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ANALYSIS OF STUCK PIPE INCIDENTS IN MENENGAI

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ABSTRACT

Stuck pipe, or sticking, and lost circulation are the two main events which cause non-productive time (NPT) in the drilling industry. A considerable amount of time and resources can be spent in efforts to free a stuck pipe. Sometimes, stuck pipe events result in breakage (either intentional or non-intentional) of the drill string, leading to a lot of money being spent on fishing. Unsuccessful fishing operations have resulted in costly alternatives including side-tracking or, worse still, well abandonment. Stuck pipe situations are very common around the world with most data gathered in the petroleum drilling industry. A stuck pipe situation has led to abandonment of a well in the Menengai drilling field, Kenya, as of the date of writing this paper. This paper explores the stuck pipe problem in geothermal well drilling. The paper presents causes of stuck pipe events, predicting their occurrence, and common methods used to free a stuck pipe. There is also a review of methods used to back off stuck string and fishing. Finally, an analysis is made of stuck pipe events in a few wells drilled in Menengai, Kenya, using the graphical analysis software *Easy View*. The results are then discussed to identify the causes of stuck pipe in Menengai.

1. INTRODUCTION

The Geothermal Development Company (GDC) is a Kenyan government-owned entity that plans to develop 5,000 Megawatts of geothermal energy by 2030 in various fields in Kenya. Currently, production drilling is ongoing in the Menengai high-temperature field located in Nakuru within the central Kenyan rift. Menengai comprises the Menengai caldera, The Ol'rongai in the northwest and parts of Solai graben to the northeast. Drilling in this field has been quite difficult due to formation challenges that have subsequently caused stuck pipe incidences, among other non-productive activities. A stuck pipe situation occurs in drilling when the drill string cannot be reciprocated along or rotated about its axis while in the well. An analysis of drilling data has shown that, on average, Menengai wells were stuck for six days (Okwiri, 2013) or 12% of total drilling time in Menengai (Makuk, 2013). The depth at around 2100 m (below Rotary Kelly Bushing) has been identified as particularly troublesome, leading to most of the stuck pipe incidences (Makuk, 2013). As of 1991, stuck pipe events were costing the drilling industry USD 200-500 million annually and occurred in 15% of the wells (Schlumberger, 1991). Sticking of the drill string is mostly viewed as an accident, although methods have been used to predict such events. It is usually a result of natural factors such as the presence of permeable formations (which can easily cave and slough) or abnormally high pressured beds. Sticking can also be influenced by the degree of hole deflection and dogleg severity causing a keyhole. Drilling parameter changes can give hints to sticking problems that might occur later, e.g. during tripping out. Bailey et al. demonstrated in the Schlumberger article (Stuck Pipe - Causes, Detection and Prevention, Schlumberger, 1991) how a water loss (from drilling mud) event during drilling later caused differential sticking during tripping out. The high costs associated with sticking form the justification for a study of the causes of stuck pipe in Menengai, with a view to preventing them. Figure 1 shows the location of some of the wells drilled in Menengai.

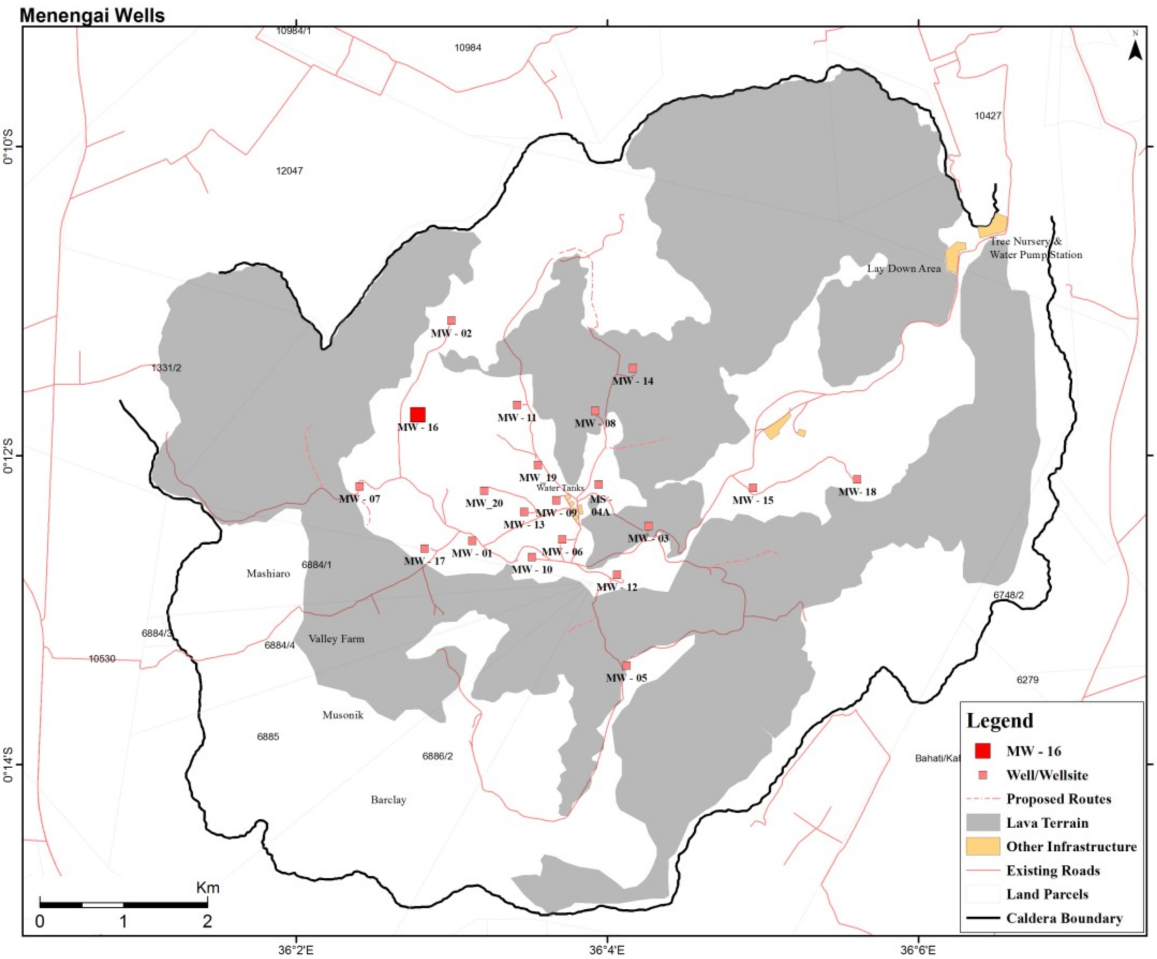

FIGURE 1: Menengai high-temperature field and location of wells (GDC, 2013)

2. CAUSES OF STUCK PIPE

There are basically 2 mechanisms for pipe sticking: differential sticking; and mechanical sticking. Their mechanism and causes are summarized in Table 1.

TABLE 1: Pipe sticking mechanism and causes (Rabia, 2001)

Mechanism	**Differential Sticking**	**Mechanical Sticking**	
Cause		Hole pack off	Formation & BHA (wellbore geometry)
	Differential Force	Settled cuttings Shale instability Fractured rocks Cement blocks	Key seating Mobile formations Under-gauge hole Micro doglegs and ledges
		Junk	Drilling into magma

2.1 Differential sticking

During drilling, the drilling fluid pressure is maintained at a higher value compared to the reservoir or formation pressure. When a permeable zone is reached, the difference in these pressures forces some of the fluid to seep into the permeable zone. As this happens, the solids in the drilling fluid are filtered out at the hole wall, forming a layer called a filter cake. If a substantial area of the string surface comes into contact with the cake formed, then only the outer wall surface exposed to the drilling fluid "sees" the higher drilling fluid pressure and the contact surface to the cake "sees" the lower formation pressure. This pressure difference pushes the pipe to stick to the hole wall and embed itself further into the filter cake with a great force (can reach more than a million pounds force). The string, thus, gets differentially stuck and the force required to pull it exceeds the yield point of the pipe. The signs of differential sticking are:

1. The pipe can neither be moved up or down nor rotated;
2. Circulation is unaffected.

The differential sticking force depends on the pressure differential and the area of contact with the porous formation zone, among other factors. To gain an understanding of factors that might influence the sticking force and the magnitudes, consider Figure 2.

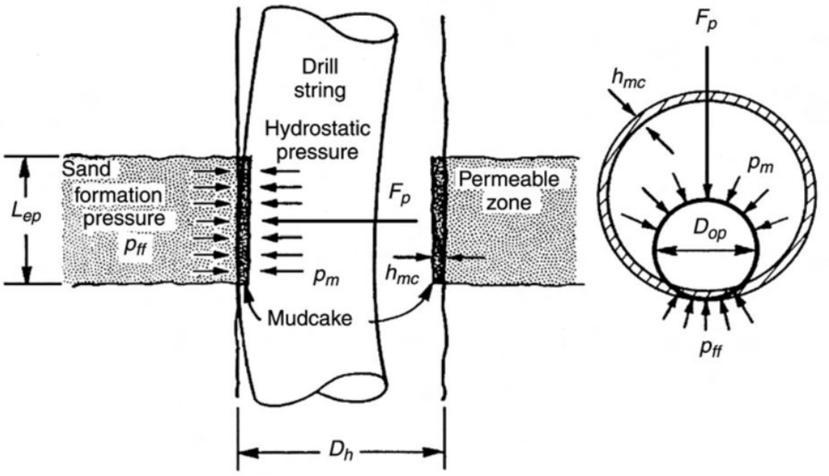

FIGURE 2: Differential pressure sticking (SPE, 2007)

Differential force = (mud hydrostatic – formation pressure) × area of contact

From Figure 2:

$$\Delta p = P_m - P_{ff} \tag{1}$$

where P_m = Pressure acting outside pipe wall;
P_{ff} = Formation fluid pressure; and
Δp = The pressure differential.

The pull force, F_p, required to free the stuck pipe is a function of the differential pressure, Δp; the coefficient of friction, f; and the area of contact, A_c, between the pipe and mud cake surfaces:

$$F_p = f\, \Delta p\, A_c \tag{2}$$

where F_p = The pull force;
f = Coefficient of friction; and
A_c = Area of contact between the pipe wall and mud cake.

The area A_c can be simply said to be the length of pipe in contact with the mud cake multiplied by the length of the perimeter of the pipe in contact with the cake; this length can be estimated to be 20% of the perimeter. A more accurate estimate of the contact area may be given as:

$$A_c = 2L_{ep} \sqrt[2]{\left\{(D_h/2 - h_{mc})^2 - \left[\left(\frac{D_h}{2} - h_{mc}(D_h - h_{mc})/(D_h - D_{op})\right)^2\right]\right\}} \tag{3}$$

where $$D_{op} \leq (D_h - h_{mc}) \tag{4}$$

Here, L_{ep} = Length of the permeable zone;
D_{op} = Outside diameter of pipe;
D_h = Diameter of hole; and
h_{mc} = Mud cake thickness.

The dimensionless coefficient of friction f can vary from less than 0.04 for oil based mud to as much as 0.35 for weighted water-based mud with no added lubricants. Equations 2 and 3 show the controllable parameters that will cause a higher pipe sticking force. These are: a high differential pressure, thick mud cake (high continuous fluid loss to formation), low lubricity mud cake (high co-efficient of friction) and excessive embedded pipe length in mud cake (delay of time in freeing operations).

Although hole and pipe diameters and hole angle play a role in the pipe sticking force, they are uncontrollable variables once they are selected to meet well design objectives. The shape of the collars can play a role in reducing sticking force, e.g. spiral or square drill collars will have lesser area in contact than cylindrical collars.

Differential sticking may be prevented by:

- Maintaining lowest continuous fluid loss;
- Keeping circulating mud free of drilled solids;
- Keeping a very low differential pressure with allowance for swab and surge;
- Using a mud system that yields smooth mud cake (low friction co-efficient);
- Maintaining drill string rotation at all times;
- Using grooved or spiral drill collars;
- Minimizing length of drill collars and Bottom Hole Assembly (BHA).

If differential sticking occurs, the following solutions are mostly used:

- Immediate working/jarring of the string downwards;
- Reducing drilling fluid hydrostatic pressure by gasifying with air or by diluting the fluid. Close attention must be paid to kick indicators while reducing hydrostatic pressure;
- Oil spotting around stuck portion of string;
- Washing over the stuck pipe.

2.2 Mechanical sticking

In mechanical sticking, the pipe is usually completely stuck with little or no circulation. This can be due to hole pack off (or bridging) or due to the formation and BHA (well geometry).

Hole pack off can be caused by any one or a combination of:

- Settled cuttings due to inadequate hole cleaning;
- Formation instability;
- Unconsolidated formations;
- Fractured and faulted formations;
- Cement blocks;
- Junk falling in well.

Formation and BHA (wellbore geometry) can also cause mechanical sticking through:

- Key seating;
- Under-gauge hole;

- Ledges and micro ledges;
- Mobile formations;
- Drilling into magma (special case; documented in Menengai and Krafla).

It is very important to understand the cause of a mechanical sticking problem because it is the key to knowing the correct action to take in freeing the stuck pipe.

2.3 Hole pack off causes

2.3.1 Settled cuttings

This is one of the major causes of a mechanical stuck pipe. It is where cuttings pack off or settle and build on the well bore and cause compaction around the BHA when the pipe is moved upwards. The compacted cuttings then prevent the string from coming up, especially during trip out. Figure 3 shows settled cuttings. The problem is more prone in highly deviated or horizontal wells since the cuttings tend to fall on the low side of the hole and are harder to clean out. These settled cuttings pile up and form beds and may compact against the BHA on trip outs. In vertical wells, good hole cleaning is achieved by the selection and maintenance of suitable mud parameters and by ensuring that the circulation rate chosen results in an annular velocity (around 100-120 feet/min) which is greater than the slip velocity of the cuttings. Besides causing stuck pipe, settled cuttings can also cause:

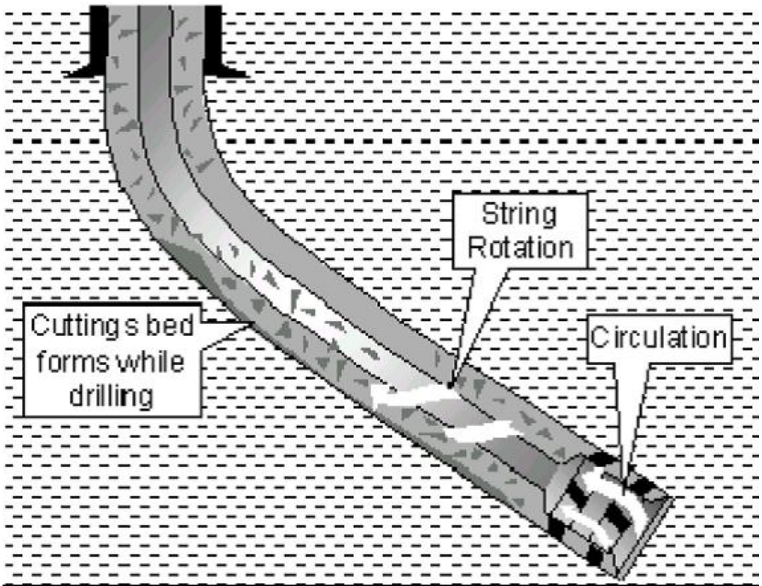

FIGURE 3: Settled cuttings due to poor hole cleaning (Rabia, 2001)

- Formation breakdown due to increased equivalent circulating density;
- Slow rate of penetration;
- Excessive overpull on trips;
- Increased torque.

Hole cleaning is one of the main solutions to prevent this stuck pipe problem and can be controlled by:

- Good mud rheology, especially yield point and gel strength;
- Controlling drill rate to ensure hole is clean;
- Checking volume of cuttings coming over to shale shaker;
- Controlling annular velocities;
- Recognizing increased over pull;
- Reciprocating and rotating pipe while circulating;
- Using viscous sweeps;
- Recognizing low side section of deviated holes;
- Regular wiper trips.

If sticking occurs, then:

- Attempt to establish circulation;
- Simultaneously apply downwards force gradually until circulation starts;
- Once circulation starts, rotate the string;
- In low angles holes, a weighted viscous pill should be used to 'float out' the cuttings;
- In high angle holes, a low viscous pill should be used to disturb the cuttings bed followed by weighted pills to carry cuttings out of hole.

2.3.2 Formation instability

This is as a result of tensile and compressive failure on the borehole wall. The borehole will fail in tension while drilling mud hydrostatic pressure induces stresses in the hole wall that exceeds the tensile strength of the rock. The borehole will fail in compression when the pressure of the drilling mud is insufficient to keep the shear stresses in the borehole wall below the shear strength of the formation (Rabia, 2001).

This problem can be solved by applying the rock mechanics principle to define working limits for mud weights to avoid tensile or compressive failure; here, the equations and methods applied in rock mechanics are quite complex and can be found in most geo-mechanics and rock mechanics literature. The result of formation instability is either borehole widening or contraction depending on the failure mode of the rock inside the well. Figure 4 shows the Inner Drucker-Prager criterion for predicting safe mud weights. Sticking to the fluids program can prevent the effects of formation instability.

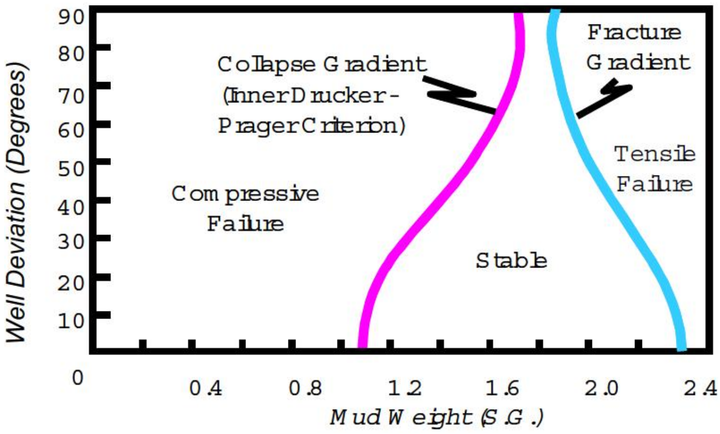

FIGURE 4: Safe mud weights envelope (Rabia, 2001)

Other solutions include making use of a well program that isolates a potential troublesome formation and speeding up the drilling process to cut down the time in drilling sensitive formations.
Formation instability can be identified by the following:

- Large amounts of angular or splintery cuttings when circulating;
- Drag on trips;
- Large amounts of hole fill.

Formation instability will cause material to fall inside the hole, creating caves or contracting the wellbore and might cause sticking. Sloughing and caving are also due to formation instability. If these occur, then the solution is establishing circulation, then working the drill string, preferably downwards; when the string is freed, circulate all material out before changing the mud properties to continue drilling.

2.3.3 Unconsolidated formations

Unconsolidated formations are usually encountered near the surface and include loose sands, gravel and silts. These collapse due to low cohesive strength; they can collapse and jam the drill string. Signs of sticking due to unconsolidated formation include:

- Increased torque;
- Drag and pump pressure increase when drilling;
- Increased rate of penetration;
- Large fill on bottom.

This problem can be prevented by using a mud system with impermeable filter cake to reduce fluid invasion into rock. Reducing annular velocity by reducing the mud flow rate will also reduce erosion of the hole wall and also reduce removal of filter cake.

2.3.4 Fractured and faulted formation

Symptoms of fractured and faulted formation include:

- Large and irregular rock fragments at shale shakers;
- Increased torque, drag and rate of penetration;
- A small amount of lost circulation.

The fractured formation falls into the well due to stresses originally holding the formation together being relieved by drilling of the hole. Excessive vibration might also cause the drill string to whip down hole and dislodge the fractured rocks. The problem can be prevented by:

- Reducing drill string vibration;
- Minimizing surge pressures;
- Sufficient hole cleaning to reduce hole pack off.

If sticking occurs, jar the string. If this is not successful, an inhibited hydrochloric acid pill may be spotted around the stuck zone to break down the material surrounding the pipe.

2.3.5 Cement blocks

Cement blocks from the rat hole might fall into the well bore and cause sticking. This can be prevented by minimizing the rat hole to a maximum of 5 feet and ensuring good tail cement at the casing shoe. If sticking occurs due to cement blocks, jar the string or inject acid solution down hole to dissolve the cement.

Green cement is improperly set cement. Green cement can occur after setting a cement plug inside the casing or open hole. If the drill string is run too fast into the top of the cement and the cement is still green, then the cement can flash set around the pipe and cause permanent sticking. Flash setting is a phenomenon that is not very well understood but a possible explanation is that the energy release while circulating and rotating could be sufficient to cause it. A good practice to prevent this is starting circulation 2 or 3 stands above the expected top of the cement and also keeping a low weight on the bit.

2.3.6 Junk falling in the well

Junk in the well can happen and common junk includes pipe wrenches, spanners, broken metal, hard hats, tool dies etc. Junk can also fall from inside the well, e.g. broken packer elements, liner hanger slips and metal swarf from the milling operation. A preventative practice is to keep the hole covered when no tools are run into the hole or when fishing out junk before drilling continues. Tools should also be in good condition and should be regularly inspected before being run in the hole.

2.4 Formation and BHA (well geometry) causes

2.4.1 Key seating

Key seating is caused by the rotational drill string coming into contact with a soft formation. The rotational action causes the tool joint to erode a narrow groove in the formation, almost equal to the tool joint diameter. This groove diameter is smaller than regular BHA component diameters below the drill pipe. On pull out, the BHA might be pulled into the narrow key seat (groove), resulting in stuck BHA.

Key seats are often seen in doglegs and ledges since they allow the string to bend and provide points of contact between the tool joint and hole walls. Key seats may also occur in casing shoes in highly deviated wells.

Key seats can be identified by these signs:

- Circulation is free when the pipe is stuck;
- Hole is tight on tripping out only;
- Tight hole position can be correlate with positions of large outer diameter members of the BHA;
- Tight hole occurs at same depth on trips.

To get free from a string stuck in a key seat, jar downwards only until free movement and rotation happens (Figure 5). Once the string is free in a downwards direction, it should be slowly pulled past the key seat using minimum tension and slow rotation. A key seat wiper tool can be run on top of the collars to clear the key seat.

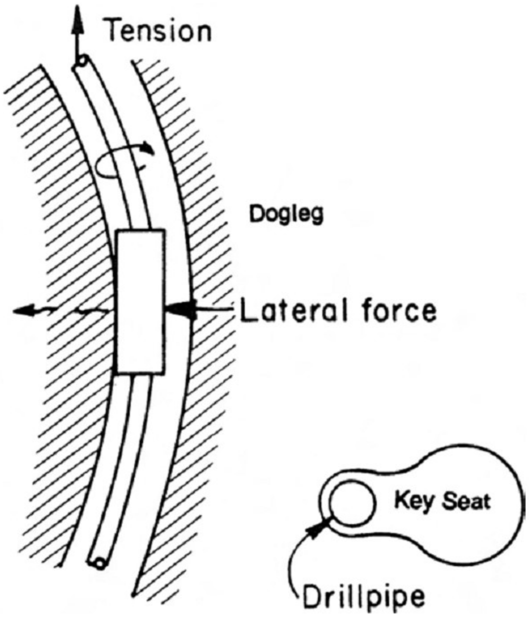

FIGURE 5: Pipe sticking caused by key seat (SPE, 2007)

2.4.2 Under-gauge hole

Drilling in an abrasive formation can result in bit and stabilizer gauge wear. The loss in gauge results in drilling an under-gauge hole. Not only is it costly to ream under-gauge sections, but a new full gauge bit and stabilizer being run in the hole can get stuck, too. This problem can be avoided by practicing caution when running in hole a new bit or stabilizer after pulling out an under-gauge bit.

2.4.3 Micro doglegs and ledges

These develop when drilling through layers of a formation of varying strength or dipping formations. A gauge hole is drilled in the harder zone and an oversized hole, caused by fluid erosion, is drilled in the softer zone. This oversized hole causes the bit and the BHA to be deflected to the low side of the hole causing a small dogleg when the next hard section is drilled (Rabia, 2001). When successive layers of hard and soft sections are drilled, then ledges and micro doglegs develop. This problem can be prevented by running slowly when tripping at alternating formation points; these areas should be noted and reamed through during trips. If sticking occurs, then jar up if stuck while running in or jar down if stuck while pulling out.

2.4.4 Drilling into magma

It has been shown that the 2011 m depth is particularly troublesome to drill through in Menengai field, Kenya (Makuk, 2013). It has also been observed that fresh glass was present in cuttings at 2082 m and 2174 m in wells MW04 and MW06, respectively (Mibei, 2012). It is believed that magma intrusions at these depths are rapidly chilled by the drilling fluid, producing glassy cuttings. Sticking problems were recorded at these depths and are believed to be related to the occurrence of glass (Mibei, 2012). The exact mechanism of sticking due to drilling into magma is not really known. The Iceland Deep Drilling Project well 1 was halted after having drilled into magma and gotten stuck, however the bit came up intact (Hólmgeirsson et al., 2010). It is reported that the magma pushed up on the drill string, lowering the hook load value. It is believed that explosive chilling of the magma (steam flashing) by drilling fluid downhole could, however, be related to this sticking problem.

A summary of signs of sticking and parameters to watch for stuck pipe problems can be well tabulated using the Baker Hughes INTEQ, 1995 workbook as shown in the Table 2, while common responses to stuck pipe problems are shown in Table 3. Figure 6 shows a flow chart that can assist in recognizing stuck pipe warning signs.

TABLE 2: Stuck pipe problems and indicators (Baker Hughes, INTEQ, 1995)

Problem \ **Indicator**	**Torque**	**Pressure**	**Drill rate**
Poor hole cleaning	Increase	Increase	Gradual increase
High overbalance	Gradual increase	No change	Gradual decrease
Mobile formations	Gradual increase	Increase	Gradual decrease
Fractured & faulted formations	Sudden erratic increase	May be unaffected	Sudden increase
Geo-pressured formations	Increase	Increase	Initial increase with a gradual decrease
Reactive formations	Gradual increase	Increase	Gradual decrease
Unconsolidated formations	Increase	Increase	Decrease
Junk	Sudden increase	No change	Sudden decrease
Cement blocks	Sudden increase	No change	Sudden decrease

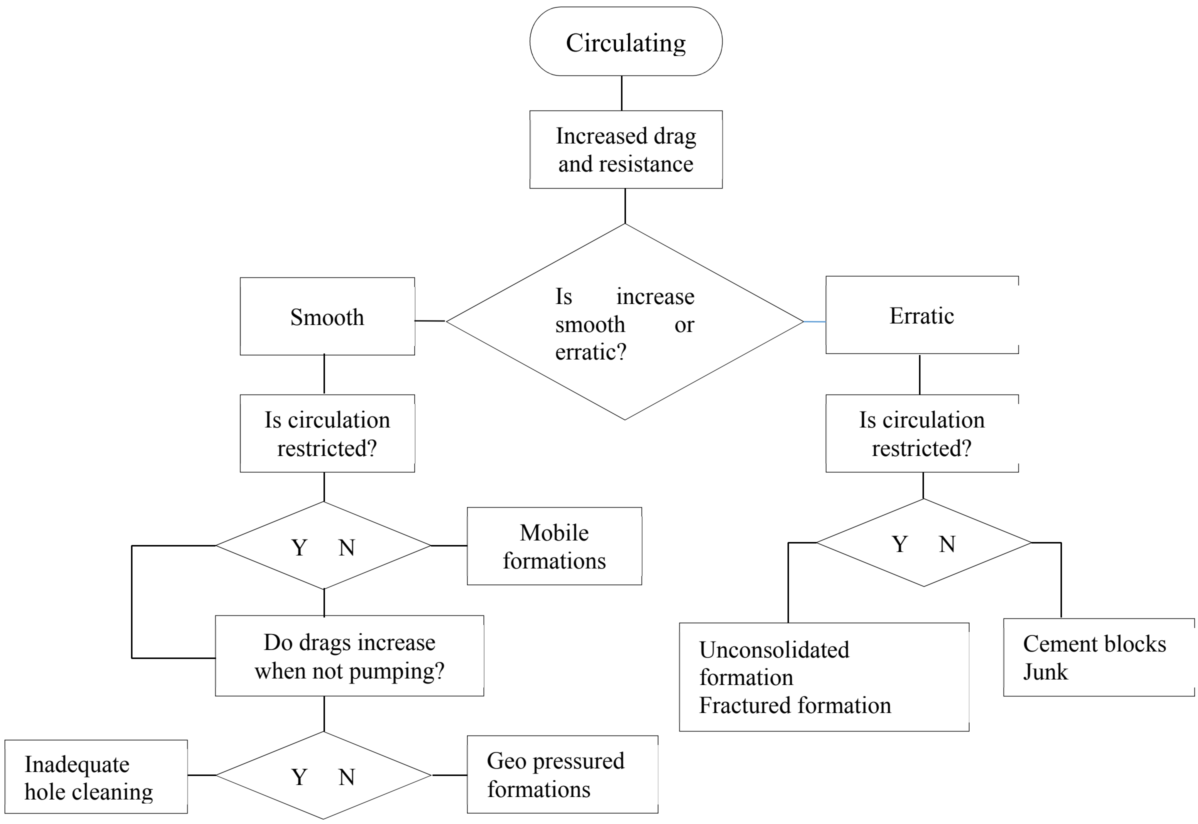

FIGURE 6: Flow chart showing stuck pipe warning signs when circulating (Kingdom Drilling, 2014)

TABLE 3: Response to analysis of borehole conditions (Baker Hughes INTEQ, 1995)

Drilling instrumentation	Borehole problem	Response of logging crew
Lithology identification and description	Formation related Differential sticking Cement related Under-gauge hole Poor hole cleaning	Identification of rock types and characteristics Identification of permeable sandstones Identification of cement in cuttings samples Identification of abrasive formations Amount of cuttings in samples
Depth and drill rate recorder	Formation related Wellbore geometry Poor hole cleaning	Identification of borehole problems from drill rate Reduced drill rate due to BHA hanging up on ledges Reduced drill rate due to poor transfer of WOB
Monitor calculations	All types of borehole problems	Monitor trends in hole conditions, and relating trends to lithology, hole deviation and BHA configuration
Pump stroke counters	Poor hole cleaning	Monitoring annular velocities to adequately clean borehole
Pore pressure evaluation	Geo-pressure differential sticking	Detecting abnormal or sub-normal pore pressure calculation of ECD and amount of overbalance
Lag time determination	Poor hole cleaning	Monitoring actual hole volume to determine actual versus theoretical lag time

3. FREE POINT DETERMINATION AND BACK-OFF OPERATIONS

At times, the driller is unable to free a stuck pipe, or the force required to pull the pipe free might be larger than the yield point of the weakest member in the driller string. At this point, the remedial measures normally applied involve spotting lubricating fluid around the troublesome area. The spotting procedure is facilitated by pinpointing the location of the stuck pipe, i.e. the depth of sticking, and is demonstrated by Figure 7.

1. An upward force F1 is applied to the pipe. This must be greater than the total weight in air to ensure that the string is in tension;
2. A reference point is marked on the drill pipe at the surface, normally at the top of the rotary table;
3. A greater upwards force, F2 is applied causing the free portion of the drill string to stretch by an amount, "e". The stretch is measured above the reference point.

After these measurements are taken, we apply the equation below to get the stuck point:

$$SPL = 735x10^3 \, X \, \frac{(w)X(e)}{(F2 - F1)} \qquad (5)$$

where SPL = Stuck pipe location;
$735{\times}10^3$= Derivation of Young's modulus for steel;
w = Weight of drill pipe (lb/ft);
e = Length of stretch (");
$F1$ = Force applied when pipe is in tension (lb); and
$F2$ = Force applied to stretch the pipe to "e" pounds.

It should be noted that the stuck pipe location calculated using the above equation is a best guess due to the following reasons:

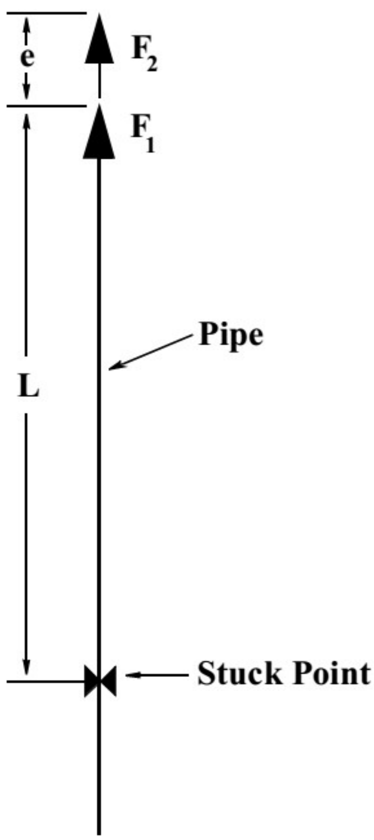

FIGURE 7: Determining stuck pipe variables (Baker Hughes INTEQ, 1995)

1. Hole friction can impede pipe stretch, especially in deviated wells;
2. The stretch measurement does not account for drill collars or heavy weight drill pipe response to pull.

For these two reasons, the equation should only be used as a starting point before a free point indicator tool is lowered through the string to determine the back off point. The accuracy range of this method is around +/- 200 feet.

3.1 Free-point indicator tool

If spotting lubricating liquid around the stuck point does not work, then a free point indicator tool is lowered in the string to more accurately determine the stuck pipe location for backing off operations.

The free point indicator tool is displayed in Figure 8 and is designed to determine the location of sticking by measuring points in the drill string where tension and/or torque is zero. The tool has a series of axial strain gauges that measure tension/torque in the string. The string is tensioned and/or torqued and the gauge measures the strains in the string; a zero reading will indicate the stuck location. The degree of the stuck pipe will vary from totally stuck (0% free) to totally free (100% free) depending on the tool measurements downhole. We should note that torque and overpull measurements will be less accurate in deviated wells due to the friction between the drill string and the hole walls. The measurements are also not very accurate in wells with doglegs.

Usually, back off attempts are made where torque and tension readings are 80-90% of the free pipe. Practically, the back off point is chosen to be the next connection above the free connection which was broken on the last trip.

3.2 Backing off the string

Backing off refers to separating the free pipe from the stuck portion, usually at a threaded connection above the free point. It can be done mechanically by applying left hand torque or in combination with an explosive charge, the latter being the preferred. A string shot, which is an explosive charge, is placed across the connection to be separated. A Casing Collar Locator (CCL) is run in hole to locate the exact connection and where to place the charge; the CCL tool distinguishes between the thinner pipe body and thicker pipe connections. The back off procedure is outlined below:

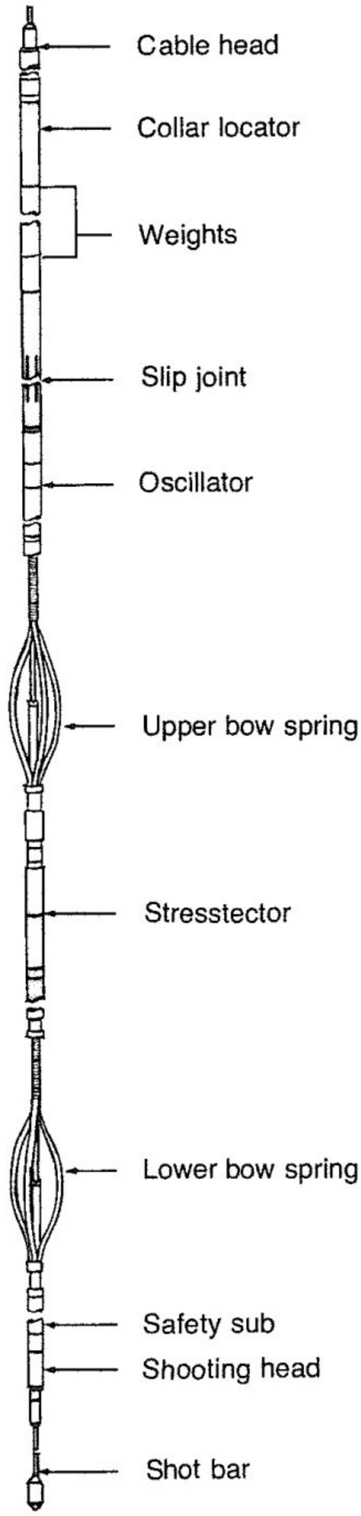

FIGURE 8: Free point tool (Short, 1981- Courtesy of Dia-Log)

- The explosive charge is run through the wire line to opposite the back off connection;
- Left hand torque is applied to the string with some over pull, the over pull/torque is maintained and the explosive charge run to the connection to be broken;
- When the charge is in position, the surface weight is slackened to the desired value and the charge is fired;

- After the charge is fired, the tool is pulled out to determine if the operation was a success; if it is, the weight indicator should show less weight on pick up;
- Sometimes, the connection doesn't get completely undone and so further left hand torque might be applied to completely undo the connection.

Sometimes, several other connections can become loosened and it is very important not to rotate the string while pulling out of the hole the stands that are above the back off point. Every joint must be torqued up when running in hole again. If the back off is at the wrong connection, it is sometimes possible to screw back in and attempt the back off again, but the chances of success are reduced.

Factors which may ensure success during back off include:

- Sufficient explosive charge that will also not damage the connection;
- Enough left hand torque;
- Backing off at a neutral point with just a small over pull.

It is often difficult to get explosives on site due to legal restrictions and, for this reason, mechanical back off is considered. Safety must be observed during back off operations because it is a dangerous operation that might lead to serious injury on the rig floor.

3.3 Twist off

This refers to breakage of the drill string while in hole. The risk of twisting off is usually greater when the drill string has many combinations of sizes of connections. This is because the heavier portions have greater momentum than the lighter, thinner tools in the same drill string. Stopping the pipe rotation quickly at the surface can cause twist off due to the momentum differences in the drill string, so large sized assemblies should be handled carefully. The slip area (usually 2-5 ft. below the tool joint) is also commonly a twist off prone area. Good drilling practices will make sure the slip area is not pre-damaged before drilling begins. Damaged pipes should be taken out of service and the string should also be regularly inspected for micro-ledges or thread damage. Washout is also a common cause of twist off. This is when the drilling assembly develops a hole due to erosion by particles in the high-pressure circulating mud. Wash outs can be detected by a process of elimination, i.e. surface equipment are checked for leakages first, then checks for down hole leakages related to the formation are also analysed; if both are ok, then further checks might lead to the discovery of a washed out portion of the string. Pump pressure and stroke recorders are very useful in analysing for washouts and should, therefore, be in good working condition.

Three cases of sudden snapping of the drill string were recorded in well MW16 in Menengai; the Easy View Screens at the time of snapping are shown in Figures 9, 10 and 11. In Figure 9, the string parted suddenly at 0740 hrs. At 0724 hrs, torque and WOB (weight on bit) suddenly dropped to 0. At 0740 hrs there was a drastic drop in the hook load from 33.23×10 kN to 11.81×10 kN, despite no rise in WOB and a constant hook height. At 0746 hrs, WOB was still 0 despite the string being lowered to 4.61 m. Subsequent picking up of the string only registered a maximum hookload of 27×10kN, and slightly erratic rotary torque (mostly zero).

In Figure 10, at 0815 hrs, the torque suddenly dropped to almost zero; then very shortly afterward, the WOB also dropped from 4.22×10 kN to almost zero. WOB never changed between 0815 hrs to the end of this recording despite the hook height changing. The hook height went up from 7.49 m at 0815 hrs to 8.04 m at 0816 hrs but the hook load and WOB remained constant. The hook load dropped from about 47×10 kN to a constant value of 40×10 kN, indicating a snapped string. In Figure 11, it was observed how torque sharply descended from 14×10 kNm to almost zero at 0128 hrs. WOB then dropped sharply at 0129 hours despite a constant hook height of 2.16 m. It was also noted that the WOB was almost zero, yet the hook load was still around 59×10 kN (it should in fact be around 65×10

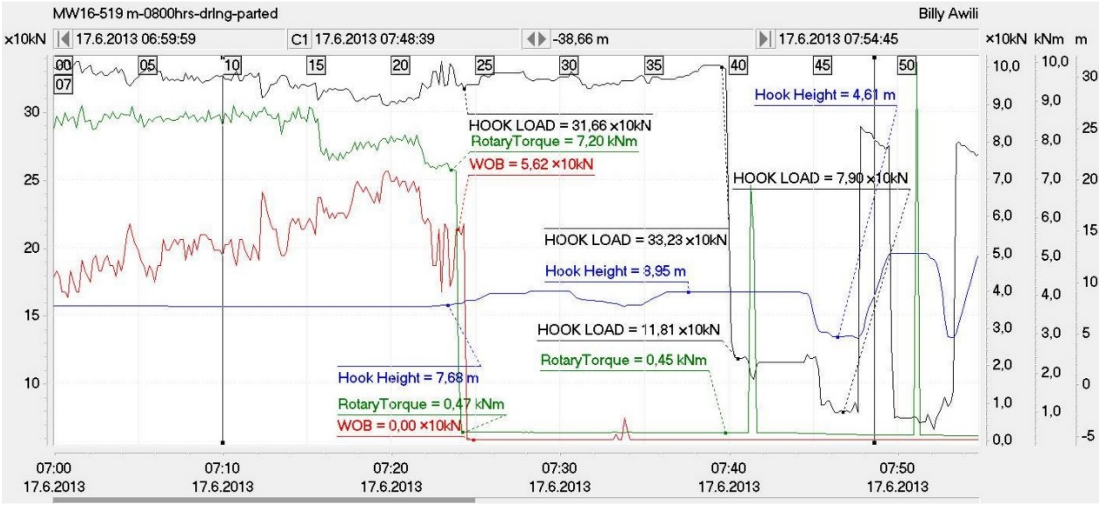

FIGURE 9: Parameters of snapping of drill string in well MW16 at 519 m

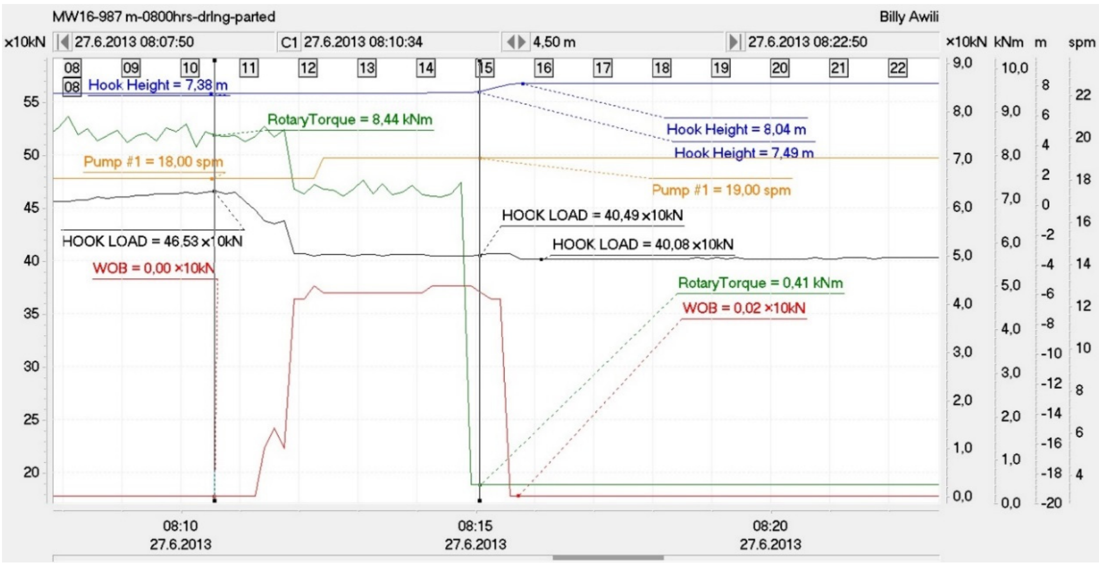

FIGURE 10: Parameters of snapping of drill string in well MW16 at 987 m

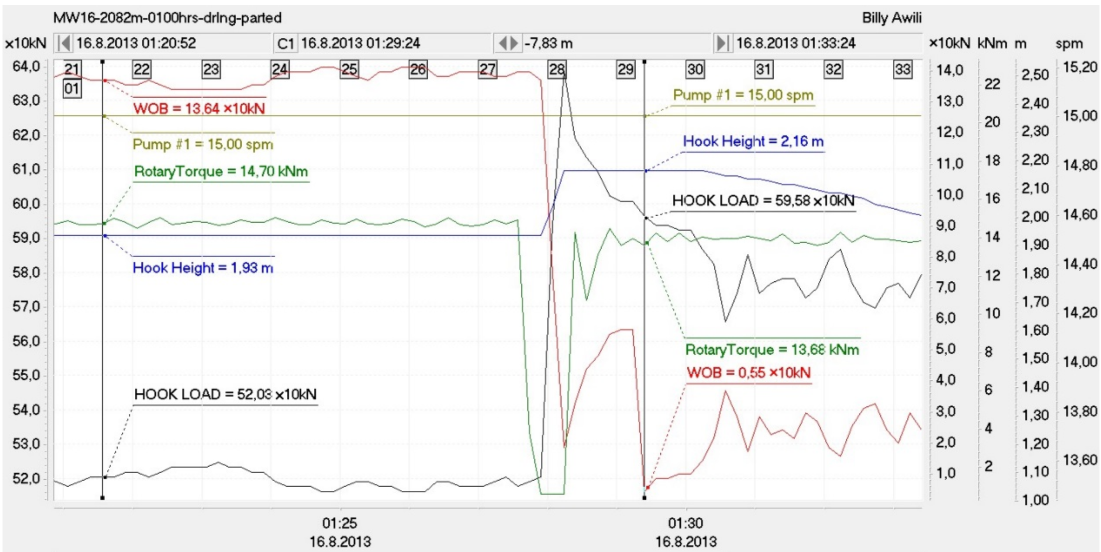

FIGURE 11: Parameters of snapping of drill string in well MW16 at 2082 m

kN when there is no WOB). The hook load also gradually dropped and while picking up the string it never got to the original hook load record of 65.6×10 kN, indicating a snapped string.

4. FISHING

Fishing is any operation or procedure to release, remove or recover tubular or other material in the well bore that adversely affects drilling, casing or completion operation (Short, 1981). Fishing operation success depends on being prepared, planning carefully, deciding correctly and knowing your fishing equipment. Fishing, generally means increased costs and all other options of economically getting out/releasing the string must be explored before fishing starts.

A review of previous fishing jobs in the area will give a good start in knowing about the formation characteristics, how sticking can occur, procedures used to fish, available tools and personnel or fishing service companies in the area. It is very important to keep accurate records of your tools, including the number of collars, drill collar size and clearance, types of jars and bumper subs, how safety joints are used etc.

After backing off, it is important to know the exact length, weight and other dimensions of the fish. Checking/inspecting the retrieved parts above the free point or backed off joint will give you an idea of what the top of fish looks like and will strongly influence the fishing assembly to be used.

A plan of action is also necessary after reviewing all the available data. It is also a good practice to try and get the fish in one piece. When fishing, select the tool that makes the strongest connection, usually a screw in connection (Short, 1981). An overshot is the second choice and a taper tap, a last resort. Milling should also be chosen as a last resort unless when dressing the fish top. Long milling jobs without properly circulating out the mills can cause them to pack around the fish and wedge it tighter. It sometimes occurs that the fishing assembly can also get stuck, leading to a second fish in hole. This problem can be avoided by careful study of the causes for the first stuck pipe and inspecting the parts backed off for indications of expected conditions down hole.

4.1 Fishing tools

The importance of selecting the best tool for the job cannot be over emphasized. The availability of fishing tools lessens with decreasing hole size (Short, 1981). It is also a fact that tools for smaller hole sizes have limited strength characteristics. Fishing tools can be run on tubular, wire line or both.

Most fishing jobs occur while using tubulars. A series of these tools have been designed to run on pipe and are operated with rotation, reciprocation or both. Some of the tools described may not be classified as fishing tools but they assist in the fishing job.

4.2 Mills

Mills do not have moving parts and they need torque to drill. Running mills on butt-shouldered tool joint type connections is better than on regular screw-type connection (tubing connection) since over-torqueing for long periods can lead to screw-type connection failures. Mills drill up junk and also dress off a fish top where it can be caught by a fishing tool. Figure 12 shows various mill types. Mills can also ream out collapsed casing, ream inside tubulars, e.g. scales and cut out sections of casing or window for side tracking. They have a cutting face specially designed with grooves to allow the passage of fluids and ground metal. The cutting face wears out after some use.

Junk mills can be flat, concave and ribbed and can ream almost any type of junk including bit cones. They expose the maximum cutting face to the junk. A concave mill is used when junk pieces are small and retains the small pieces in the hole before they are circulated out. Flat bottomed and ribbed mills are used to drill out larger junk pieces. Preferred clearance between hole size and casing and mills can be given by the manufacturer of the tool.

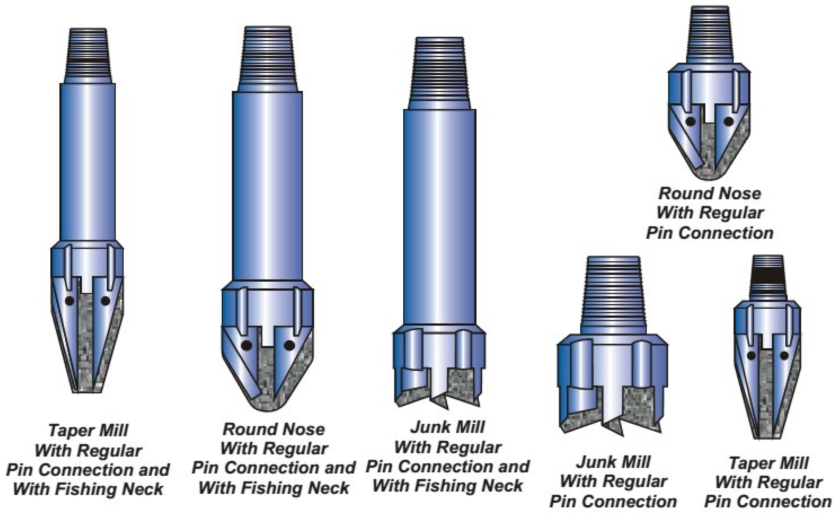

FIGURE 12: Assorted mills (Parveen, 2013)

Skirted mills have short sleeves connected to the lower outer edge of the mill which centres the mill over the fish.

Cement mills are similar to junk mills but the fuller-gauge provides an increased amount of cutting surface to mill cement. Roller cone bits are more efficient in drilling out cement but when the hole is small, the small bit used has weaker bearings that could result in lost cones, so the cement mill can be used in this case.

Pilot mills have a hard cutting surface bottom extension or can be connected to a pilot bit to mill drill collars, drill pipe, casing liners and rotary shoes. Sometimes they can be used to enlarge inside diameters so that fish can be caught with an inside catch tool.

Throated mill has a long heavily constructed body with cutting material on the mill bottom and some material deposited on the inside (throat) of the mill. It can be used to cut a fishing neck on the fish, and also to wash over the top of the fish, similar to a mill shoe.

4.3 Overshot

This is the most important and widely used tool in fishing. It consists of an upper sub, a bow or body, a lower sub that holds the grapples or slips and a guide shoe. Figure 13 shows an overshot and accessories. The tool can be run as a single unit to catch one size of fish or stacked to catch different sizes of fish. The overshot is usually connected at the bottom of a bumper sub-jar-collar assembly. The tool is lowered onto the fish, the top of the fish then passes through the shoe guide, through the slip

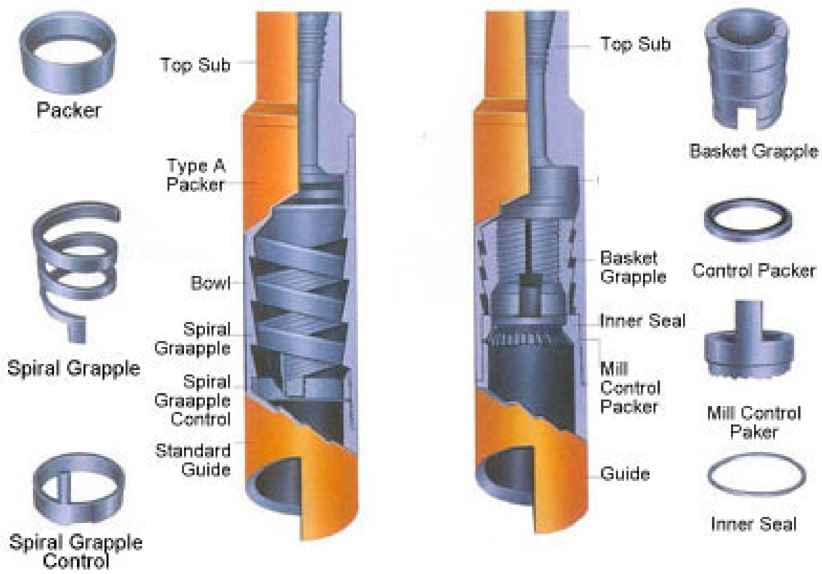

FIGURE 13: Bowen overshot and accessories (Parveen, 2013)

section and into the bowl of the overshot. When the fishing assembly is picked up, the slips (or grapples) firmly hold onto the fish. The fish is then worked until it is free and is pulled. String shots can be run down through the fish to back it off, or other operations can be conducted as needed. If the fish cannot be recovered or it becomes necessary to release the fish, the assembly is torqued to the right and bumped down to release the overshot slips. The fishing assembly can then be pulled out.

The overshot can be fitted with slips or grapples (basket or spiral). When basket grapples are used, the fish must have a clean top. Most overshots are fitted with a circulating pack off to enable cleaning/circulating out material on top of the fish before latching onto it, and through the fish after latching on. Some overshots have small mill shoes (guide, rotary and mule) at the bottom for dressing off the fish top before engagement. A bowl extension can also be fitted to the overshot to allow it to engage the fish at a lower depth than the fish top. A wall hook can be used to latch onto a fish that is laid over in a wash out. A knuckle joint can be used if the wall hook is unsuccessful.

4.4 Junk basket

Junk basket is similar in looks to an overshot, it has an upper body, a bowl (or basket), a sub to hold the retainer fingers and a shoe. Retaining fingers swivel upwards to let the junk pass up into the bowl and they return to their original horizontal position to retain the junk (bit cones, slip fragments, hand tools, etc.). Normally, some type of drag-tooth drilling shoe is used on the junk basket. Sometimes, the retaining fingers can break and release the fish. To solve this problem, the junk is drilled down until a core is cut and plugged to the bottom of the basket. The whole core plus the junk on top of core is then pulled out.

Reverse circulation junk basket has special channels and ports near the shoe that direct the fluid flow centrally from the periphery of the shoe into the centre of the basket. As the junk sweeps into the basket, the fluid moves through additional ports into the annulus. Figure 14 shows a picture of this tool. In operation, circulation is through the junk basket, around the shoe and up through the annulus. A ball is then dropped inside the tool to divert fluid flow and help sweep the junk into the basket.

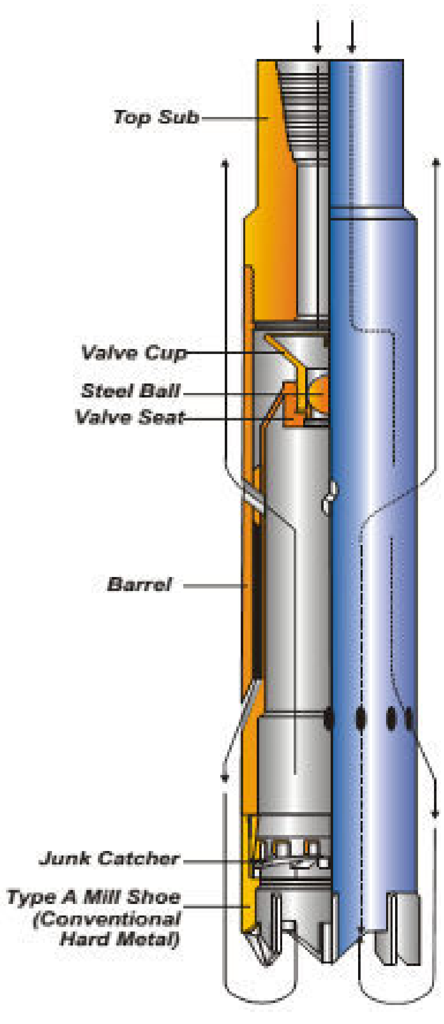

FIGURE 14: Reverse circulation junk basket (Parveen, 2013)

4.5 Other fishing tools

Wash-over pipe. Specially sized tubes are connected to allow circulating out debris between its inner diameter and the fish outer diameter. The pipes are chosen to optimize circulation. The pipe is normally fitted with a wash over shoe at the bottom. The shoe has teeth to clear out the debris. The pipes can be connected at the bottom of an overshot assembly so that the fish is engaged once the debris is cleaned out.

The pipe spear or *casing spear* is used to catch the fish on its inside diameter. It has a cage fitted with a j-slot and is actuated by drag springs or friction blocks that contact the inner walls of the fish. It is run at the bottom of the fishing assembly and then positioned inside the fish. Left hand torque is then applied to release the slips; the whole assembly is then moved down a short distance and then picked up slowly. The slips then move outwards and engage the inner wall of the fish. Torqueing right and bumping down will release the spear.

One demerit of the spear is that you cannot jar downwards while using them since this action releases the fish. The slips must also be released before the fishing tool can be pulled out since the slips are upside-down; so in case the spear assembly is stuck, it will be problematic to retrieve the spear alone. *Taper tap* is an inside catch tool with an upper connection and a tapered body made of special steel. The tapered body has threads on its surface that are similar to those of a machine tap used to cut internal threads. It is connected to the bottom of the fishing assembly, run into the hole and screwed into the fish, which can then be pulled out after working, if necessary. It has several weaknesses: it is good in straight pulling but cannot withstand appreciable jarring or bumping. It works by cutting threads and so a longer tap would cut longer/stronger threads but then a longer tap also implies a tool that will break easily when bent. The threads cut are also weak so it's easy to jar the tool out of the fish. The tool has no releasing mechanism and if it were to be backed out of the fish, the top part of the fish would also become undone with the tap. The tool is usually released by jarring first but this can, at times, lead to breaking of the top, leaving a piece in hole. Jarring is usually done for a short time before the assembly is backed off above the tap and a more efficient fishing string run in hole. This tool is therefore used only in special occasions because of its many demerits.

Die collar is a tool that catches the external surface of a fish. Its upper part is connected to the bottom of a fishing assembly and the lower internal part is an elongated taper with threads. The tool cuts threads and then connects to the fish and then the fish is recovered. It cannot withstand long jarring periods and the thread connection to the fish is also weak.

Knuckle joint changes the direction of the line through the axis of the tools run below the knuckle joint from the line through the axis of the assembly above the knuckle joint. It is run at the bottom of the fishing assembly and is hydraulically actuated by mud pressure where the lower part is thrown out of alignment with the top part of the tool. This off-setting then is useful in catching fish in washed out sections of the hole. Bent subs and bent joints can perform the same function.

Wall hook is a hook shaped tool that is constructed as part of a washover shoe. It is used to guide the top of the fish towards the centre of the overshot in a washed out zone. It is positioned just off the top of the fish and the entire assembly is slowly rotated; the hook then guides the fish.

Jars deliver a sharp heavy upward impact on the equipment connected below them. The down hole assembly is first stretched and stores energy; then when the jars trip, the assembly above the jars travel upward rapidly for a distance equal to the stroke length of the jars. The travelling assembly is stopped suddenly at the end of the stroke and this imparts a force to the tools suspended from the jars. Collars are run immediately at the top of the jars to provide additional momentum/greater impact at the end of the stroke. Jars can be mechanical or hydraulic, the latter being more common. Jars are usually run above the fishing tool and below the collars.

Bumper sub complements the jars. It acts by driving the fish downwards. It consists of a free travelling mandrel that provides a stroke length. The string is picked up and lowered rapidly through the stroke length. At the end of the stroke, the fishing assembly imparts a sharp downward blow to the fish that is located below the bumper sub. Drill collars above the bumper sub increase the intensity of the downward blow. The bumper sub is located between the jars and the fishing tool.

Junk sub or *boot basket* catches large fragments in the fluid flow stream near the bit. The time needed to mill fragments/junk is, therefore, eliminated/reduced and consequently the life of the bit/mill is extended. It has tool joints at both ends and a bowl fixed on its body extending from near its bottom tool joint to about two thirds of the distance between the two tool joints. It is run immediately above a mill or bit. Milled metal pieces are carried over the annular space and into the bowl due to the reduced fluid flow speed at the increased cross-sectional area at the bowl; Fluid flow at this area also causes eddy currents which make the debris drop into the bowl. The junk is retrieved on pull out.

Safety joints are run in the fishing assembly and release the assembly from the fish, if the fishing assembly must be pulled out for whatever reason, e.g. the jar in a fishing assembly might be malfunctioning and so the fishing assembly will need to be backed off to examine the jar. If there's no safety joint then it might be necessary to run a string shot to back off.

5. MENENGAI STUCK PIPE DATA ANALYSIS

Tables 4 and 5 show how stuck pipe events are distributed over the drilling activities in 10 Menengai wells. This table will assist in identifying operations during which stuck pipe mostly occurs.

TABLE 4: Drilling activities during stuck pipe in Menengai

Well	Depth of sticking (m)	Activity during sticking	No. of hours stuck	Freed	Hours spent fishing	Total drilling days (spud in to capping)	Total depth (m)
MW01	114	Drilling	1	Yes	0		
	125	Drilling	3	Yes	0		
	380	POOH	3	Yes	0		
	378	Casing-Stuck	-	Yes	0		
	2206	Casing	8	Yes	0	79	2206
MW02	109	POOH	72	Yes	0		
	133	RIH	<12	Yes	0		
	135	Ream	<12	Yes	0		
	165	POOH	1	Yes	0		
	207	Drilling	3	Yes	0		
	213	Drilling	17	Yes	-		
	218	Drilling/Reaming	77	Yes		125	3200
MW03	113	Drilling	0.75	Yes	0		
	167	Drilling	0.5	Yes	0		
	1187	Drilling	0.5	Yes	0		
	2093	Drilling/Reaming	216	No back- off	648	100	2112
MW04	2117	Drilling	216	No-parted string	0	83	2117
MW06	2202	Drilling	268	No-parted string	0	96	2202
MW07	59	Drilling	27	Yes	0		
	105	Drilling	<6	Yes	0		
	149	Drilling/Reaming	20	Yes	0		
	151	Drilling	5	Yes	0		
	1184	POOH	37	Yes	0		
	2135	Drilling	9	No-parted string	0	132	2136
MW08	58	Drilling	1	Yes	0	126	2355
MW09	1950	Drilling	1	Yes	0	107	2088
MW13	1648	RIH	2	Yes	0	161	2012
MW21	326	Drilling	4	Yes	0		2730

TABLE 5: Total hours stuck (10 wells)

Operation	Hours
Drilling	883.75
POOH	37
RIH	14
Total	**934.75**

Table 6 shows the history during selected stuck pipe events. The recommended pumping rates are calculated based on recommended good practices for geothermal drilling.

TABLE 6: Operational activities during sticking (from GDC well completion reports)

Well	Depth stuck (m) & date	Operational activities in a span of 24-48 hours	Pumping rates and returns
MW07	59 08-02-12	Drilled 26" well from 43.19 to 59.06 m with brine-returns OK. The drill string got stuck while making a connection. Worked the string and applied pull up to 200 klbf. Pumped hi vis mud at every 15 minutes while working stuck pipe up and down. No returns. Pumped L.C.M. in mud into the hole while working the string. Received returns to the surface. Pumped aerated water into the hole. Received returns on surface. The string was freed.	Approx. 1717 l/m full returns *Recommended pumping = 7295 l/m of water
MW07	149 20-02-12	Drilled 17-1/2" hole from 133 to 149.25 m with intermittent partial & full returns. Experienced drilling break from 134-138 m with cuttings fully flowing out. Circulated the hole at 149 m. While lifting the string off bottom, it got stuck with high torque and high Stand pipe pressure experienced. Worked the string up and down while pumping brine, then introduced air. Applied tension to 160 kN. Gained 1 foot. Thereafter, rotation and circulation was lost. Poured 2 drums drilling detergent into the active mud tank and pumped through the string. Not much progress observed. Pumped hi-vis mud into the hole. Very little gain observed. Worked the pipe up and down without gain. There was no pressure in the stand pipe pressure. All fluids pumped got lost into formation. Decided to cure loss zone by pumping hi-vis mud mixed with walnut shell and mica flakes. This was repeated several times. Worked the string and introduced air. Leakage on the stand pipe observed. Continued pumping brine at 200 strokes per minute while repairing the leakage. Introduced air and pressure indicated 800 psi. The string got free and full returns observed on the surface. POOH and prepared the string for plug job. Pumped 4 m^3 of cement slurry at 112 m. POOH to shoe and WOC to cure.	Approx. 2720 l/m full returns Recommended pumping = 3107 l/m of mud
MW07	1184 15-04-12	Drilled 12-1/4" hole from 1200 m to 1205 m with mud- Returns ok. Circulated the hole with 10,000 strokes of hi-vis mud to clean hole. POOH to shoe and did a wiper trip. Encountered a tight spot at 1070 m. Circulated the hole and spotted hi-vis mud at bottom. POOH from 1205 to 1184 m while back reaming. Pump went off while attempting to connect back the stand that had been removed. Saver sub damaged. Installed circulating head and circulated the hole - returns received on surface. On connecting the saver sub to string, it was noted that the string got stuck. Circulating with mud returns ok. Pumped high vis mud while working the string.	1717 l/m full returns Recommended pumping = 1413 l/m of mud
MW07	2135 25-05-12	Drilled 8-1/2" hole from 2134.09 to 2135.93 m with aerated water and foam - no returns. The string got stuck at 2135.93 m at 0200 hrs. Worked the string by applying torque. Circulated with aerated water and foam while working the string. Applied pull 310 klb and torque of 28 kNm. The string was freed at 1100 hrs and regained rotation. Circulated and POOH. POOH experiencing high drag from the bottom to 965 where there was no drag. Part of the BHA left in the hole. Two 6-1/2" drill collars, and 8-1/2" bit left in the hole. Waited for instructions from management. Decision made to RIH liners.	2040 l/m no returns Recommended pumping = 1100 l/m of water
MW09	1948 22-10-12	Drilling 8½″ hole with aerated water and foam. Partial returns. Drill string sticking from 2300 to 0000hrs.	2210 l/m partial returns. Recommended pumping = 1100 l/m of water

TABLE 6: Continued

MW21	326 28-12-13	Drilling 17-1/2" hole with water and mud sweeps till 326m. Got stuck at 0200 hours and lost circulation. Circulated hi-vis mud while working the string for 4 hours when string was freed. POOH after circulating to remove collapsed debris. POOH to 291 m and reaming the section between 291and 326 m.	3060 l/m full returns *Recommended pumping = 6213 l/m of water

***T**hese water pumping rates are difficult to achieve practically and therefore the problem is mitigated by using high-viscosity mud sweeps at regular intervals to ensure sufficient hole cleaning. We also note that the upper sections of a well are usually drilled with slower ROP, and therefore the fluid annular velocity necessary for sufficient hole cleaning is lower. Cuttings also reach the surface faster since the well is still shallow.

5.1 Easy View diagrams and analysis

Drilling parameters during selected stuck pipe events were analysed using Easy View Software to easily recognise trends at the moment of sticking and before the stuck pipe event. The drilling data was recorded using data loggers at the rig site. This data was then downloaded in Excel files in 10 second intervals and has been the input into Easy View software. This analysis will assist in identifying the causes of the stuck pipe and possible solutions. The diagrams have been displayed and described in the subsequent pages. Other conditions not captured by the data loggers during the stuck pipe events have also been listed (these other conditions include pumping rates and amount of returns at shale shakers).

5.1.1 Well MW07 - Stuck at 2135 m at 0145 hrs during drilling

The trend in Figure 15 shows that the string got stuck at 0145 hrs. We see a sudden drop in WOB from 5.92 to 0 kN, the rpm also drops to 0 from 70. The pump rate, bit location and ROP remain constant. It can be observed that the driller then tries to pick up the string and it is stuck as it has to be pulled to over 84.35 tonnes. There were no circulation returns at the moment of sticking and the pumping rate was 2040 l/m of aerated foam and water.

The trends prior to sticking are displayed in Figure 16. From 0100 hrs to the sticking time at 0145 hrs, stand pipe pressure varies by 3 bar (between 5,27 MPa and 4.97 MPa). The other parameters appear to

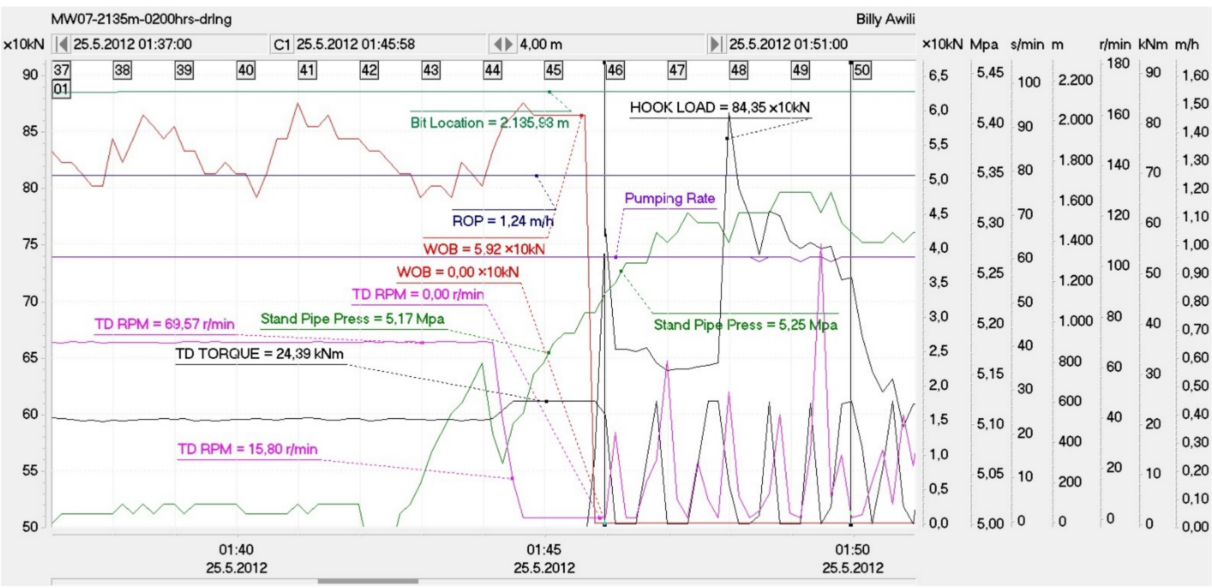

FIGURE 15: Parameters at sticking in well MW07 at 2135 m

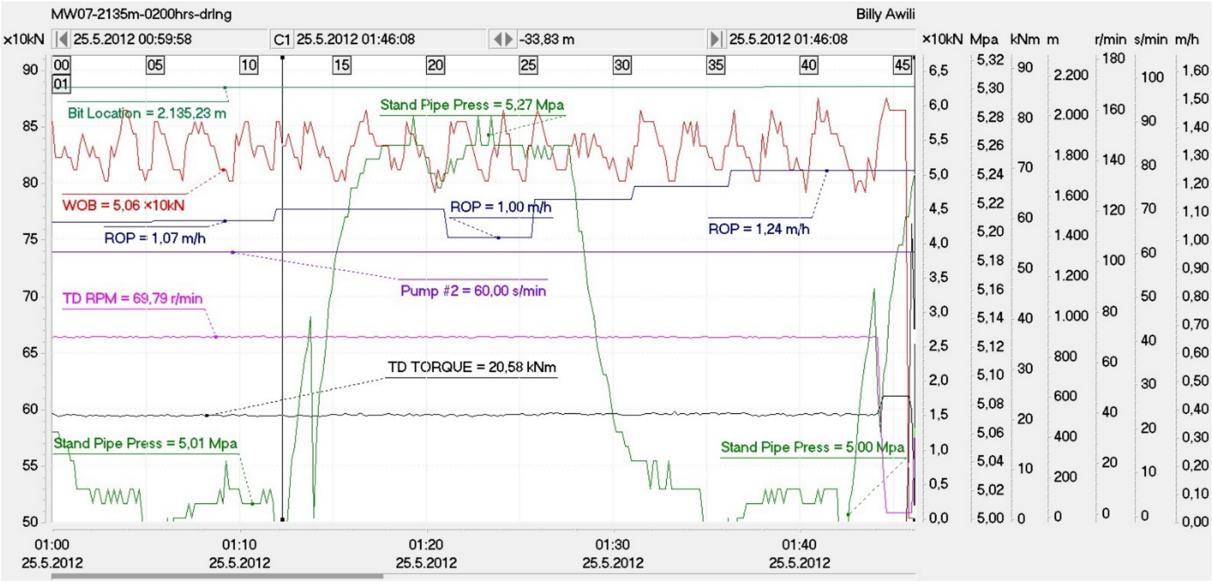

FIGURE 16: Parameters prior to sticking in well MW07 at 2135 m

be unchanging. Pumping rate was 2040 l/m of aerated foam & water and there were no returns prior to the sticking. Appendix I shows sample of data for production of Figure 16.

5.1.2 Well MW09 - Stuck at 1948 m at 2229 hrs during drilling

The trend in Figure 17 shows the parameters at the moment of sticking in well MW09 at 1948 m. The trends prior to sticking are shown in Figure 18. Appendix II shows sample of data for production of Figure 18.

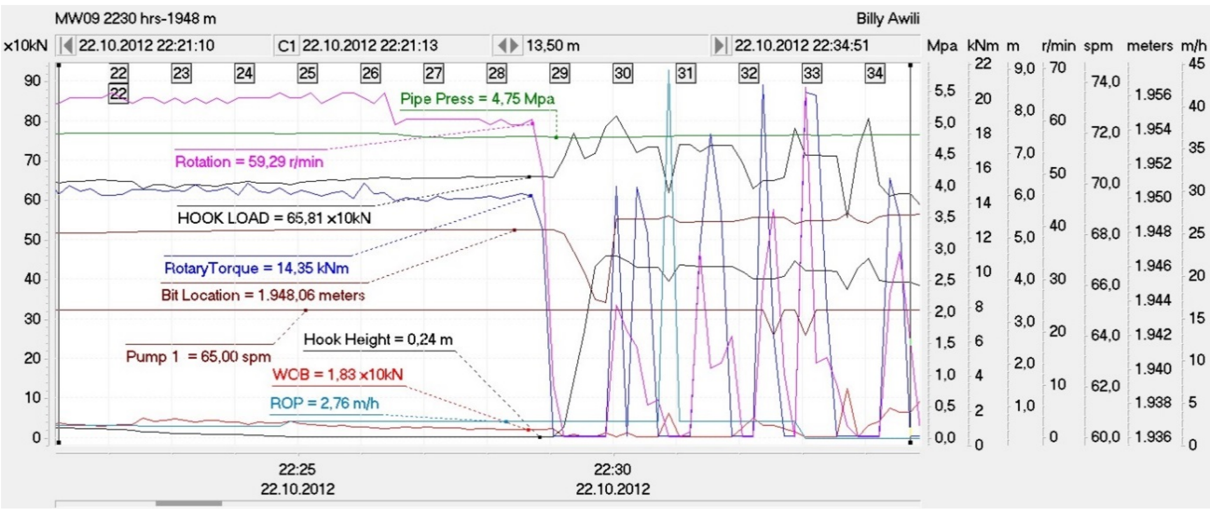

FIGURE 17: Parameters at sticking in well MW09 at 1948 m

We see that the string gets stuck at 2229 hrs when the rotation speed and rotary torque suddenly drop to zero. This occurs at the end of the drill pipe joint, evidenced by the value of hook height, i.e. the hook height is constant at about 0.41 m which implies it is the end of the current drill pipe joint. WOB is also observed to dip to zero. Pump rate and pressure do not change. There were partial returns during this stuck pipe event and the pumping rate was 2210 l/m of aerated water and foam. The trends, prior to sticking, show that the rotation speed, pipe pressure and torque are quite regular through the drilling of this joint of drill pipe, just until the sticking point.

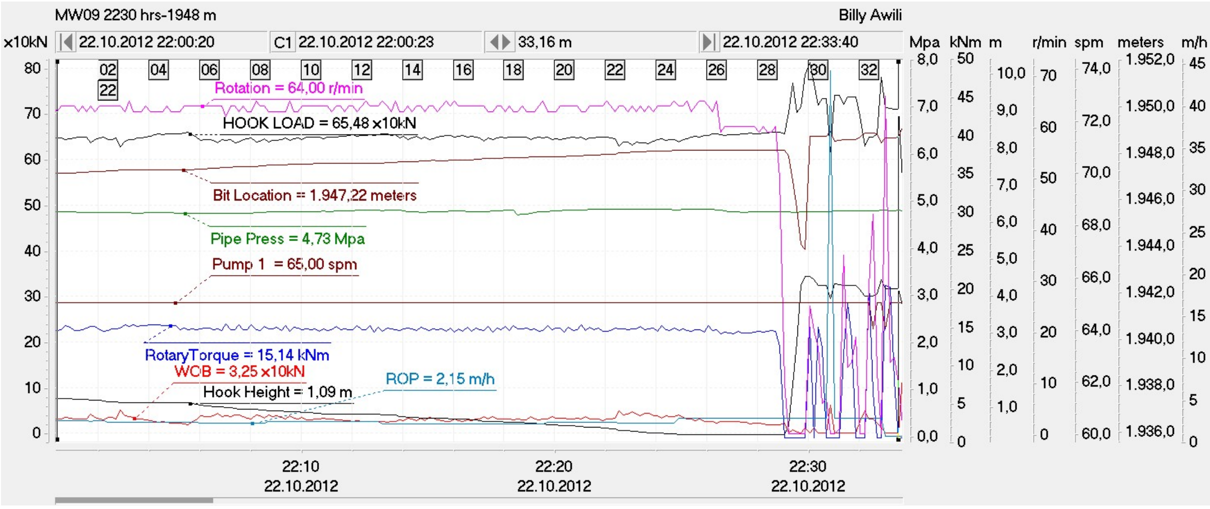

FIGURE 18: Parameters prior to sticking in well MW09 at 1948 m

The results seen in the above diagrams imply that the possible reasons and types of sticking are as shown in Table 7. Parameters not captured in Easy View have been obtained from Menengai well completion reports (see Table 6). Appendices 1 and 2 show samples of data sheets used in the Easy View analysis. The possible causes are inferred from notes on stuck pipe that were discussed earlier in this paper. The data necessary to carry out the Easy View analysis for most of the stuck pipe incidents, especially for the earlier wells, were unavailable.

TABLE 7: Possible causes of stuck pipe in Menengai wells

Well	Depth stuck (m)	Torque	WOB	ROP	Returns	Other	Possible cause
MW07	2135	Increase	Unchanged	Increase	No	Well inclined 24°	Pack-off caused by poor hole cleaning or a new lost circulation zone.
MW07	59	Freed by swithching from drilling with brine to aerated fluid					Settled cuttings due to poor hole cleaning.
MW07	149	Sudden increase	-	Sudden increase	Full	Pipe pressure increase	Fractured & faulted formation.
MW07	1184	Freed by pumping water instead of mud					
MW09	1984	Sudden drop	Unchanged	Unchanged	Partial	Rotation speed suddenly 0.	Fractured & faulted formation. Cement block/junk
MW21	326	Unchanged	Unchanged	Sudden decrease	Partial	Circulated till free	Poor hole cleaning

6. DISCUSSION

The results show that the causes of stuck pipe are several in Menengai. Unconsolidated formation is problematic but has been mitigated through using cement plugs. As earlier mentioned, sticking due to fracture and faulted formation can be controlled by reducing drill string vibration, minimizing surge pressures and sufficient hole cleaning to reduce hole pack off. Sticking due to poor hole cleaning can be reduced by ensuring the hole is clean of cuttings. There are several ways to ensure good hole cleaning including ensuring good mud rheology, especially the yield point and gel strength, controlling the drill rate to ensure the hole is clean, checking the volume of cuttings coming over to the shale shaker and controlling annular velocities. Sticking caused by drilling through micro doglegs and ledges can be prevented by running slowly when tripping at alternating formation points; these areas should be noted and reamed through during trips.

6.1 Loss of returns while drilling with water and air

Drilling the production zone is quite a challenge, especially when there are no returns and cuttings cannot be carried to the surface. The drilling programme in Menengai usually recommends blind drilling in the production section when there are no returns. The choice of drilling fluid is restricted to water, aerated fluid and foam. Mud improves hole cleaning but cannot be used in the production zone since it will block the sensitive feeder zones. This problem can be solved by the use of liquid drilling fluid polymer. This compound increases water viscosity, thereby helping a lot with cutting carrying capacity; it does not affect formation permeability adversely. Polymer, however, does not improve gel strength and will, therefore, not suspend cuttings if pumping is stopped. Sweeping the hole with polymer can still be introduced in Menengai to assist in hole cleaning as it has been successfully used in Iceland.

6.2 Drill string snapping/ tubular washout

An incident of snapped string was encountered after one day of working a stuck pipe in well MW07 at 2135 m. The pull applied was 310,000 lb force and 28 kNm torque which still did not exceed the yield point (378,605 lb force tensile yield strength and 53 kNm torsional yield strength) of the 5'' OD drill pipe (considered the weakest member of the drill string). The BHA snapped at a collar connection. Weakening of drill string members could be caused by drilling fluid wash out or corrosion by acidic water that is used as a drilling fluid. These two problems can be solved by using corrosion inhibitor compounds and by using caustic soda in the drilling fluid. Caustic soda is used to maintain alkalinity so that acidic fluids do not attack metal. Corrosion inhibitors work by various mechanisms to inhibit the oxygen present in drilling/production fluids from corroding pipes or equipment (Schlumberger Drilling, 2014). It has also been shown that aerated fluids erode drill pipes at a higher rate than non-aerated fluids (Budi Kesuma Adi Putra, 2008).

6.3 Deviation surveys

These can greatly assist in correcting trajectories and avoiding sticking related to hole geometry. The Totco survey tool and the electronic multi shot tool can be dropped in the drill string during trip outs to quickly measure the inclination. These tools are popular since they eliminate the non-productive time associated with setting up a conventional deviation survey.

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Finally, thanks to Almighty Jehovah who protected me from illness and harm during my stay and studies.

NOMENCLATURE

BHA = Bottom hole assembly;
ECD = Equivalent circulating density;
ft = Feet;
hi-vis = High viscosity;
klbf = Kilo pounds-force;
klbs = Kilo pounds;
kN = Kilo Newton;
kNm = Kilo Newton-metre;
lb = Pound;
l/m = Litres per minute;
LCM = Lost circulation material;
POOH = Pull out of hole;
psi = Pounds-force per square inch;
RIH = Run in hole;
ROP = Rate of penetration (m/h);
RPM = Revolution per minute;
SPM = Strokes per minute;
WOB = Weight on bit (kN);
WOC = Wait on cement;
" = Inches.

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APPENDIX I: Sample data used to produce Figure 16

Date	Hook load	Wob	Stand pipe pressure	Rotary torque	Hook height	Pump #2	Pump #3	Drilling time	Bit location	Drilled depth	Td torque	Td rpm
yyyy.mm.dd hh:mm:ss	×10 kN	×10 kN	MPa	kNm	m	s/min	s/min	min/m	m	m	kNm	r/min
2012.05.25 01:39:59	48.98	5.06	5.02	0.57	17.13	60	60	48.23	2135.86	2135.86	20.75	69.38
2012.05.25 01:40:09	48.98	5.06	5.01	0.57	17.13	60	60	48.23	2135.86	2135.86	20.75	69.56
2012.05.25 01:40:19	49.33	4.72	5.01	0.56	17.13	60	60	48.23	2135.86	2135.86	20.97	69.38
2012.05.25 01:40:29	48.98	5.06	5.01	0.57	17.12	60	60	48.23	2135.86	2135.86	20.81	69.38
2012.05.25 01:40:39	48.47	5.57	5.01	0.57	17.1	60	60	48.23	2135.89	2135.89	20.59	69.38
2012.05.25 01:40:49	48.47	5.57	5.01	0.57	17.1	60	60	48.23	2135.89	2135.89	21	69.47
2012.05.25 01:40:59	47.95	6.09	5.02	0.57	17.08	60	60	48.23	2135.9	2135.9	20.91	69.56
2012.05.25 01:41:09	48.3	5.75	5.01	0.57	17.08	60	60	48.23	2135.9	2135.9	21.06	69.47
2012.05.25 01:41:19	48.3	5.75	5.02	0.57	17.08	60	60	48.23	2135.9	2135.9	20.94	69.84
2012.05.25 01:41:29	48.12	5.92	5.02	0.57	17.08	60	60	48.23	2135.9	2135.9	20.72	69.38
2012.05.25 01:41:39	48.47	5.57	5.02	0.57	17.08	60	60	48.23	2135.9	2135.9	20.69	69.56
2012.05.25 01:41:49	48.47	5.57	5.02	0.57	17.08	60	60	48.23	2135.9	2135.9	20.91	69.56
2012.05.25 01:41:59	48.47	5.57	5.02	0.56	17.08	60	60	48.23	2135.9	2135.9	20.91	69.56
2012.05.25 01:42:09	48.64	5.4	4.97	0.56	17.08	60	60	48.23	2135.9	2135.9	20.5	69.75
2012.05.25 01:42:19	48.64	5.4	4.97	0.57	17.08	60	60	48.23	2135.9	2135.9	20.62	69.47
2012.05.25 01:42:29	48.81	5.23	4.97	0.56	17.08	60	60	48.23	2135.9	2135.9	20.94	69.66
2012.05.25 01:42:39	48.98	5.06	5.01	0.57	17.08	60	60	48.23	2135.9	2135.9	20.94	69.56
2012.05.25 01:42:49	48.98	5.06	5.02	0.57	17.08	60	60	48.23	2135.9	2135.9	20.81	69.75
2012.05.25 01:42:59	49.33	4.72	5.04	0.56	17.08	60	60	48.23	2135.9	2135.9	20.81	69.56
2012.05.25 01:43:09	49.16	4.89	5.07	0.57	17.08	60	60	48.23	2135.9	2135.9	20.59	69.56
2012.05.25 01:43:19	49.16	4.89	5.09	0.57	17.08	60	60	48.23	2135.9	2135.9	20.78	69.66
2012.05.25 01:43:29	49.33	4.72	5.11	0.57	17.08	60	60	48.23	2135.9	2135.9	20.81	69.66
2012.05.25 01:43:39	48.81	5.23	5.12	0.57	17.08	60	60	48.23	2135.91	2135.91	20.53	69.56
2012.05.25 01:43:49	48.98	5.06	5.14	0.57	17.07	60	60	48.23	2135.91	2135.91	20.81	69.56
2012.05.25 01:43:59	49.16	4.89	5.16	0.57	17.06	60	60	48.23	2135.92	2135.92	20.72	69.84
2012.05.25 01:44:09	48.64	5.4	5.09	0.57	17.05	60	60	48.23	2135.93	2135.93	20.91	69.47
2012.05.25 01:44:19	48.3	5.75	5.06	0.57	17.05	60	60	48.23	2135.93	2135.93	22.66	39.09
2012.05.25 01:44:29	48.12	5.92	5.1	0.57	17.05	60	60	48.23	2135.93	2135.93	24.41	14.16
2012.05.25 01:44:39	47.95	6.09	5.11	0.98	17.05	60	60	48.23	2135.93	2135.93	24.38	0

Date	Hook load	Wob	Stand pipe pressure	Rotary torque	Hook height	Pump #2	Pump #3	Drilling time	Bit loca-tion	Drilled depth	Td torque	Td rpm
yyyy.mm.dd hh:mm:ss	**×10 kN**	**×10 kN**	**MPa**	**kNm**	**m**	**s/min**	**s/min**	**min/m**	**m**	**m**	**kNm**	**r/min**
2012.05.25 01:44:49	48.12	5.92	5.15	3.08	17.05	60	60	48.23	2135.93	2135.93	24.41	0
2012.05.25 01:44:59	48.12	5.92	5.16	3	17.05	60	60	48.23	2135.93	2135.93	24.38	0
2012.05.25 01:45:09	48.12	5.92	5.18	0.58	17.05	60	60	48.23	2135.93	2135.93	24.41	0
2012.05.25 01:45:19	48.12	5.92	5.19	0.6	17.05	60	60	48.23	2135.93	2135.93	24.41	0
2012.05.25 01:45:29	48.12	5.92	5.19	0.58	17.05	60	60	48.23	2135.93	2135.93	24.38	0
2012.05.25 01:45:39	48.12	5.92	5.21	0.58	17.05	60	60	48.23	2135.93	2135.93	24.41	0
2012.05.25 01:45:49	56.2	0	5.21	0.58	17.05	60	60	48.23	2135.93	2135.93	24.41	0
2012.05.25 01:45:59	76.31	0	5.23	0.58	17.05	60	60	48.23	2135.93	2135.93	21.78	0
2012.05.25 01:46:09	65.66	0	5.24	0.58	17.05	60	60	48.23	2135.93	2135.93	0	33.84
2012.05.25 01:46:19	65.66	0	5.26	0.58	17.05	60	60	48.23	2135.93	2135.93	0	0
2012.05.25 01:46:29	65.48	0	5.26	0.58	17.05	60	60	48.23	2135.93	2135.93	0	0
2012.05.25 01:46:39	65.83	0	5.26	0.58	17.05	60	60	48.23	2135.93	2135.93	12.53	14.16
2012.05.25 01:46:49	64.45	0	5.29	0.58	17.05	60	60	48.23	2135.93	2135.93	24.38	22.97
2012.05.25 01:46:59	63.77	0	5.28	0.58	17.05	60	60	48.23	2135.93	2135.93	0	62.25
2012.05.25 01:47:09	63.94	0	5.29	0.58	17.05	60	60	48.23	2135.93	2135.93	0	7.31
2012.05.25 01:47:19	63.94	0	5.31	0.58	17.05	60	60	48.23	2135.93	2135.93	0	0
2012.05.25 01:47:29	64.11	0	5.3	0.6	17.05	60	60	48.23	2135.93	2135.93	11.53	22.22
2012.05.25 01:47:39	64.28	0	5.3	0.58	17.05	60	60	48.23	2135.93	2135.93	24.44	7.12
2012.05.25 01:47:49	64.45	0	5.3	0.58	17.05	60	60	48.23	2135.93	2135.93	24.41	0
2012.05.25 01:47:59	86.62	0	5.28	0.58	17.05	60	60	48.23	2135.93	2135.93	8.03	49.88
2012.05.25 01:48:09	79.92	0	5.31	0.58	17.05	60	60	48.23	2135.93	2135.93	0	8.81
2012.05.25 01:48:19	77.52	0	5.31	0.57	17.05	60	60	48.23	2135.93	2135.93	0	0
2012.05.25 01:48:29	74.08	0	5.31	0.58	17.05	59	60	48.23	2135.93	2135.93	1.66	2.91
2012.05.25 01:48:39	77.86	0	5.31	0.58	17.05	60	60	48.23	2135.93	2135.93	24.28	9.38
2012.05.25 01:48:49	77.52	0	5.33	0.58	17.05	60	60	48.23	2135.93	2135.93	0	40.78
2012.05.25 01:48:59	75.28	0	5.33	0.58	17.05	60	60	48.23	2135.93	2135.93	0	1.78
2012.05.25 01:49:09	74.59	0	5.33	0.58	17.05	59	59	48.23	2135.93	2135.93	0	0
2012.05.25 01:49:19	75.11	0	5.33	0.58	17.05	60	60	48.23	2135.93	2135.93	23.94	25.88
2012.05.25 01:49:29	74.59	0	5.31	0.58	17.05	60	60	48.23	2135.93	2135.93	0	108.47
2012.05.25 01:49:39	74.77	0	5.33	0.57	17.05	59	59	48.23	2135.93	2135.93	3.28	8.44
2012.05.25 01:49:49	71.84	0	5.3	0.58	17.05	60	60	48.23	2135.93	2135.93	23.91	24.94

APPENDIX II: Sample data used to produce Figure 18

Date	Hook load	Wob	Pipe pressure	Rotary torque	Hook height	Rotation	Pump 1	Drilling time	Bit location
yyyy.mm.dd hh:mm:ss	×10kN	x10kN	MPa	kNm	m	r/min	spm	min/m	meters
2012.10.22 22:56:53	69.47	0	5.7	0.47	4.19	0	70	88.72	1948.62
2012.10.22 22:57:03	69.61	0	5.7	0.47	4.19	0	70	88.72	1948.62
2012.10.22 22:57:13	66.66	0.98	5.7	0.47	4.09	0	70	88.72	1948.72
2012.10.22 22:57:23	67.5	1.41	5.72	0.47	4.13	0	70	88.72	1948.69
2012.10.22 22:57:33	75.94	0	5.72	0.47	4.37	0	70	88.72	1948.46
2012.10.22 22:57:43	65.25	1.97	5.73	0.47	4.06	0	70	88.72	1948.75
2012.10.22 22:57:53	64.69	2.95	5.74	0.47	4.03	0	70	88.72	1948.79
2012.10.22 22:58:03	81	0	5.75	0.47	4.55	0	70	88.72	1948.28
2012.10.22 22:58:13	77.48	7.45	5.75	0.47	4.52	0	70	88.72	1948.28
2012.10.22 22:58:23	72.7	0.98	5.77	0.47	4.33	0	70	88.72	1948.48
2012.10.22 22:58:33	66.52	1.12	5.78	0.47	4.16	0	70	88.72	1948.66
2012.10.22 22:58:43	65.81	1.83	5.79	0.47	4.14	0	70	88.72	1948.69
2012.10.22 22:58:53	68.2	0.14	5.78	19.32	4.14	22	70	88.72	1948.69
2012.10.22 22:59:03	68.34	0	5.77	17.5	4.14	0	70	88.72	1948.69
2012.10.22 22:59:13	68.2	0	5.75	9.63	4.14	9	70	88.72	1948.69
2012.10.22 22:59:23	68.2	0	5.75	0.9	4.14	6	70	88.72	1948.69
2012.10.22 22:59:33	68.2	0	5.75	0.47	4.14	0	70	88.72	1948.69
2012.10.22 22:59:43	58.92	8.72	5.75	0.47	3.86	1	70	88.72	1948.97
2012.10.22 22:59:53	73.55	0	5.77	0.47	4.33	0	71	88.72	1948.47
2012.10.22 23:00:03	89.02	0	5.77	0.47	4.83	0	70	88.72	1947.98
2012.10.22 23:00:13	79.31	0	5.78	0.47	4.45	0	70	88.72	1948.32
2012.10.22 23:00:23	68.06	0	5.79	0.47	4.16	0	70	88.72	1948.65
2012.10.22 23:00:33	56.95	11.11	5.79	0.47	3.85	0	70	88.72	1948.96
2012.10.22 23:00:43	75.8	0	5.8	0.47	4.38	0	70	88.72	1948.45
2012.10.22 23:00:53	91.27	0	5.8	0.47	4.85	0	70	88.72	1947.97
2012.10.22 23:01:03	78.89	1.55	5.8	0.47	4.51	0	70	88.72	1948.3
2012.10.22 23:01:13	68.34	0.14	5.82	0.47	4.21	0	70	88.72	1948.6
2012.10.22 23:01:23	71.3	0	5.82	15.84	4.21	30	70	88.72	1948.59
2012.10.22 23:01:33	71.16	0	5.82	21.61	4.21	0	70	88.72	1948.59
2012.10.22 23:01:43	71.02	0	5.82	16.45	4.21	1	70	88.72	1948.59
2012.10.22 23:01:53	71.02	0	5.82	13.88	4.21	4	70	88.72	1948.59
2012.10.22 23:02:03	71.02	0	5.82	5.86	4.21	38	70	88.72	1948.59
2012.10.22 23:02:13	71.02	0	5.82	14.49	4.21	0	70	88.72	1948.59
2012.10.22 23:02:23	70.88	0	5.82	5.52	4.21	0	70	88.72	1948.59
2012.10.22 23:02:33	71.02	0	5.82	3.24	4.21	1	70	88.72	1948.59
2012.10.22 23:02:43	71.02	0	5.82	0.47	4.21	0	70	88.72	1948.59
2012.10.22 23:02:53	70.88	0	5.82	0.47	4.21	0	70	88.72	1948.59