DIAMOND DRILLING FOR CORE SAMPLING

The drilling for, and recovery of core samples from the earth's crust, sometimes at distances of up to 3Km from the surface, is subject to many practical problems. One of these problems involves the jamming of core samples inside the recovery cylinder during drilling.

There is a need to analyse the forces involved when the recovery cylinder is sliding over the core. Several simple mechanisms associated with naturally occurring variations in rock and soil structure were suggested as possible causes of jamming.

The results suggest that the simplest mechanisms are not the cause of the problem, but combinations of these simple mechanisms might well be the cause. The results and discussion indicate some experiments that would be useful in a further study of the problem, and data from the drilling operations that should be kept for further analysis.

1. Introduction

Longyear Australia is an Adelaide-based company specialising in the manufacture and export of core drilling equipment. In core drilling, rather than in drilling of a simple hole, the drill bit cuts an annular hole and the central portion, the core, is extracted and used for sampling.

Typical clients include mining companies who perform assays on the cores in pursuit of mineral deposits, and engineering companies who are looking for fractures and geological structure that might impact on major civil engineering projects such as dams.

The drilling may be vertical, horizontal, or in any other appropriate direction, and the cores may be taken at distances in excess of one kilometre from the drilling rig and its operator.

Since the purpose of the drilling is to inspect cores to determine the specific properties of the (inhomogeneous) ground, it follows that prior knowledge of the mechanical properties of this ground is, at best, imprecise. The design of the mechanism that holds the drill bit and also allows recovery of the cores must be able to cope with a variety of rock types and particle sizes, as well as fine particles and wet clays produced by the drilling process.

The design of the drilling equipment is constantly under review, and the occurrence of blockages in some situations has been identified as a problem. Any modification of design leading to reduced blocking would improve performance.

2. The problem

The equipment for this core drilling is illustrated in figures 1(a), 1(b) and 1(c). It consists of an outer cylinder with a diamond impregnated bit at the end, and a reamer attached to the side. The bit cuts an annular hole leaving a central core. The inner cylinder is used to extract the core.

The outer cylinder and bit rotate and are pushed forward during drilling. A bearing at the upper end of the inner cylinder allows it to be pushed forward with the outer cylinder, while (in principle) not rotating during drilling. In practice, the bearing and water coolant transmit some rotational torque to the inner cylinder during drilling. When a standard core length, typically 2 metre, is enclosed by the inner cylinder drilling temporarily stops. Tugging the inner cylinder snaps the core, and the inner cylinder and core are withdrawn and the core removed. The inner cylinder is then returned to inside the outer cylinder and further drilling occurs until another standard core length is ready to be recovered.

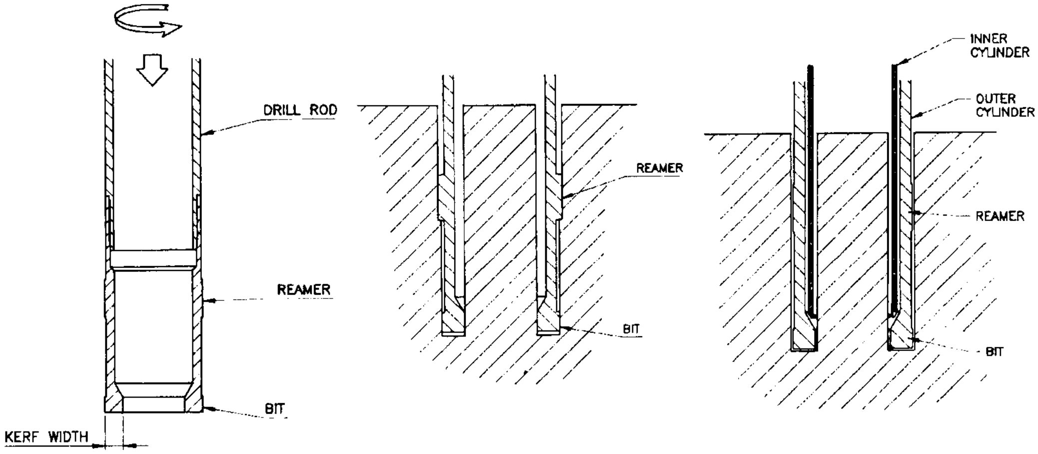

Figure 1: (a), (b) and (c) Diamond studded drill bit and cylinders.

Unfortunately, drilling does not always follow the ideal description given above. In particular, in some circumstances drilling is prevented because jamming of the core in the inner cylinder prevents the inner cylinder, and hence the outer cylinder, from being pushed forward. Drilling is prevented until the inner cylinder is recovered, and the cause of the jamming removed.

Repeated recovery of the inner cylinder with small amounts of core is very time consuming and greatly increases costs.

The problem presented to the study group was to attempt some modelling of mechanisms that might lead to the core jamming. Successful analysis and identification of such mechanisms might lead to modifications of the current design of the equipment to reduce the amount of jamming.

3. Some possible causes of blockages

Several mechanisms were suggested that might lead to friction forces on the inner cylinder sufficiently large to prevent this cylinder being pushed along the core. These include:

1. Wedging action of fractures in the core (see figure 2);
2. Gravel bed providing large normal forces against the cylinder wall during compression of the bed (see figure 4(a));
3. Bent core jamming against the side of the (straight) inner cylinder (see figure 4(b));
4. Large particles blocking the axial motion (see figure 5(a));
5. Small particles between the core and cylinder wall pressing the core against the opposite side of the cylinder (see figure 5(b));
6. Long bent driving column jamming against the drill hole;
7. Blockages occurring at the entrance to the inner cylinder.

These mechanisms are discussed in the following sections and some analysis is presented.

3.1 Wedging action of fractured cores

A simplified fractured core is illustrated in figures 2(a) and 2(b). The suggested mechanism causing blocking is that the friction force from contact between the cylinder and the core causes the upper part of the core to slide down the fracture surface. This will increase the normal force between the cylinder and both parts of the core, which in turn will increase friction forces between the cylinder and both parts of the core stopping further motion.

We first consider the special case of a *plane* fracture surface at an angle ϕ to the axis of the cylinder (see figure 3). The following notation is used:

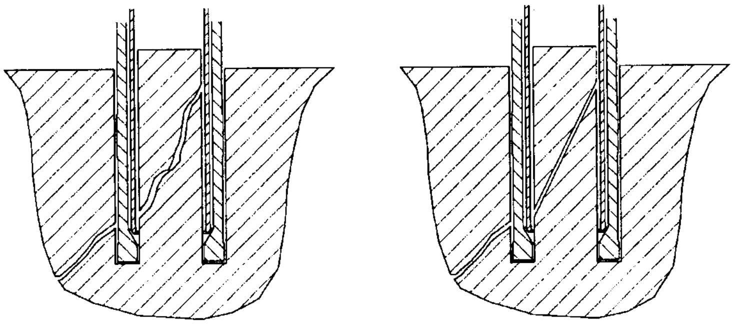

Figure 2: (a) and (b) Fractured cores.

F_1 is the friction force between the cylinder wall and the upper piece of fractured core,
F_2 is the friction force between the fracture faces of the core,
F_3 is the friction force between the cylinder wall and the lower piece of fractured core,
N_1 is the normal force between the cylinder wall and the upper piece of fractured core,
N_2 is the normal force between the fracture faces of the core,
N_3 is the normal force between the cylinder wall and the lower piece of fractured core,
F_t is the downward force on the core above the fracture,
F_b is the upward force on the core below the fracture.

Let μ_1 be the coefficient of friction between the inner cylinder and the core surface, and let μ_2 be the coefficient of friction between the two fracture surfaces (of rock). Let $\mu_1 = \tan\alpha_1^*$ and $\mu_2 = \tan\alpha_2^*$ where α_1^* and α_1^* are angles of friction. Define α_1 , α_2 and ν such that $0 \le \alpha_1 \le \alpha_1^*$, $0 \le \alpha_2 \le \alpha_2^*$ and $0 \le \nu$.

Then

$$
\begin{aligned}
F_1 &= N_1 \tan\alpha_1 && (1)\\
F_2 &= N_2 \tan\alpha_2 && (2)\\
F_t + F_1 &= N_1 \tan(\alpha_1 + \nu)\,. && (3)
\end{aligned}
$$

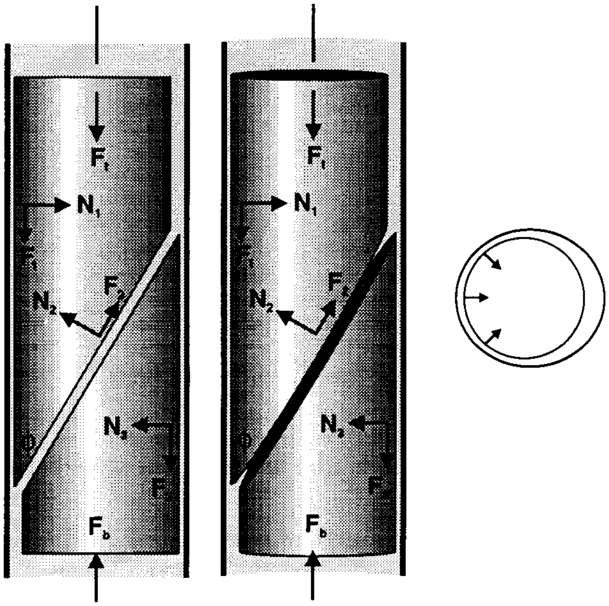

Figure 3: (a), (b) and (c) Forces acting on a fractured core.

(a) Preliminary analysis for rectangular section core and cylinder

The forces on the pieces of core are shown in figure 3(a). At equilibrium:

$$\begin{aligned} F_t + F_1 &= N_2 \sin\phi + F_2 \cos\phi && (4)\\ N_1 &= N_2 \cos\phi - F_2 \sin\phi \,. && (5) \end{aligned}$$

Substitution from equations (2) and (3) into equations (4) and (5) gives:

$$\begin{aligned} N_1 \tan(\alpha_1 + \nu) &= N_2 \sin\phi + N_2 \tan\alpha_2 \cos\phi\\ N_1 &= N_2 \cos\phi - N_2 \tan\alpha_2 \sin\phi \end{aligned}$$

and so

$$\begin{aligned} N_1 \tan(\alpha_1 + \nu) \cos\alpha_2 &= N_2 \sin\phi \cos\alpha_2 + N_2 \sin\alpha_2 \cos\phi\\ N_1 \cos\alpha_2 &= N_2 \cos\phi \cos\alpha_2 - N_2 \sin\alpha_2 \sin\phi \,. \end{aligned}$$

Simplifying and dividing gives:

$$\begin{aligned} \tan(\alpha_1 + \nu) &= \tan(\phi + \alpha_2)\\ \alpha_1 + \nu &= \alpha_2 + \phi \end{aligned}$$

where $\alpha_1 + \nu < \pi/2$ and $\alpha_2 + \phi < \pi/2\,.$

If the forces are such that $\alpha_1 = \alpha_1^*$, while $\alpha_2 < \alpha_2^*$ then slipping occurs at the cylinder wall not the fracture surface.

If the forces are such that $\alpha_1 < \alpha_1^*$, when $\alpha_2 = \alpha_2^*$ then slipping occurs at the fracture surface, not the cylinder wall.

From physical data, we find that usually $\mu_1 < \mu_2$. Thus $\tan\alpha_1^* < \tan\alpha_2^*$, so $\alpha_1^* < \alpha_2^*$.

If

$$\alpha_2^* + \phi > \pi/2$$

then

$$\alpha_2 < \alpha_2^*$$

and so slipping at the core fracture does not occur. In this case, slipping of the cylinder along the core occurs if

$$\alpha_1^* = \alpha_2 + \phi - \nu\,.$$

The normal forces N_1 and N_3 are related to the elastic deformation of the core and the cylinder which contains it and unless the fractured pieces of core have moved relative to one another, the deformation is very small and the normal forces are small.

If

$$\alpha_2^* + \phi < \pi/2$$

and if ν is sufficiently large (i.e. F_t is large), while ϕ is small, then increasing F_1 and F_3 could allow α_2 to reach the value α_2^*, while $\alpha_1 < \alpha_1^*$. This now means slipping occurs at the fracture surface not the cylinder wall.

If F_t is sufficiently large, then increasing F_b will initiate slipping at the fracture surface and an increase in the normal forces on the core. (F_b increases when the friction forces F_1 and F_3 increase.) If F_t remains constant as F_b increases, the other forces will increase because slipping at the fracture increases N_1 and N_3 which in turn allows F_1 and F_3 to increase. Eventually F_t/N_1 , and hence ν, becomes sufficiently small for slipping to occur at the cylinder wall.

However, if $\alpha_1^* > \alpha_2^* + \phi$ the angle α_1 cannot reach α_1^* and hence no slipping occurs between the core and the cylinder, and the axial and normal forces will increase as F_b increases, causing a blockage.

For a fixed force F_t on the upper core, three cases have been identified :

1. If $\alpha_2^* + \phi > \pi/2$, no slipping occurs between the fracture surfaces and slipping can occur between the core and the cylinder. Typically a low axial force will produce slipping.
2. If $\alpha_2^* + \phi < \pi/2$ and $\phi - \nu > 0$, some initial slipping can occur at the fracture surface, then axial slipping between the core and the cylinder wall can follow. A sufficiently large applied axial force will

cause the axial slipping, but if the force needed for this is greater than the applied force available then a blockage results.

3. If $\alpha_2^* + \phi < \pi/2$ and ν is large while ϕ is small enough, slipping will occur at the fracture surface and no slipping occurs at the cylinder wall so the core jams in the cylinder. This relationship between the angles of friction is unlikely unless the core distorts the cylinder sufficiently to make sliding of the core along the cylinder wall very difficult.

A force on the core above the fracture will cause the fracture to slip if the angle of the fracture is sufficiently close to the vertical. This will increase the normal forces between the cylinder wall and the core requiring greater axial forces F_1 and F_3. However increasing the axial driving force on the cylinder will eventually become sufficient for the inner cylinder to slip along the core.

If $F_1 = F_3$ the axial driving force needed to cause the cylinder to slip along the core can be calculated when the fracture surfaces are not slipping.

Since $F_b = F_1 + F_3 + F_t$ and if we define $K = F_b/F_t$ then $K > 1$.
If there are n such fractures in a core then $F_b = K^n F_t$

This geometric increase in F_b with the number of fractures, could mean that a very large driving force is required to initiate sliding of the cylinder along the fractured core. The occurrence of several fractures in a core could lead to the need for a larger force than is available to slide the cylinder completely along the core. This could lead to a blockage.

(b) Circular section core and cylinder

Suppose the normal pressure p between the inner cylinder and core is constant everywhere the core and cylinder touch (i.e. for $-\vartheta < \theta < \vartheta$). The normal force N_1 is given by

$$\begin{aligned} N_1 &= \int_S p \cos\theta dS \\ &= \int_{-\vartheta}^{\vartheta} p\cos\theta \; h(\theta) \; r d\theta \end{aligned}$$

where $h(\theta)$ is the height of an element of the contacting surfaces.
Now $h(\theta) = H + r(1+\cos\theta)\tan\phi$ and so

$$\begin{aligned} N_1 &= \int_{-\vartheta}^{\vartheta} p\cos\theta(H + r(1+\cos\theta)\tan\phi) r d\theta && (6) \\ &= 2pr(H + r\tan\phi)\sin\vartheta + pr^2\tan\phi(\frac{1}{2}\sin 2\vartheta + \vartheta) . && (7) \end{aligned}$$

The axial friction force F_1 satisfies

$$\begin{aligned} F_1 &\leq \mu_1 \int_S p\,dS && (8)\\ &= \mu_1 \int_{-\vartheta}^{\vartheta} p h(\theta) r\,d\theta && (9)\\ &= \mu_1 p r \int_{-\vartheta}^{\vartheta} (H + r(1+\cos\theta)\tan\phi) r\,d\theta && (10)\\ &= \mu_1 (2pr(H + r\tan\phi)\vartheta + (2pr^2\tan\phi)\sin\vartheta)\,. && (11) \end{aligned}$$

Notice that the limiting friction force given by equation (11) is slightly greater than $\mu_1 N_1$ from equation (7). The difference is

$$F_1 - \mu_1 N_1 = \mu_1(2prH(\vartheta - \sin\vartheta) + pr^2\tan\phi(\vartheta - \sin\vartheta\cos\vartheta))\,.$$

This means the axial friction force between the core and the inner cylinder, to be overcome by the driving force, is a bit larger than that given in section (a).

3.2 Gravel bed providing large normal forces against the cylinder wall during compression of the bed

In some preliminary analysis we considered the effect of a shallow gravel bed between two pieces of rock core. Axial forces on these pieces of rock core would cause the compressed gravel bed to exert a normal force on the cylinder wall. This contact provides friction to oppose sliding of the inner cylinder along the core. An upper bound on the normal and friction forces was obtained by considering the pressure to be transmitted without loss as in an incompressible fluid at rest. This argument indicated that the friction would not prevent axial sliding. This prompted more detailed analysis, using the following notation:
F_v is the total force on the bed due to compression by the upper piece of core;
P_v is the pressure on the bed due to the upper core of radius r.
P_n is the normal pressure between the gravel bed and the inner cylinder;
F_n is the normal force between the gravel bed and the inner cylinder;
F_c is the axial friction force between the gravel bed and the inner cylinder;
μ_c is the coefficient of friction between the gravel bed and the inner cylinder;
X is the depth of the gravel bed, and x be the depth to an element of the bed; and
ρ is the density of the gravel bed.
Let $k = P_n/P_v$. So $0 < k \leq 1$ with $k = 1$ if the pressure is transmitted without loss.

Therefore

$$\begin{aligned} F_v &= F_t + F_1 \\ P_v &= F_v/\pi r^2 \\ P_n &= kF_v/\pi r^2 . \end{aligned}$$

(a) Shallow gravel beds

We have:

$$\begin{aligned} F_n &= \int_0^X 2\pi r P_n dx \\ &= \frac{2kF_vX}{r} \end{aligned}$$

and

$$F_c \leq \int_0^X \frac{2\mu_c k F_v}{r} dx .$$

The frictional forces, due to the compressed gravel bed pressing on the inner cylinder, satisfy

$$F_v = F_t + F_1 \leq F_t + \mu_1 N_1 \simeq F_t$$

because N_1 is small. Here F_t is approximately the weight of the upper core. So if the gravel bed is shallow, X is small and F_c is of the same order of magnitude as F_t. Such a value of F_c could not alone resist the driving force that can be applied to the cylinder.

(b) Deeper gravel beds

In deeper gravel beds, of density ρ, the weight of the bed and the variation of pressure across it must be considered, so the downward force is

$$F_v(x) = F_t + \rho g \pi r^2 x + \int_0^x \frac{2\mu_c k F_v(\xi)}{r} d\xi$$

and so

$$\frac{dF_v(x)}{dx} = \rho g \pi r^2 + \frac{2\mu_c k F_v(x)}{r}$$

with $F_v(0) = F_t$. This linear differential equation has solution

$$F_v(x) = \frac{\rho g \pi r^3}{2\mu_c k}(exp(\frac{\mu_c k x}{r}) - 1) + F_t exp(\frac{\mu_c k x}{r})$$

and so

$$\begin{aligned} F_c &= \int_0^X \frac{2\mu_c k}{r} F_v dx \\ &= \frac{\rho g \pi r^3}{2\mu_c k}(exp(\frac{\mu_c k X}{r}) - 1) - \rho g \pi r^2 X + F_t(exp(\frac{\mu_c k X}{r}) - 1) . \end{aligned}$$

The growing exponential shows that F_c can become large enough to cause blocking if X is large enough. In the drilling equipment we were considering, X/r would be less than 100.

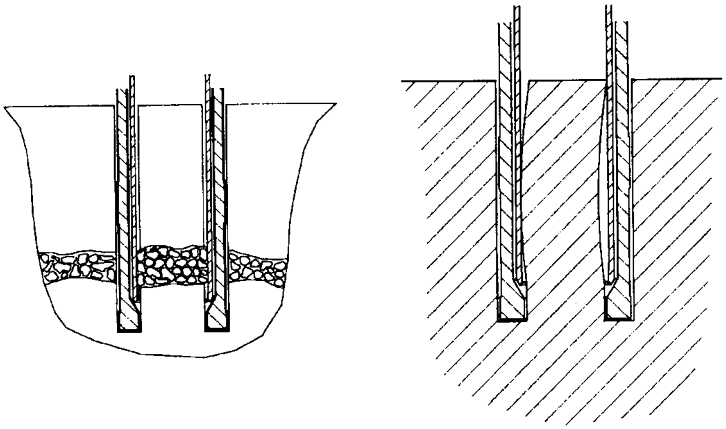

Figure 4: (a) Shallow gravel bed. (b) Bent core.

3.3 Bent core jamming against the side of the (straight) inner cylinder

For there to be a friction force F_1 between the cylinder wall and the bent core sufficient to prevent sliding of the cylinder, then

$$F_1 \leq \mu_1 N_1$$

Since the driving force available to overcome this friction can be as large as 5 tonne , and a typical value for μ_1 is 0.1 , then N_1 would need to be very large. The bending moment of N_1 about the central point of contact of the core with the cylinder would then be large enough to snap the bent piece of core, and this would probably happen before serious distortion of the inner cylinder occurred. This does not mean that after the bent core is snapped, the cylinder will not be jammed, but it does mean that the mechanism suggested by figure 4(b) is not alone the cause of any jamming.

3.4 Large particles blocking the axial motion

The normal force between the cylinder wall and the large particle illustrated in figure 5(a) could be of the same order of magnitude as the force N_1 in Section 3.3, but here the force is compressive, and the particle might withstand crushing. Such force could distort the inner cylinder sufficiently to cause jamming.

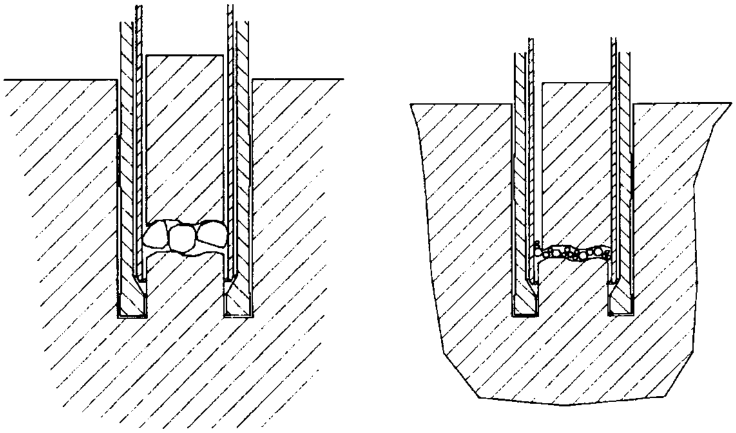

Figure 5: (a) Bed of large particles. (b) Small particles between core and cylinder.

3.5 Small particles between the core and cylinder wall pressing the core against the opposite side of the cylinder

Small particles are a by-product of the drilling process, and of any snapping or crushing of the core, as well as being present due to the occurrence of gravel beds or natural rock fractures. It appears likely that small particles are present between the inner cylinder wall and the core. They can contribute to increased friction forces in several of the mechanisms described above by creating large normal forces. Two situations can be envisaged:

(i) The particles start to rotate to an orientation that requires a greater clearance space;

(ii) The particles fall into a narrowing wedge-shaped space.

In the first case, sufficient force would be available to break a small particle, and a considerable number of particles would need to be trapped, to cause jamming. However, particles trapped in this manner might exert sufficient force on the core to increase the likelihood of a blockage by multiple acute angle fractures.

In the case of small particles trapped in a wedge-shaped space between the core and the tube, very high forces might be generated. In this case even if the particles are crushed, there needs to be sufficient volume available to allow the particles to spread out and thus avoid the narrowing section of the wedge. If the particles cannot spread out the force created is determined by the elastic properties of the core and the tube as they are compressed and tensioned (respectively) in creating sufficient space to accommodate the particles.

A smaller gap between the tube and core would reduce the size of particle that could enter the gap. A smaller particle requires less force to break it, and it also requires less distortion of the tube and core to allow it to pass the constriction. In both cases a smaller particle creates lower axial forces.

An analysis of the forces shows:

1. The force F required to break a layer of particles is proportional to the number (n) of particles and to the cross sectional area ($A = \pi d^2/4$). Thus F is proportional to nd^2.
2. The number of particles of diameter d from volume V of material is proportional to V/d^3 hence F is proportional to V/d.
3. Assuming linear elastic behaviour this gives F proportional to d, and hence both F and d are proportional to $V^{1/2}$.
4. For an initial gap of size D between the tube and the core, containing a single particle also of initial size D, the force created in the wedge is proportional to $D^{3/2}$. For a layer of particles of constant width and initial size D, the force is proportional to $D^{1/2}$.
   In both cases the smaller gap leads to lower radial forces and hence lower axial friction forces on the tube. Rotating the tube with near zero axial force, so the particles are not forced further into the wedge, may move the particles out of the wedge and allow them to move to a less critical position in the gap between the tube and the core.

Two effects make the force non-linear:
(i) unless the particles have room to expand as they break, the force rises more rapidly than that given above, once the particles are reduced to less than half of their original size.
(ii) A fracture through the core does not produce smooth surfaces, and hence after movement the initial contact area across the fracture is low and the initial compression of the core is obtained with lower forces until a larger area of contact is created by crushing of the initial contact points. These non-linearities indicate the ratio of forces created by larger particles would be greater than that indicated by the above expressions.

3.6 Long bent driving column jamming against the drill hole

When a fairly deep hole is being drilled, the long driving shaft subject to torsional load is likely to bend with consequent rubbing of the shaft on the drilled hole. This is particularly likely if the hole is not vertically down, or if there is any serious resistence at the drill to the forces and torques being applied. The forces on the drive shaft due to such rubbing have not yet been analysed. It is possible that these forces contribute to the blocking.

3.7 Blockages occurring at the entrance to the inner cylinder

During the meeting there was considerable discussion about redesign of the lower end of the inner cylinder and of the grabbing mechanism. No successful modelling or rational analysis has been completed. The discussion raised a number of issues that, at the moment, would appear to be better studied by experimentation.

3.8 Policies for avoiding blockages

All the mechanisms for blockages in the tube proper (as opposed to the tube entry) create force proportional to the coefficient of friction between the tube and the core. It is clear that a low coefficient of friction is needed to reduce the likelihood of blockages and the inner surface of the tube should be smooth. A soft low friction surface such as teflon or polyurethane may not be tough enough to avoid damage by tearing and hence might not last very long. The alternative of a hard smooth inner surface to the tube seems more practical.

As the applied axial forces generate the radial forces that in turn produce the static friction forces which resist the axial motion of the core into the tube, rotation of the tube (probably slowly to avoid excess disturbance of the core) with no axial force on the tube may be possible. Without the axial forces the static friction may be much lower. Once sliding has begun axial motion can be initiated with a small axial force. This would appear to be the mechanism used by some of the better operators to reduce the number of blockages.

A low clearance between the tube and the core allows only the entry of smaller particles into the gap. These smaller particles create lower radial forces and hence less friction on tube core contacts. Thus a small clearance should help reduce this type of blockage.

4. Collection of data

Many measurements now made for geological purposes disappear at the end of a job, or are not made available for drilling performance analysis. Such measurements include the length of each core and geological features of the core.

It is recommended that these measurements, together with cylinder and bit identification and a note of the position and type of any blockages, be recorded to help with future design modifications.

It is also recommended that the inner cylinder be inspected for scraping and distortion following removal of cores, and relevant details noted after removal of blocked cores.

Further data could be obtained from automatic logging of data from the modern rig control system. Such data includes drilling force, feed rate, angular speed of the drill and water pressure, and should be recorded with the corresponding other data mentioned above.

From maintenance records, data could be obtained about the reason for discarding an inner cylinder, its condition when it is discarded, its age, number of holes drilled, and distance drilled.

5. Experimental program

Several simple experiments that could assist in determining the nature of blockages and the validity of the above analysis were discussed during the meeting.

1. An experiment that simulates the pushing of a fractured core through a cylinder could be carried out. Possibly the cylinder could be transparent. The argument above indicates that for relevant material properties and dimensions, the *fractured core* can be pushed through the cylinder.
2. An experiment could be carried out, that simulates a core containing a *bed of small particles* being pushed through a cylinder. The argument above indicates that for relevant material properties and dimensions, the core containing the *bed of small particles* can be pushed through the cylinder.
3. An experiment could be carried out that simulates a core containing a *bed of several large particles* being pushed through a cylinder. This mechanism could cause blocking, and the experiment might throw light on the situation.
4. Another experiment that might prove very useful is to try to simulate the pushing through a cylinder of a core where several small particles lie between the core and the cylinder wall. This experiment could be carried out firstly, for a simple cylindrical core, and perhaps be repeated with a fractured core.
5. Oscillation of the mechanism
   During the discussion it was suggested that some axial oscillation of the mechanism might dislodge some material jammed between the core and

inner tube. The purpose is to get at least partial alleviation of the problem. Past experience suggests such a process is not likely to have general success.

6. Reverse water flow
   Normally there is flow of water for the purpose of cooling and some lubrication, *down* between the outer and inner cylinders, and *up* outside the outer cylinder. Some redesign might allow *upward* flow of water inside the inner cylinder. This might lead to some unblocking by movement of some particles caught between the core and the inner cylinder. However, even if this process was successful in dislodging some particles, the water might destroy some, or all, of the value of this section of core. It is considered that an experiment would be worth while, but probably the mechanism would be unacceptable in practise.
7. Modification of lower end design
   During the meeting there was considerable discussion about redesign of the lower end of the inner cylinder and of the grabbing mechanism.

6. Conclusion

Several simple mechanisms were suggested as possible causes of the blocking problem. Some modelling and analysis of these mechanisms has been carried out and it appears that several of the simplest mechanisms are not, by themselves, the cause of blocking. Combinations of several of these mechanisms could very well cause the problem. The modelling and analysis carried out has thrown some light on the problem and a number of experiments have been suggested, as well as a program of data collection.

Acknowledgements

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