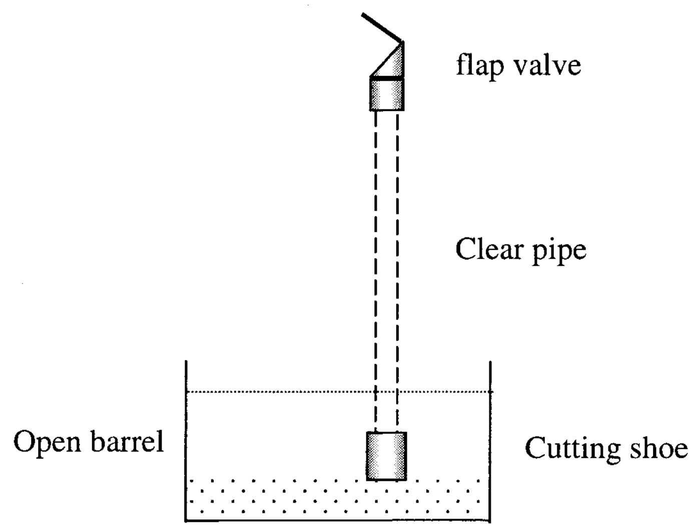
Summary of results for section 4.2.

1. A reduction in head can increase discharge by at least 50%.
2. A high solid-load fluid can reduce discharge by 80%
3. The cutting shoe greatly improves discharge.

4.3 Particle movement within the drill string.

An experiment was created to study particle movement within the drill string. The flap valve and the cutting shoe were attached to either end of a clear plastic pipe which has the same internal and external diameters as the original drill string. (see figure 4.3.1). Various sized sand and gravel particles were placed in an open ended barrel. The drill was then operated by hand and the particle movement within the pipe was observed.

Figure 4.3.1. Particle observation experiment



It was observed that the water and gravel ascends uniformly with the up-stroke of the pipe. Gravel particles then begin to settle downwards as the down-stroke takes place. They appear to lose approximately one third of the height gained during the previous up-stroke. An attempt to video the process was made to allow actual measurement of particle movement but this was unsuccessful. Using either a fast up-stroke or fast down-stroke appears to retard upward gravel movement, and progress is slow. There is little movement internally within the water and it travels up the pipe almost as a single entity.

These results suggest that 'chaotic' water movement is not responsible for particles being held in suspension, but merely the fact that the down-stroke is faster than the settling velocity of the particles enabling cutting removal. Jones and Hughes

(1996) present the following equation for the settling velocity of a particle in a drilling fluid:

$$v_s = 2R_c^2\,(p_c - p)g\,/\,9\eta$$

Where v_s = settling velocity; R_c = radius of cutting; p_c = density of cutting; p = fluid density; g = gravity; and η = Newtonian viscosity.

It can be seen from this equation that an increase in fluid density will reduce the settling velocity and so theoretically the fluids with a high solid load may well reduce settling velocities to insignificant levels. However, the reduction in particle settling velocity provided by the high solid load is a poor trade-off against the 80% loss in discharge discussed in section 4.2. Unfortunately it is impossible to recreate a high solid load fluid and observe particle settling velocities in the clear tube as the muddy water obscures any view of the gravels. Methods for studying settling velocities in non-transparent fluids usually measure the average gravity-driven settling velocity by using magnetic techniques, ultrasonic techniques, and radioactive techniques (Jin & Chenevert, 1994). These techniques are not within the scope of this investigation.

The experiment has provided some insight into the particle movement in the drill string; although creating conditions similar to the reality of drilling whilst maintaining the ability to observe the particles is not possible.

Summary of results for section 4.3.

1. A high solid load fluid can reduce the settling velocity of particles during the down-stroke.
2. Water movement within the drill string is fairly uniform.

Chapter 5. Discussion.

The overall aim of this thesis is to predict ways in which the effectiveness of the Sludging drilling technique can be improved. Several major causes for a loss of discharge have been identified, and a 'shoe model' has been developed which describes the extent to which the effectiveness of the drill could ideally be enhanced. The thesis also has several major objectives. These include the development of a mathematical model of 'sludge' movement in the drill pipe, and to test, evaluate, and if necessary modify the model. All of these objectives have been achieved.

Four hypotheses were proposed. Hypothesis number one states that the cutting shoe will increase discharge to a value greater than that predicted in model 1. This statement has proved to be true. Indeed, the results are as much as double those of model one and follow a trend similar to the curve of the cutting shoe model. This implies that the cutting shoe model is very relevant, and it can be concluded that the cutting shoe has two major functions. Firstly to break the material into which the borehole is being drilled, and secondly to greatly increase the discharge of the drill.

Hypothesis number two states that the drill will not achieve the discharge predicted by the cutting shoe model due to the effect of friction, head and viscosity. The field tests did not produce discharges as high as those predicted. However, the possible reasons for this result are somewhat unexpected. The effects of head, viscosity, and internal and external pipe friction, were identified in chapters two and three as the most likely sources for a loss in predicted discharge. When an increasing amount of mud is added to the water, the viscosity of the fluid remained comparable to that of clear water. This suggests that the fluid can be treated as an ideal fluid and internal pipe friction will be minimal. An inverse relationship between head and discharge was observed for the drill confirming that the height at which the flap valve operates has a large impact on the achievable discharge. More surprisingly, the experiments have shown that a high solid load in the drilling fluid may be responsible for reducing discharge by the greatest amount, 20% of the discharge recorded for clean water. The fact that this experiment was repeated and similar results were achieved gives this result a certain degree of credibility. If a reduction factor of 80% is applied to the shoe model then the predicted discharges fall within a similar range to those measured during the field test. This effect is therefore certainly a topic for future investigation. A field test should be designed where all cuttings are collected and either sorted or sieved to compile a cutting size profile. The density of the fluid over the period in which the cuttings are collected should also be measured. In this way the relationship between cuttings, fluid density and discharge could be analyzed in more depth.

The third hypothesis states that the penetration of the drill will correlate with the discharge of the drill. A strong positive correlation between penetration and discharge is shown by four different sets of results. It is therefore reasonable to suggest that the drill operates most effectively when discharge is high. Discharge facilitates penetration and not vice versa. Therefore by striving to increase discharge by reducing both operating head and solid load in the fluid, the drilling rate may be much improved. When the cutting shoe is attached, both the upward velocity and discharge of the fluid in the drill string will be greater in the down-stroke than the up-stroke, as the cutting shoe increases the volume of water being forced through the pipe. This increases the rate of cutting removal from the base of the hole providing a fresh surface for the drill to cut.

The fourth hypothesis states that a mid-range stroke length of 0.5m will produce the highest discharge. This was never proved or indeed investigated to any great degree. A large stroke length of 0.5m+ is impractical in terms of physically maintaining the action. In addition, when a new pipe is attached to the drill string, it is often the case that there is not enough room between the pulley at the top the rig's frame and the hook attached to the drill string for a long stroke length to be possible. In general, correlations between discharge and stroke length are weak, with negative and positive correlations present for the different cycle types. This is not the result that either of discharge models predicts. There are at least two possible explanations for this anomaly. First is the obvious lack of information. Each of the three correlations is derived from between four and six pieces of data. Alternatively, it is simply that there are other factors with a far greater influence in determining discharge. Head and fluid density have been shown to have a large influence in reducing discharge, each of which change constantly during drilling. Add to this the ever-changing hardness of the rock which is being drilled, and any direct correlation between stroke length and discharge may rapidly become masked.

There are many practical lessons to be learned from carrying out the field tests. It was noticeable during field testing that the drill needs to be operated at some height above the bottom of the hole when drilling restarts. Only when a reasonable discharge is being achieved should the drill be gradually lowered onto the floor of the borehole. To start sludging immediately on top of cuttings that have settled to the base of the borehole usually results in the drill string becoming blocked. A good discharge and the gradual approach to these cuttings reduces this problem. Even when this hurdle is overcome, a low discharge and a high penetration rate will inevitably lead to the pipe becoming clogged, and so the strong positive correlation between penetration and discharge is convenient to say the very least. Operation recommendations can be found in appendix 3.

The lack of field test data, particularly with regard to the relationship between stroke length, stroke type, discharge and penetration makes it difficult to reach positive conclusions. This problem is largely as a result of difficulties in measuring discharge. The cuttings often become trapped between the flap valve and the drill string preventing the creation of a vacuum. The drill string often becomes clogged which can take a long time to correct. The regular occurrence of both these problems makes achieving a sustained period of constant discharge somewhat of a rarity. In addition, each time the drilling stops for what can be a brief period of time, the cuttings in the pipe seem to fall to the bottom of the drill string. Encouraging this sediment to move again can take hours.

Chapter 6. Recommendations for future research.

1. A field test (described in the discussion) should be developed to understand the relationship between solid load in the drilling fluid, and discharge. This would involve the collection, measuring and sieving of cuttings, and the measurement of fluid discharge, viscosity and density. The relationship between these variables can then be explored in detail.
2. Several toughened steel cutting shoes with a range of diameters should be developed. Comparisons can be made between the discharge that the drilling rig achieves with each shoe. The shoe model can be adapted for the changes in shoe diameter and compared to field test results. It is possible than one size is more effective than the others, or that one cutting shoe is more efficient in relation to the predicted discharge.
3. The relationship between discharge, stroke length, and penetration in hard material should be studied. This thesis has only considered soft material. It will be of interest to compare the relationships that have been observed between variables in soft material, when the drilling rig operates in hard materials.
4. A deep borehole should be drilled using the low-cost drilling rig, and the effect that the increasing weight of the drill string has on penetration and discharge should be studied. It is possible that the additional weight will improve penetration, but this may affect the efficiency of the discharge in comparison to the predicted discharge. It is possible that additional penetration provided by the drill string weight will increase the ratio of cuttings to fluid discharge, and reduce the effectiveness of the drilling rig. The cycle rate may also decrease as the energy required to lift the drill string increases. This will change the maximum point at which the drilling rig could operate on the discharge models.

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Appendix

Appendix 1. Field Test / experiment Procedures.

1.1 Field test for stroke length and stroke rate, discharge and penetration

1. The initial borehole was started using a hand auger to depth of approximately 0.8m. This was cased with 4 inch borehole casing to aid the direction of drilling. A window was cut into the side of the casing (0.28m x 0.0085m) at the level of the setting pit inlet for fluid to flow into the hole.
2. The low-cost rig was used to drill through 4m of clay. Measurements proved difficult as clay gets trapped between the flap valve and the drill string preventing a suitably long period of continuous discharge to occur.
3. Below 4m there is sandstone. Discharge was measured by recording the time to fill a 5 litre bucket from the outlet pipe at the base of a cement-mixing tray (see figure 4.1.1).
4. 5 minute periods of drilling took place. Stroke length and cycle rates were kept constant for each period. During this time the discharge was measured repeatedly, and the number of stroke per 30 seconds was counted in order to calculate a cycle rate. Stroke length was kept constant by tying string horizontally at 0.1m intervals between the rig supports in front of the operator. The rope used to operate the drill was also marked at 0.1m intervals. This allowed the operator to judge stroke length despite the downward movement of the drill. Penetration was measured after each 5 minute run.
5. The process was repeated for different stroke types (even, fast up, fast down) and different stroke lengths.

1.2 Head-discharge graph from the sealed borehole

1. The experiment was carried out in a sealed borehole. The arrangement for fluid collection in appendix 1.1 was used. A single length of drill pipe was used with the flap valve at the top, and the cutting shoe attached to the base.
2. A constant head of water in the borehole was achieved using a hosepipe from which water ran continuously into the borehole during measurement.
3. The drill was operated by hand. The volume of fluid discharged from the drill was measured for a 90 second period. Stroke rate was kept constant and stroke length was 0.3m. Discharge was calculated for a range of different heads.

1.3 Viscosity/density -discharge graph from the sealed borehole

1. The experiment was conducted using a sealed cased borehole. A barrel with a hole in the base was placed over the exposed borehole casing and a watertight seal between the two was made using bentonite. This allows a constant head of water to be maintained whilst pumping. The discharge was measured with a head of approximately 0.85m at the top of the up-stroke, and a stroke length of 0.3m was used throughout the experiment.
2. Initial measurements were made with clear water. The solid load of the water was gradually increased by adding soil to the barrel and borehole and stirring thoroughly. Both viscosity and discharge were measured each time soil was added.
3. The method was repeated at a later date without the cutting shoe, and the density of the discharged water was measured.

Appendix 2. Field Test / Experiment Data

2.1 Field test data for stroke length and stroke rate.

borehole depth At start of period (m)	time (mins)	Cycle rate (s)	Stroke type	Stroke length (m)	Drill string length (m)	pumping Head (m)	Average discharge (l/s)	Penetra - tion (mm)	Penetration rate (mm/min)
3.310	5	1.00	Normal	0.2	4.663	1.718	0.51	45	9
3.355	5	0.77	fast-up	0.2	4.663	1.673	0.66	20	4
3.375	5	0.87	fast-down	0.2	4.663	1.653	0.19	10	2
3.385	5	1.20	Normal	0.3	4.663	1.643	0.16	10	2
3.395	5	0.83	fast-up	0.3	4.663	1.633	0.24	15	3
3.410	5	0.97	fast-down	0.3	4.663	1.618	0.38	30	6
3.440	5	1.03	Normal	0.4	4.663	1.588	0.69	40	8
3.480	5	1.03	fast-up	0.4	4.663	1.548	0.86	125	25
3.605	5	1.15	fast-down	0.4	4.663	1.423	0.48	55	11
3.660	5	0.91	Normal	0.2	5.163	1.868	---	30	6
3690	5	0.94	fast-up	0.2	5.163	1.838	0.48	55	11
3.745	5	0.94	Normal	0.3	5.163	1.783	0.47	55	11
3.800	5	0.94	fast-up	0.3	5.163	1.728	0.63	20	4
3.820	5	0.94	Normal	0.4	5.163	1.708	0.45	40	8
3.860	4	1.15	fast-up	0.4	5.163	1.668	0.67	45	11

2.2 Data for head-discharge graph from the sealed borehole.

Head (m)	No. of strokes	Time (s)	Vol (l)	Discharge (l/s)
0.55	100	89	22	0.25
0.70	100	108	18	0.17
100	100	101	13.5	0.13
115	100	101	4.5	0.04
130	100	98	2.5	0.03

2.3 Data for viscosity – discharge graph from the sealed borehole.

	Time (s)	No. of strokes	Viscosity (s)	Discharge (l)	Shovelfuls of soil	Cumulative shovelfuls of soil
1	90	69	26	22	0	0
2	90	69	26	21	+3	3
3	90	69	27	19	+3	6
4	90	69	27	16	+6	12
5	90	67	27	12	+6	18
6	90	66	27	12	+6	24
7	90	69	27	4	+6	30

2.4. Field-test data for penetration, head and discharge graphs.

Head at start (m)	Head at finish (m)	Average head (m)	Change in head (m)	Time for drilling (min)	Penetration rate (m/min)	Discharge (l/s)	Notes./Pipe length
1.71	1.20	1.46	0.51	2.30	0.20	0.28	7.5m + ends
1.03	0.63	0.83	0.40	1.00	0.40	0.56	
1.96	1.61	1.79	0.35	1.00	0.35	0.32	9m sand
1.59	1.46	1.53	0.13	1.00	0.13	0.28	clayey lense
1.44	0.96	1.20	0.48	1.00	0.48	0.46	

2.5. data for density – discharge graph

Shovelfuls of soil	time (s) Strokes	Strokes	Volume (l)	Density (kg/m^3)	Discharge (l/s)
1	90	94	10	987	0.111
2	90	94	8	997	0.088
3	90	93	7.5	993	0.083
5	90	97	6	1008	0.066
7	90	94	4	1015	0.044
10	90	94	3.75	1035	0.042
13	90	95	4	1049	0.044

Appendix 3. Operation Recommendations

(based on measurement and observation)

1. Maintaining a high discharge from the drill is advisable to achieve a high penetration rate.
2. Keep pumping head low to achieve a high discharge– ideally use 1m length pieces of drill string.
3. Keep density of drilling fluid low to achieve a high discharge – use a large settling pit.
4. A stroke length of 0.3m seems to be a good trade off between head loss and stroke length to maximize discharge.
5. When recommencing drilling, operate the base of the drill string above the sediment to achieve a good discharge, and then gradually lower the drill string to remove the accumulated sludge. Drilling the sludge immediately will lead to blockage of the drill pipe.
6. Do not leave the drill string in an uncased borehole when it is not in use. The highly saturated walls may collapse and entomb the drill string.
7. There is no advantage to using either a fast up-stroke or fast down-stroke.