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Review of the Mechanisms for Preventing, Diagnosing, and Treatment of Pipe Sticking in Drilling Operations

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Abstract

Stuck pipe is a prevalent and costly issue in drilling operations, with the potential to cost the petroleum industry billions of dollars annually. To reduce the likelihood of this issue, efforts have been made to identify the causes of stuck pipes. The main mechanisms that cause stuck pipes include drill cutting of the formation, inappropriate hole-cleaning, wellbore instability, and differential sticking forces, particularly in highly deviated wellbores. The significant consequences of a stuck pipe include an increase in well costs and Non-Productive Time (NPT), and in the worst-case scenario, the loss of a wellbore section and down-hole equipment, or the need to sidetrack, plug, or abandon the well. This paper provides a comprehensive review of the challenges associated with pipe sticking during drilling operations. The mechanisms of pipe sticking, analysis of differential sticking factors, guiding principles to minimize differential sticking, diagnosis approaches, and different treatment methods are discussed. This paper can serve as a guide for any problem involving stuck pipes in the petroleum industry.

Keywords: Mechanical sticking, differential sticking, wellbore geometry, hole-pack off, mud cake.

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1- Introduction

The petroleum industry is a vital global industry that exerts significant influence on the global economy. Its operations span continents, and it possesses one of the most valuable non-renewable assets in the industry. Drilling operations are one of the most important sectors of the petroleum industry [1]. While engaged in the exploration and development of oil and gas resources, drilling operations often encounter various obstacles and operational issues. However, it is crucial to mitigate these drilling problems to ensure the safety and profitability of both offshore and onshore drilling operations. [2]. One of the most common significant challenges encountered during the drilling process is pipe sticking [3].

The term "stuck pipe" refers to the difficulty of losing the capacity to move the drillstring. If a drillstring becomes stuck, a time-consuming and costly freeing technique is required to restore movement [4, 5]. Inappropriate drilling procedures, poor rheological properties of the drilling fluid, instability of the wellbore, insufficient hole cleaning, etc., are some of the essential elements that might cause a pipe sticking occurrence [6], [7]. Moreover, the occurrence of a pipe sticking is one of the most common wellbore instability concerns observed while drilling operations, accounting for 36% of all drilling difficulties [8, 9]. Pipe sticking happens around 50% of the time while tripping, 10% when bottom drilling, and 20% when operating the pipe at a connection and reaming [10]. Consequently, the worst fears of the drillers are NPT, coupled with the rising expense of rig time. Stuck pipes can be caused by a variety of reasons or operational activity. In other words, based on the reasons that caused the problem, pipe sticking might be mechanical or differential [11].

A mechanical sticking pipe is caused by a physical obstacle or limitation that happens when the drill string is moving. It may be divided into two categories: (1) Wellbore geometry due to wellbore geometry issues, which include key seat or an under-gage hole; and (2) Hole bridges and pack-off due to accumulated cuttings or wellbore instability [12]. In other words, wellbore instability and insufficient hole cleaning are two of the most common reasons for mechanically stuck pipes [13]. On the other hand, the majority of wellbore instability issues are caused by swelling of the shale strata and enlargements of the wellbore, which are caused by shear failure due to extremely low mud pressure [14, 15].

The next type of stuck pipe is differential sticking. It occurs when a drill string encounters a filter cake deposited on a permeable formation due to differential forces that are generated from overbalanced mud pressure acting on the drill string, i.e., when the drilling fluid pressure in the wellbore exceeds the formation pressure, a resultant force pushes the pipe against the wall of the borehole [9, 16].

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This article offers a thorough analysis of pipe-sticking issues, focusing on differential and mechanical pipe sticking difficulties that can occur during drilling operations. Also, the parameters that influenced the mechanical and differential stuck pipe were analyzed. Eventually, techniques for diagnostics, avoidance, and treatment were used to minimize the stuck pipe issues.

2- Mechanism of the Stuck Pipe

Occurrences of stuck pipe might happen while drilling, tripping in and out, back reaming, running casing, and logging [17]. During drilling operations, the stuck pipe is the major cause of NPT. It takes place when the force required to extract the drillstring from the wellbore exceeds the drill string's maximum permissible tensile strength. This indicates the drillstring, or at least a section of it, cannot spin or reciprocate within the wellbore [18]. Fig. 1 depicts the Integrated Project Management (IPM) Schlumberger, stuck pipe course. In this course, the stuck pipe occurrence was distributed by operations. Drilling, connecting, tripping in, coring, logging, cementing, and equipment failure are all examples of these operations. Despite the techniques that anticipate such incidents having been developed, the sticking pipe is deemed an accident [19].To take the proper steps for the best prevention, it is essential to recognize these mechanisms and the many components involved. Fig. 2 presents the types of stuck pipe mechanisms and the issues that are associated with the occurrence of the pipe sticking.

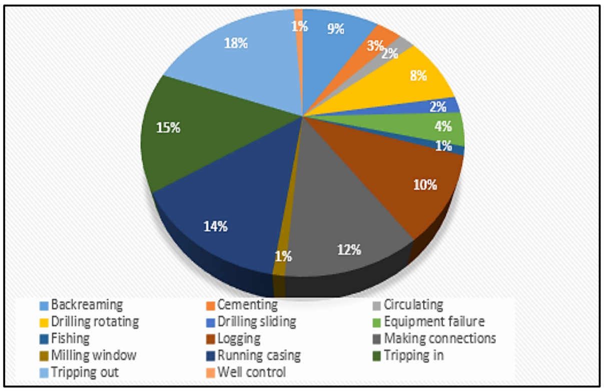

Fig. 1. IPM Events Involving Stuck Pipes by Activity in 2009 [17]

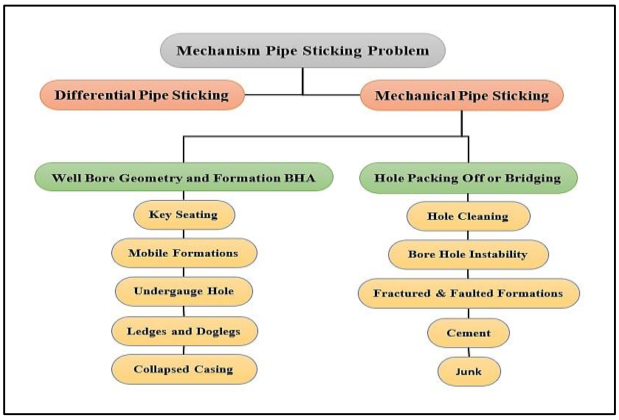

Fig. 2. Types of Stuck Pipe Mechanisms and Causes [20]

2.1. Mechanical Pipe Sticking

Mechanical sticking is often characterized as sticking because of hole-pack off / bridging and wellbore geometry, and it typically occurs while the pipe is moving. An inadequate cutting slip velocity is the major cause of hole-pack-off, also known as solid induced pack off. Some of the main causes are inadequate mud qualities, improper hole cleaning, and failed pumps [21].

a. Wellbore Geometry

Occurrences of stuck pipe can also happen as a result of undergauge holes, ledges, microdoglegs, keyseats, and stiff Bottom-Hole Assembly (BHA), as well as rapid or significant alterations in the borehole orientation and design. Micro doglegs and ledges develop when drilling formations of varying strengths 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. The most prevalent of these issues, known as keyseats, simply arise when there is enough dogleg, pipe rotation, sideload, and time. During this process, the pipe effectively cuts a slot through the formation. Due to the increased drill string tension, which creates a higher sideload and longer rotational time to cut through a dogleg. Consequently, the keyseats generally happen at shallower open-hole depths. After tripping out of the hole, the BHA becomes trapped at that keyseat. Formation keyseat is aided by ledges that result from interbedded hard-soft formations [20, 22-24].

There are a number of practical indicators that might point to the existence of an undesirable wellbore configuration. As an illustration, a keyseat that trips out of the hole creates constant torque and drag spikes at the tool joints and vice versa. The BHA enters high dogleg (i.e., possible keyseat) depth when there is sudden drag, which is another sign. Because interbedded, hard-soft strata encourage ledge development, such indicators in interbedded, hard-soft strata may indicate that a keyseat was really produced [25]. Fig. 3 displays the mechanical pipe sticking due to the keyseat.

b. Hole-Pack off / Bridging

The most typical reason for a pipe to become stuck worldwide is packing off and bridging. Inadequate hole cleaning, geomechanical rock mobility, and/or formation instabilities are the major causes of bridging or hole-pack-off. Small pieces of formation, cement, or junk settle around the drill string, preventing circulation of mud with no string movement likely, which is called hole pack off. The definition of a hole bridge is when medium to large pieces of formation, cement, or junk settle around the drill string, allowing restricted circulation of mud with little to no drill string movement. This kind of sticking mechanism commonly occurs while removing drill string from the hole or connecting the pipes, but it can also happen after the pipe has been motionless with the pump turned off for some time. Also, it occasionally occurs when running in the hole. Additionally, this kind is distinguished by the impossibility of or restriction of circulation with extremely high standpipe pressure, as well as limited rotational and axial motion [20- 26].

Based on hole cleaning, the characteristics of the drilled rock, and the stress regime, many factors affect this mechanism's fundamental causes, with the exception of stuck pipes caused by debris and cement. Shales that have undergone mechanical stress, reacting shale, fracturing formations, and vertical stress are some of the more notable and pertinent examples. Operationally, a variety of indicators can be used to detect hole bridging and hole-pack off, including a sudden rise in circulating pressure, extreme torque and drag, a decrease in set-down weight while running in the hole, a reduction in cutting dimensions, or an abundance of anomalous and large cuttings over the shakers [20, 25].

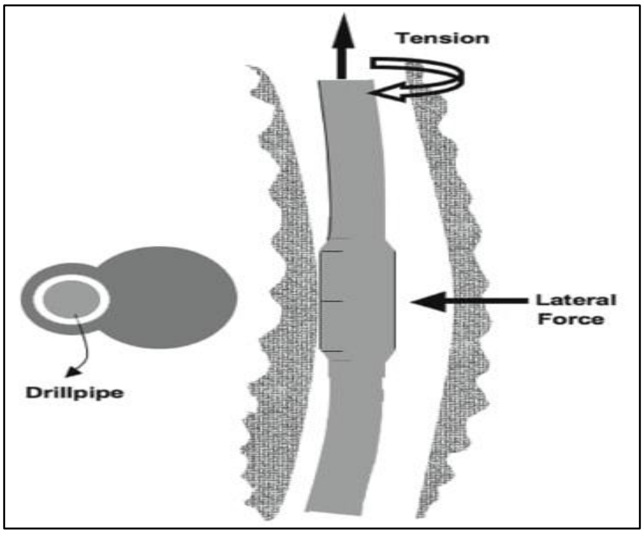

Fig. 3. Keyseat Mechanical Sticking [22]

c. Prevention techniques

Depending on what caused the sticking, several approaches are taken when dealing with mechanical pipe occurrences. Circulating fresh water could be able to release the pipe, for illustration, if the issue is caused by the salt layer squeezing. However, an appropriate preparation of the circulating mud's characteristics, such as viscosity and filtration, can work in the case of cuttings settling. In other situations, applying extra mud density to raise the hydrostatic pressure in the annulus or jarring in deviated boreholes would solve the problem. Workover, which involves either sidetracking the well or drilling through the stuck pipe, is the final resort in critical circumstances. Since it is so expensive, this technique is only considered as a last resort after all other options have been exhausted [22-27].

2.2. Differential Pipe Sticking

Differential sticking is a significant drilling issue caused by a difference in pressure between the mud's hydrostatic pressure and the formation pressure. This occurs to a considerable extent in the production reservoirs section (i.e., in the porous and permeable formation),[22]. A thick filter cake and a drill string kept immobile for an extended period of time within an open hole are two more variables that promote differential sticking. Differential pipe sticking is often identified when pipe mobility in either the upward or downhill orientation is difficult, but because the blockage is on just one side of the pipe, free circulation may be rapidly created. A significant withdrawal force should be exerted to exceed the mud cake's shear strength in order to remove a pipe stuck due to differential sticking. As illustrated in Fig. 4, the force needed to draw the drill string along the wellbore depends on the pressure difference, total contact surface area, and frictional factor. Eq.1 is used to calculate the differential sticking force [19, 20, 28].

$$Differential\ sticking\ force = (Ph - Pf) * A * friction\ factor \quad (1)$$

Where: Ph is the hydrostatic pressure of mud (psi); Pf is the formation pressure (psi); A is the effective contact area (in2); friction factor depends on the formation and drill collar surface it varies from 0.15 to 0.5.
The effective contact area can be estimated using Eq. 2.

$$A = 2h\sqrt{\left(\frac{Hs}{2} - tmc\right)^2 - \left(\frac{Hs}{2} - tmc\left(\frac{Hs-tmc}{Hs-ODp}\right)\right)^2} \quad (2)$$

Where: h is the thickness of the permeable zone; tmc is the thickness of the filter cake; Hs is the hole size; ODp is the out diameter of drill pipe or drill collar.

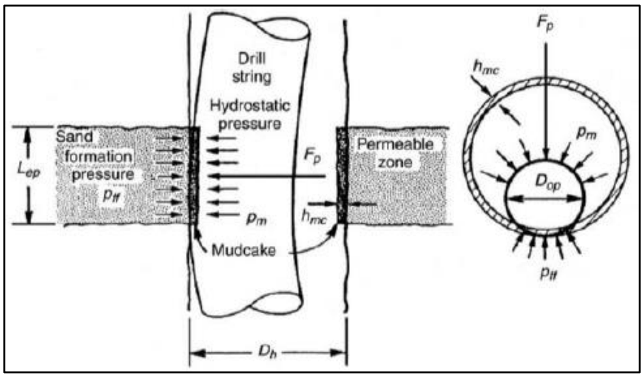

Fig. 4. Pipe Sticking under Differential Pressure and Length of Embedded Pipe [19]

- Analysis of Differential Sticking Factors

A pipe cannot get differentially stuck until five fundamental conditions are met: permeable formation, difference pressure (overbalance), mud filter cake, contact area (between pipe and wall), and immobile string. The possibility and intensity of differential sticking are increased over time, which is a spontaneous aspect that is always taken into account. These elements all contribute in different ways to raising the likelihood of the undesirable outcome of a differential pipe sticking [25].

a. Differential Pressure

One of the key contributing elements to differential sticking is the pressure difference, and it must be reduced as much as possible to minimize the probability of the differential sticking. Obviously, we are incapable of controlling the pore pressure in the reservoir. The mud weight must be led through in order to manage the differential pressure. The mud weight window would suddenly widen while drilling into a depleted reservoir, causing the anticipated mud weight to be excessively high. Consequently, a high pressure difference would be risky in terms of differential sticking as well as lost circulation issues [4, 22]. There is one additional variable that we must deal with, specifically the stability of the borehole. It is possible for a borehole to fail (collapse) if the mud column pressure inside the wellbore is too low. There are three principal stresses prior to drilling activity. These stresses are known as the in-situ stresses (i.e., vertical stress, maximum horizontal stress, and minimum horizontal stress). If we have full knowledge about the in-situ stresses, the minimal mud weight that is required to avoid the breakdown and breakout of the borehole could be determined, thus reducing the likelihood of the pipe sticking issue. Although determining the in-situ stresses requires complex geotechnical and reservoir modeling, it is possible if all relevant data is available [29-31].

b. Mud Filter Cake

In contrast to the mud weight previously mentioned, we have much more control over the mud's composition and other characteristics. The fundamental requirement for allowing for filtrate invasion and the dynamic production of mud cake on the wall is having a porous and permeable layer [32]. In every well, it is undesirable for the drilling fluid to flow into the formation, but it is crucial to prevent this from happening when there is a significant possibility of the differential sticking. Moreover, a thick mud cake will form as a result of the accumulation of the solid component of the drilling mud, which increases the probability further if fluid is lost to the reservoir in a zone where differential sticking is problematic [20-23]. Since it is necessary to know the precise characteristics of the mud in order to maintain the optimum size distribution and plastic viscosity, the drilling solids content in the mud is often rigorously restricted where solids content creates uncertainty [8]. Wells with a significant differential sticking hazard require extra care for solids management. Finally, to reduce the contact area, the filter cake should be as thin as possible. It should also lose filtrate from the cake to the formation at a moderate rate, since larger still-pipe periods would be possible as a result of the increased shear strength and effective stress [4].

c. Contact Area

The contact area between the drill string and the mud cake is another aspect that significantly affects differential sticking. In a straightforward scenario, the contact area is influenced by four parameters, in which the drill string's diameter at the permeable formation is constant. The first one is the length of the permeable formation. However, we frequently have to drill very lengthy portions in high permeability rocks, and we cannot attempt to drill less in this formation since it may be the target of the drilling when it is the hydrocarbon-saturated formation [20- 22]. The second parameter that affects the contact area is the difference between the thickness of the mud cake and the borehole radius. The radius of the hole is fixed, and it is governed by both mechanical and economic variables. The thickness of the mud cake, on the other hand, was covered in the preceding section. By minimizing the fluid loss, the amount of particles, and the temperature of the drilling mud, we were able to thin the mud cake [33, 34]. The third factor that affects the contact area is the difference between the outer diameter of the drill string and the borehole diameter. The term "pipe-to-borehole diameter ratio" is frequently used in the literature. There are several ways to lower this ratio. However, the BHA, which is a part of the drill string, typically experiences differential sticking since the pipe-to-borehole diameter ratio is the largest [33].

d. Other Factors

There are several more factors that are equally significant but not directly related to the ones mentioned above. The first one is static time, which is one of the prerequisites for differential sticking. Therefore, wherever feasible, static time should be avoided. This is due to the fact that as soon as the drill string is motionless, the pressure in the contact zone starts to fall. This keeps happening as long as there is enough pressure difference between the formation and the mud cake to collect filtrate from the mud cake. Then, a decrease in fluid pressure causes a transfer of the pipe's differential force to the cake's solids. Consequently, shear strength inside the cake develops as a result of the rise in this stress between solids, and the contact force between the pipe, solids, and mud cake also increases [4, 33-35].

The second parameter is the formation of rocks. There are different formations that present different levels of danger for differential sticking. Accordingly, the optimal formation has a low pore pressure and a high permeability in terms of differential sticking [22-25].

The third factor that may impact the differential stick is the well path and its inclination. The pipe is held against the borehole wall by differential pressure with the help of inclination angles. It's particularly dangerous when the potentially porous layer has a dogleg. The drill string rests on the bottom wall of the borehole at a high angle. This might be a risk when drilling a formation with low pore pressure. Also, high inclination angles have the additional drawback of causing a groove at the bottom of the borehole due to the motion of the body or tool joint of the pipe. The intensity of the groove would be governed by the tool joint of the pipe, the hardness of the formation rocks, the rotation of the drill string, etc. Furthermore, due to the greatly increased contact area and the fact that the groove curvature will be extremely similar to that of the tool joints that generated it, it significantly increases the chance of differential sticking [4, 20-33].

The last factor that may have a substantial role in differential sticking is hydraulics, particularly the flow pattern. In other words, the turbulence in the flow pattern can prevent differential sticking because it reduces the development of filter cakes, which in turn prevents differential sticking. On the other hand, turbulent flow is not always controllable since it has a higher propensity to leak off, causing loss of the fluid into the formation and the potential for differential sticking [20, 36].

3- Approaches for Preventive, Diagnostic, and Treatment

Techniques for avoidance focus on limiting the elements that impact how severe the sticking occurs, as discussed previously. Thus, the best mud properties for preventing differential sticking may be obtained by using lower solids content, minimal filtrate loss, and avoiding the use of excessive mud weight. For good control and borehole stability, the mud weight must be kept to a minimum [32]. In terms of pipe/cake, the pipe must be at least partially embedded in mud cake before a noticeable change in pressure is seen at the cake/pipe contact. The creation of differential sticking may be avoided by keeping a thin cake, which will minimize pressure change [37].

Regarding to the contact area, a high ratio of borehole-to-pipe diameters, BHA design optimization, and avoiding significant borehole deviations can all help reduce the contact surface area between drill collars and cake, which needs to be kept to a minimum. The best BHA design should have adequate stabilizers to keep the length of a destabilized BHA to a minimum and should include drill collars that are no longer than necessary, preferably twisted drill collars like spiral or square shaped collars. Heavy-weight drill pipes can be used to make up for the lower weight on a bit that results from decreasing drill collars [33- 38].

The third key component is static time. On the other hand, when the mud properties are poor and the velocity in the annulus is excessive, differential pressure sticking incidents can be decreased by shortening the time duration at which the drill pipe is motionless [28]. For activities that need static drill string, there should generally be a preplanned strategy to reduce down-hole time. Therefore, persistent rotating up the drill string can be taken into account while drilling and tripping connections, particularly when the BHA is in opposition to a sticking zone with a significant risk [32].

One or more of the warning indicators would occur once the drill string is differentially stuck throughout a drilling activity: a rise in slack-off weight, an increment in drag and torque while trying to move the drill string. The difference between differential sticking and other types of sticking is that, unlike mechanically stuck pipe, when the string is differentially stuck, the circulation is completely continuous and unobstructed even if it is impossible to spin or reposition the string. These diagnoses and indicators are utilized to determine the kind of sticking that occurs during activities [19, 39].

Different remedies for differential pipe sticking events have been created and put to use. Traditionally, efforts at torqueing and jarring are the first steps in the release action plan. These techniques may be successful in the case of a minor stick. Controlling the mud qualities might be thought of for remediation if the initial mechanical methods fail [22]. Generally, there really are two basic fluid-based restoration methods. The first involves lowering mud column pressure to levels close to or less than the formation pressure in an effort to lessen or eliminate the differential pressure and thereby avoid the differential sticking. The second method involves utilizing spotted pills to gradually decrease or get removal of the forces keeping the pipe stuck [40].

It is important to note that reducing the mud pressure may not always be a solution when a formation is likely to result in borehole failure, potentially leading to a mechanically stuck pipe. Additionally, simply reducing the differential pressure may not be sufficient to release the pipe, as the contact between the pipe and the filter cake can significantly enhance the sticking force [32]. Consequently, circulating water or lighter mud in the borehole after the pipe has been trapped may lead to a decrease in borehole pressure due to the hydraulic pressure of the mud cake, which can decrease the pressure necessary for balance [35].

Using the spotting fluids to lubricate the drill string and dehydrate the mud filter-cake to crack the wall of the borehole, reduce contact forces, and release the differential pressure is another typical method for dealing with differential pipe sticking. Furthermore, the use of stronger fluid treatment options, such as strong acids, may be necessary when spot fluids are insufficient in releasing the stuck pipe [27]. Finally, in the worst circumstances, the well might be sidetracked, plugged, or abandoned as a final resort since none of those methods were effective in releasing the pipe [1].

4- Conclusions

This study plays a fundamental role for the researchers interested in developing any project to reduce the issue of pipe sticking. The conclusions of this study can be summarized as follows:

- The current approaches for assessing and predicting stuck pipes lack the necessary level of precision to be significantly effective in reducing lost time and costs in drilling operations.
- Differential sticking avoidance focuses on managing the parameters that impact the severity of sticking.
- Unrestricted mud circulation can be used to identify differential pipe sticking during drilling when the pipe becomes stuck but cannot be spun or repositioned. In contrast, in mechanical sticking, circulation is limited with little to no string motion.
- Torqueing up and jarring may be insufficient to release the pipe, and spotting fluids are often the primary repair method for differential sticking.

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مراجعة آليات منع وتشخيص ومعالجة التصاق الأنابيب في عمليات الحفر

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الخلاصة

الأنابيب العالقة هي مشكلة شائعة مرتبطة بعمليات الحفر، ويمكن أن تكلف صناعة البترول مليارات الدولارات سنويًا. من أجل تقليل احتمالية حدوث المشكلة، تم بذل جهود لتحديد أسباب الأنابيب العالقة. من المعروف أن قطع الصخرية المحفورة ، خاصة في حفرة البئر شديدة الانحراف، والتنظيف غير المناسب للبئر، وعدم استقرار حفرة البئر، وقوى الالتصاق التفاضلية هي الآليات الرئيسية التي تسبب هذه المشكلة. تتمثل العواقب الكبيرة للأنابيب العالقة في زيادة تكاليف البئر والوقت غير المنتج (NPT). علاوة على ذلك ، قد يؤدي أسوأ الظروف إلى فقدان قسم من حفرة البئر ومعدات الحفر السفلية، أو قد ينحرف البئر عن مساره أو يسد أو يتم التخلي عنه كقرار نهائي. تتضمن هذه الورقة مراجعة كاملة للتحديات التي تواجهها الأنابيب الملتصقة التي تحدث أثناء عمليات الحفر. تمت مناقشة آليات التصاق الأنابيب ، وتحليل عوامل الالتصاق التفاضلية، والمبادئ التوجيهية لتقليل الالتصاق التفاضلي، ونهج التشخيص، وطرق العلاج المختلفة. أخيرًا، يمكن استخدام هذا الورق كدليل لأي مشكلة تتعلق بالأنابيب العالقة في صناعة البترول.

الكلمات الدالة: الالتصاق الميكانيكي، الالتصاق التفاضلي، الشكل الهندسي لتجويف البئر.