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Enhancing Stuck Pipe Risk Detection in Exploration Wells Using Machine Learning Based Tools: A Gulf of Mexico Case Study

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Abstract

We present a case study on the utilization of a machine learning (ML)-based computational tool for detecting stuck pipe risks early in live operations. The system was used in two Gulf of Mexico (GoM) wildcat exploration wells. The risk detection approach is based on a novel technology using physics-informed machine learning models to analyze real-time data and detect potential stuck pipe incidents in live operations. The ML models were pre-trained on a variety of wells from different fields. The system was designed for out-of-the-box usage, which supports operational monitoring for exploration wells without pre-training on offset well data. The methodology and the process of integrating the computational tool into live operations, and the flow of data between the tool and the drilling operation is described. Additionally, the paper delves into drilling practices that helped to prevent stuck pipe and examine specific incidents that were unavoidable.

The application ran stably throughout the operations, with high uptime and few false warnings in both wells; on average, fewer than one false alert was observed per day of operations. The pre-trained models proved effective, requiring no additional training; this generalizability is an important prerequisite for utility when applied to exploration wells, where offset data may be unavailable. However, due to lack of personnel to follow up the system's outputs in real-time, the benefits were limited. The first well was drilled without stuck pipe incidents. Some sticking risk symptoms were identified during the operation, especially in a fault zone. The post-well analysis indicates that good drilling practices were enough to mitigate the risks. The drilling practices responsible for the success of the operation will be discussed. In the second well, there were stuck pipe incidents. The application provided some indications of stuck symptoms but with some limitations for how far in advance the risk could be detected. The causes of the stuck incidents, the challenges in avoiding them, and updates to the risk detection system for identifying these, will be explored. Based on the experience described in the paper, the authors will offer recommendations for optimal technology utilization both from the application's and organizational perspectives.

Introduction

One of the main sources of Non-Productive Time (NPT) in drilling and well construction are stuck pipe events. According to Alshaikh et al. (2019), stuck pipe incidents may account for approximately 15% of NPT. Based on analysis by Skalle (1998), stuck pipe incidents can occur in all types of well operations, from tripping/reaming (56%) to on-bottom drilling (14%), as well as periods where the drill string is stationary (30%). The main causes of stuck pipe incidents are differential sticking (25%), packed hole (42%) and jammed pipe (20%). Stuck pipe is estimated to cost the industry in excess of $580MM per year, based on inflation-adjusting the figures reported by Bradley et al. (1991); 25% of the total cost related to NPT annually may be attributed to stuck pipe (Muqeem et al. 2012). Environmental damage, health and safety issues may also arise from Stuck Pipe incidents. Consequently, reducing risks of stuck pipe and its associated problems is a critical cost and safety driver in any well operation.

In recent years, many computational methodologies for stuck pipe prevention have been proposed and published, some applying Machine Learning (ML) techniques in place of, or in addition to, industry-standard physical models. The publications reported mixed levels of success; most of the solutions and case studies described in this research area were either limited in their effectiveness, for example to certain well types or wells in specific fields, or those using specific downhole equipment and BHA configurations, or only tested on historical datasets (Al Dushaishi 2021, Alsaihati 2021, Alzahrani 2022, Brankovic 2021, Elahifar 2022, Elmousalami 2020, Khanh Do 2021, Mopuri 2022, Nautiyal 2022, Singh Saini 2020, Zhu 2022, Kaneko 2023). Furthermore, only a small number of the aforementioned works report on results from usage in the field for these solutions (Bahlany 2021, Salehi 2022).

The ideal drilling-focused ML/AI system would be generally applicable out-of-the-box to any well, during all relevant operations and agnostic to well specifications or equipment choices. This is especially relevant for exploration wells, which carry a higher degree of uncertainty given that they are often drilled in uncharted territory, where geological conditions are uncertain, and where little or no offset well information is available. Systems capable of adapting to a broad variety of well conditions, in unfamiliar wells, can be effectively used in live operations to rapidly analyze and respond to changing geological or well conditions. This increases situational awareness and thus reduces the risk of drilling problems, such as stuck pipe, that contributes to costly NPT. In addition to utilizing such versatile systems in live operations, this kind of tool can also be used in the planning phases of upcoming wells to build a stuck pipe risk roadmap, in cases where offset well data is available. Learnings from offset well analysis can in turn be used to adjust or optimize future well designs.

This paper presents two case studies of running an automated stuck pipe risk detection system (SPRDS) on live operations for two Gulf of Mexico wildcat exploration wells, in order to test the generalizability of the methodology to previously unseen situations, and to verify that stuck pipe risk symptoms could be identified early in these scenarios, with minimal false alarms being raised. This work also reviews the mitigating actions taken by the drilling teams in a variety of near-miss risk scenarios.

Methodology and Processes

The risk detection system consists of multiple modules targeted at common mechanisms which can cause stuck pipe issues, and the risk symptoms associated with these. The system monitors for signs of differential sticking, mechanical sticking, poor hole cleaning, restrictions and tight spots. The three mechanisms specified account for over 90% of stuck pipe incidents (Skalle 1998). Operations covered within scope of the monitoring system include drilling, hole opening, tripping in or out, (back)reaming, static time between stands, and circulation; these are the major operations in which the aforementioned stuck pipe mechanisms typically occur. The system requires the following input parameters: time, hole depth, rotations per minute (RPM), hookload (HKL), block position, standpipe pressure (SPP), bit depth, mud flow in, mud density in, and trajectory surveys. These measurements are widely available.

The SPRDS utilized in the Gulf of Mexico drilling operations described in this paper is composed of three agents, named differential sticking (DS), hole cleaning (HC) and mechanical sticking (MS). Each agent is designed to target symptoms commonly observed when these stuck pipe mechanisms are present, but they are also capable of detecting different types of risks. Each agent contains modules that identify risk factors on different timescales. The first set focuses on longer to medium-to-long timescales (for example spanning many stands), which are instrumental in recognizing stuck symptoms that gradually develop, a key feature for the tool's predictive capability. Additionally, the agents feature modules that target shorter timescale risks, such as instantaneous overpulls. These modules are suitable for identifying risks that occur abruptly and without early symptomatic indicators. After the live GoM operations concluded, additional modules were added to the system, which detect short-timescale pressure and torque spikes coinciding with stable flow rates and rotary speeds, which can potentially indicate hole cleaning and mechanical restrictions respectively. These retrospectively added modules and their impact will be discussed further in the *Results and Discussion* section.

The solution uses a set of physics-informed modules targeting specific problems related to the mechanisms of stuck pipe, such as forecasting the evolution of static friction symptoms using regression models for analyzing differential sticking risks, or estimating downhole ECD using a deep neural network, and forecasting its evolution for a view into potential hole cleaning issues. Collectively, these modules tracking risk symptoms on various timescales provide comprehensive detection capabilities for stuck pipe risk. More information about the system's underlying methodologies are available in previously published works by the authors and their collaborators, which describe the risk detection modules targeting differential sticking (Meor Hashim 2021a), mechanical sticking (Bin Othman 2022) and hole cleaning (Robinson 2022) issues. In addition, techniques for programmatically identifying certain rig states and events that contribute to false warnings (if left undetected) have also been published by the authors (Robinson 2023); detection of these rig events enables the SPRDS to actively eliminate false warnings from these sources, without compromising on the system's sensitivity to stuck pipe risk symptoms.

In developing the system and training its underlying ML models, historical datasets were used from offshore (deep and shallow water) and onshore wells, located in a variety of regions, such as Northern Europe, the Middle East, onshore North America, offshore West Africa, the Gulf of Mexico (not including offsets from the field of interest in this paper), South America, Central Asia and South East Asia. These included a blend of well trajectories (vertical, deviated and horizontal), bit types, varying section sizes and both Positive Displacement Motors and Rotary Steerable Systems as downhole steering devices. Wells used in the training datasets were deliberately not used for model validation; validation and holdout testing datasets each used a set of independently drilled wells to prevent any information leakage between datasets. This approach is intended to more closely approximate using the detection system in production on entirely new wells, and is thus a superior test for generalizability than using an alternative training/validation data splitting scheme, such as randomly splitting data (a common approach used in ML applications). In this context, randomly splitting data from a set of wells for training and validation would not provide useful insights into a model's capability to generalize, due to the information leakage between the training and testing data, which are sampled from the same set of wells The system's ability to provide strong performance on holdout test wells in fields it has not previously been exposed to – in this case historical well data - was necessary to demonstrate before starting any drilling operations on exploration wells, given the lack of offset well data in these cases. This testing step, using held-back historical data, aims to imitate the system's use on exploration wells. No offset well data, from nearby Gulf of Mexico fields where the SPRDS was ran in live operations within the scope of this paper, were used to train the system's underlying ML models. This proves the models' generalization capability, an important feature for using the models in exploration wells, which are naturally more challenging due to the lack of offset wells and the uncertainty associated. A detailed discussion of historical results conducted prior to the drilling operations in this work is presented in a previous paper by the authors (Payrazyan 2023). In addition to the aforementioned stuck pipe related case studies published by the authors, operators utilizing the system have also published case study articles with examples from live operations (Meor Hashim 2020, Meor Hashim 2021b, Meor Hashim 2021c, Rosli 2021, Yusoff 2021).

An important aspect of the SPRDS is the ability to alert users of significant risks and abnormalities, without overloading the user with alerts for minor risks. The system's sensitivity is configurable, allowing users to easily tailor each agent for specific well types and conditions for more flexibility. For each agent, there are three recommended sensitivity presets, vertical wells (high sensitivity), deviated wells (standard sensitivity), and extended reach wells (low sensitivity). A low sensitivity means the system requires more significant deviations in the monitored parameters (such as hookload or ECD) to trigger a warning. When the sensitivity is set to high, less significant changes are required to trigger warnings. In vertical wells, high sensitivity is recommended because in vertical wells we usually do not expect significant deviations. The opposite is true for extended reach, where for example more drag is expected, and high sensitivity would cause too many warnings.

During operations, the risk detection system was deployed on cloud servers, and connected to the operator's WITSML server through an Application Programming Interface (API). The WITSML 1.4.1 data were provided with a 0.2 Hz sampling frequency (one sample per 5 seconds). The risk detection system had previously been successfully tested with data sampling frequencies ranging between 0.1-1 Hz. Data with sampling rates higher than 1 Hz are rarely available from WITSML stores, and would need to be obtained by direct connection to the rig-site systems.

The output of the SPRDS was visualized in a dedicated template on the WITSML viewer used for visualizing the well data. The output was visible at the rig (mudlogging unit and drilling supervisor`s office) and at the onshore office on a dedicated screen. The template was configured in a horizontal time-based layout, with the drilling data presented in the uppermost track. Below this track, the outputs from each of the three agents — DS, MS, and HC — were displayed sequentially, as illustrated in the Results and Discussion section. Under each agent track, a corresponding status curve was provided. This status curve communicates the system's findings; the status is green when no risks were identified by the agent, yellow when medium stuck pipe symptoms were detected (referred to as *warnings*), and red when more severe symptoms were identified (referred to as *alarms*). Each alert is accompanied by a descriptive message that specifies the type of risk that was identified.

A training session was conducted before the software deployment, thus the offshore and onshore drilling teams were able to interpret the software output. A communication protocol was defined where the mud logger would notify the drilling supervisor for further action when the stuck pipe risk detection system provided warnings or alerts. Onshore, due to a lack of 24/7 monitoring resources available, the office team performed spot checks on the risk detection system's outputs to check whether any stuck pipe risk alerts were raised.

Key Performance Indicators (KPIs)

Analysis of stuck pipe risk monitoring systems is based on alerts relating to certain events of interest (stuck pipe issues), hence the main performance metrics used to assess the system in these cases studies were Recall, Precision, and the mean number of false warnings observed per day of operations, averaged across the duration of the well. The definitions of these metrics are provided in Equations (1) through (3).

$$\boldsymbol{Recall} = \frac{True\ Positives}{True\ Positives\ +\ False\ Negatives} \tag{1}$$

$$\boldsymbol{Precision} = \frac{True\ Positives}{True\ Positives\ +\ False\ Positives} \tag{2}$$

$$Mean\,false\,warnings\,per\,day = \frac{False\ positives}{N.\,days\,of\ operations} \quad (3)$$

Precision and Recall are commonly used metrics for assessing binary classification systems; in this context, Recall quantifies the proportion of stuck pipe symptoms or events (true positives) that were alerted by the SPRDS; precision describes the proportion of alerts raised which were valid or "positive". Precision and the average occurrence rates of false alert per day are often more easily interpreted indicators from a monitoring engineer's perspective, for whom a key concern is the cognitive or attention expense that comes from false alerts. A typical target value for this metric used in previous field-tests is (on average) fewer than 2 false alerts per day of operations, while target values used for recall and precision are usually 0.9 and 0.8 respectively.

Operational characteristics

Details about the two offshore exploration wells are provided in this section. Both wells were drilled in the same concession block, as part of the same back-to-back drilling campaign.

Well 1

Well 1 is an offshore (51 m water depth) exploration well drilled in the South-East Gulf of Mexico, Sureste Basin, with its main target in the Upper Miocene defined by a flat seismic event. The wellbore was planned as a deviated S-shape well with about 265m max. lateral offset and a planned total depth of 3484 mMD (3400 mTVDSS). Reports from the offset wells indicated that there had been stuck pipe incidents in these wells. The post well geological column for Well 1 can be found in Fig. 2.

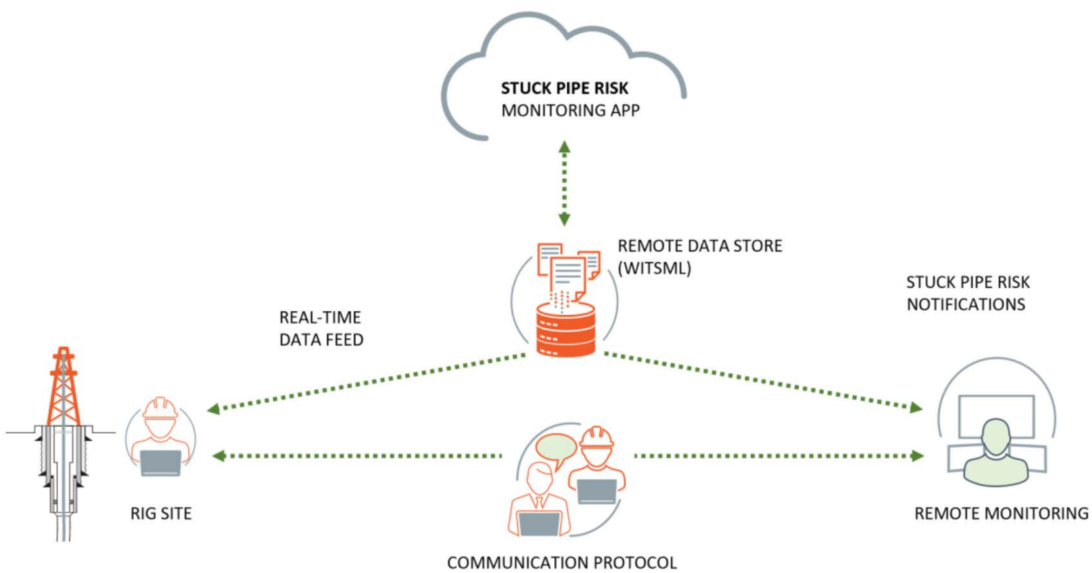

Figure 1—A high-level view of the operational setup used for monitoring the two Gulf of Mexico exploration wells. Due to the lack of a 24/7 Real-Time Operating center for these operations, monitoring responsibilities were split between the drilling engineers and the mud loggers.

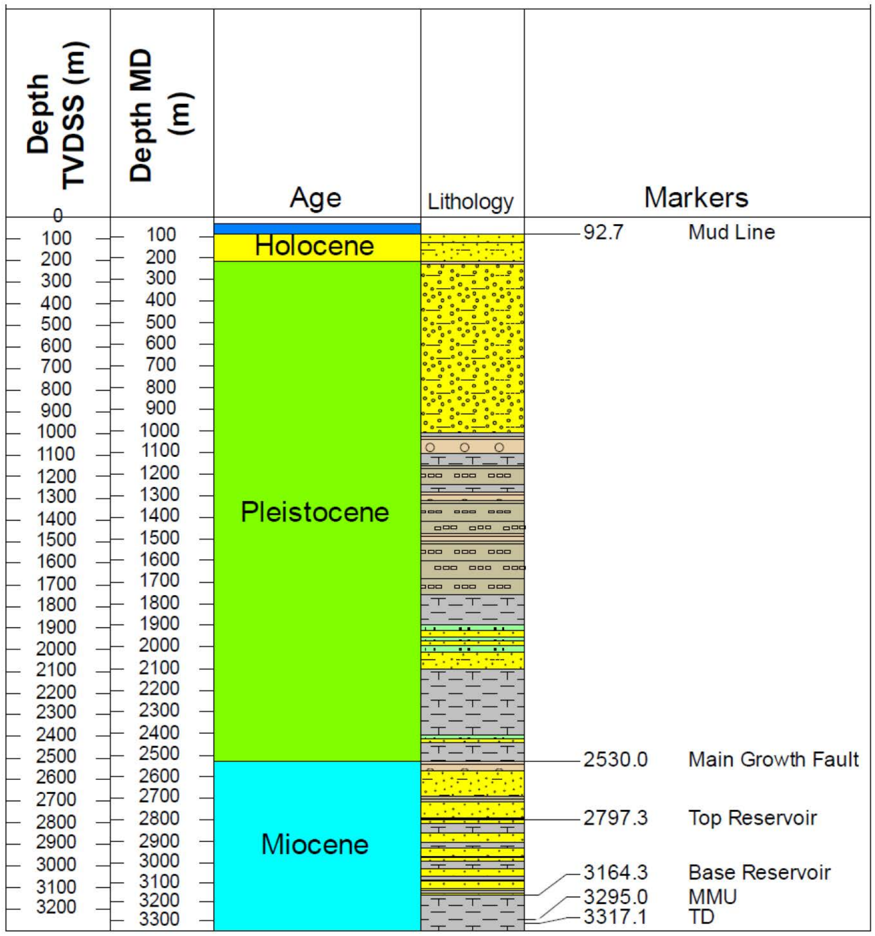

Figure 2—post well geological column for Well 1.

The main wellbore was drilled to a total depth of 3317 mMD. Afterwards a sidetrack was drilled from 2641 to 3084 mMD for coring the hydrocarbon bearing sand intervals. The well was successfully drilled without stuck pipe incidents.

The SPRDS was used for the main wellbore and sidetrack on the following sections and operations:

- 36" Open Hole
- 30" Conductor
- 26" Open Hole
- 20" Casing
- 17 ½" Open Hole
- 13 5/8" × 13 3/8" Casing
- 12 1/4" × 14 ½" Open Hole
- 11 ¾" Liner
- 10 5/8" × 12 ¼" Open Hole
- 9 5/8" Casing
- 8 ½" × 9 ½" Open Hole
- 7 5/8" Casing

- 6 ½" Open Hole
- 8 ½" Open Hole (Sidetrack)

Well 2

Well 2 is the second exploration well of the drilling campaign. The prospect was planned with one target interval in the Upper Miocene and an upside in the overlying Lower Pliocene-Upper Miocene section. The well was planned as a deviated J-shape well with about 550 m max lateral offset and a planned total depth of 4693 mMD (4600 mTVDSS). A surface location at the southern edge of the prospect, with a water depth of 98 m, was chosen. Reports from the offset wells indicated that there had been stuck pipe incidents. The well was drilled to 2625 mMD, shallower than initially planned.

The post well geological column for well 2 can be found in Fig. 3.

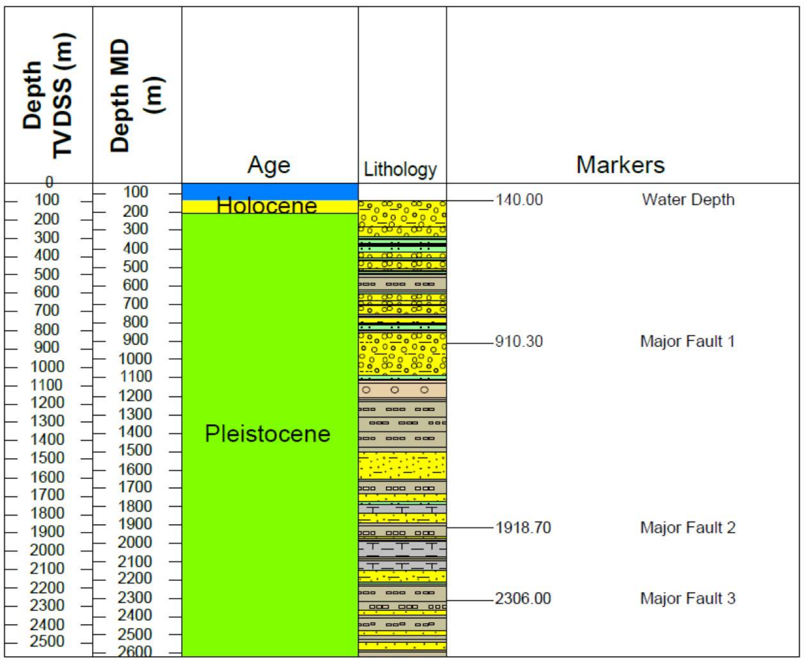

Figure 3—Post well geological column for well 2.

The SPRDS was used for well 2 on the following sections and operations:

- 36" Open Hole
- 30" Casing
- 26" Open Hole
- 20" Casing
- 17 ½" Open Hole
- 13 5/8" × 13 3/8" Casing
- 12 ¼" Open Hole

The pre-defined communication protocol could not be followed continuously due to the lack of available 24/7 monitoring resources, however the results were constantly displayed on a dedicated screen at the remote office as well as on the rig in the mud logging unit and the drilling supervisor's office, allowing the office team to perform spot checks on the risk detection system's outputs. Stuck pipe incidents were encountered and will be discussed in the next section.

Results and Discussion

The system ran with high stability and uptime throughout the two wells drilling operations; the operator's robust data and analytics infrastructure was a key contributor to this. Low false warning rates were observed for both wells. The SPRDS effectively identified stuck pipe risks in both operations.

On the first well, the good drilling practices successfully mitigated the eventual risks, and the well was drilled without stuck pipe incidents. On the second well, there were stuck pipe occurrences and the SPRDS detected some of the incidents. As will be shown in this section, not all incidents manifest early symptoms thus not allowing early detection by an ML/AI system that uses the surface drilling data outlined in the *Methodology and Processes* section.

In some cases, the stuck pipe indications will only become apparent shortly before the incident often manifesting as abrupt spikes in torque, pressure, hookload, or a combination of these. The SPRDS version utilized during the drilling of both Well 1 and Well 2 uses the three mentioned parameters as input for predicting ECD and HKL for medium-term risk detection, but did not incorporate a system for the detection of short-timescale risk symptoms associated with SPP and torque spikes. In response, the system was upgraded, introducing two new features able to identify short-time risks related to sudden changes in SPP and instant torque. The torque risk detector, included as a sub-system of the MS agent, was designed to identify torque spikes with stable or falling rotary speeds. The SPP risk detector was included as a HC sub-system and identifies increases in SPP at constant flow rates. After the system was upgraded, specific cases where SPP and torque changes were the only stuck pipe risk indicators were tested retrospectively using historical data. Running the SPRDS in historical wells allows for the assessment of the system performance and the impact of improvements done in the software, which were proven effective as will be shown under *Well 2* results. In the following sections, selected cases from each well are presented to further illustrate these points.

Well 1

The drilling program was completed successfully without any stuck incidents (drillstring or casing). Throughout the entire operation, the risk detection system maintained high uptime and delivered real-time, reliable outputs with minimal false warnings. The KPI's are detailed in Table 1 for reference.

Table 1—Risk detector system performance for well 1

Performance Parameter	Metric
SPRDS operational time	162 days
SPRDS uptime	99%
WITSML server uptime	98%
SPRDS Average False Warnings per day	0.15 per day (24 false warnings)
SPRDS Recall	1.0
SPRDS Precision	0. 81

Table 2—Cases for Well 1

Relevant Observations			
Date	**BHA**	**Operational Details**	**SPRDS output**
11/11/2022 05:30-9:00	17 1/2" BHA	Reamed down from 1000 m to 1011 m with WOB 2-5 klbs, 900 gpm – 1450 psi, 50 rpm – 1.1k ft.lbs	DS agent provided 1 warning due to increase in friction. HC agent provided 2 warnings due to forecast increase in fluid friction. See output in ***Case 1***
		Observed hard cement cuttings over shakers from lag depth +/- 990 m.	
		Tagged 20″ Float Collar @ 1011 m.	
		Drilled out Float Collar from 1011 m to 1012 m w/ WOB ±15 klbs, 900 gpm – 1450 psi, 50 rpm - 5k ft.lbs (±50 min).	
		Continued drilling out hard cement in 20″ shoetrack from 1012 m to 1030 m (6 m above 20″ Shoe) with WOB 10-15 klbs, 900 gpm - 1450 psi, 60 rpm - 5k / 8k ft.lbs.	
		Note: – Observed hard cement cuttings over shakers. – worked 17-1/2″ PDC bit 3 times across Float Collar @ 1011 m & confirm free passage.	
30/11/2022 00:00-03:00	12 1/4" BHA	Reciprocated string and completed circulating bottoms up after flow check: – 700 gpm / 1600 psi, 50 rpm / 1-3 kft-lb. – Circulated and conditioned mud from 1.28 sg to 1.30 sg.	DS agent warning due to a predicted increase in static friction. HC agent raised alert due to forecast increase in ECD. See output in ***Case 2***

The following cases provide an overview of the scenarios encountered during Well 1, wherein the SPRDS identified anomalies related to pipe and fluid drag, indicating potential stuck pipe risks. The risks were in all cases low risks and were effectively managed by the rig following good operational practices. Even though there were no stuck pipe incidents realized, the SPRDS identified risks during multiple independent passes through the depth zone ranging from 2443 meters to 2520 meters, as shown in Cases 1 to 2. This was interpreted as an indication of unstable hole conditions when approaching the main fault between the Pleistocene and Miocene formations, shown in Fig. 2.

Case 1: Cement cuttings while drilling shoe track @ 1010 m

While drilling the shoe track, cement cuttings resulted in constrained pipe movement and fluid friction; correspondingly, a warning was raised by the HC agent, as seen in Fig. 4. Observation of hard large cement cuttings at the shakers was reported in the Daily Drilling Report (DDR), which acts as an independent confirmation of the validity of the hole cleaning risk warnings raised by the monitoring system.

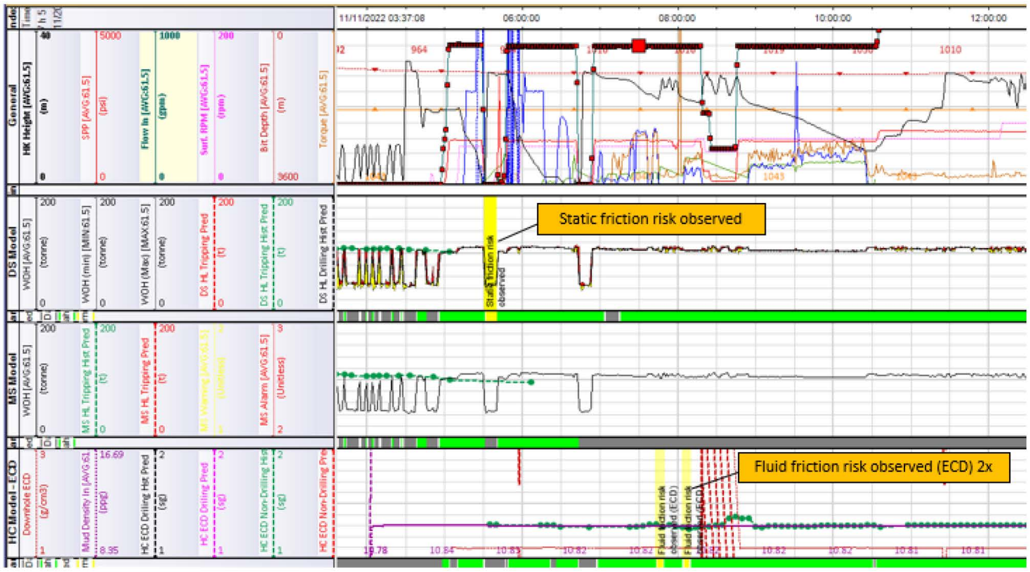

Figure 4—Case 1: DS agent provided a warning due to string static and the HC agent provided warnings at the interval with cement cuttings, highlighting the obstructions in pipe movement and fluid circulation caused by the cuttings.

Case 2: Potential increase in friction at 2520m

As seen in Fig. 5, the DS agent raised a warning due to a predicted increase in static friction, and the HC agent raised an alert based on forecasted ECD increases. This is interpreted as a low stuck pipe risk and was mitigated by the drilling team. The drilling team conditioned the mud and reciprocated and rotated the string. Following these actions, no further HC or static friction warnings were raised, which is interpreted as the risk having been mitigated by the intervention.

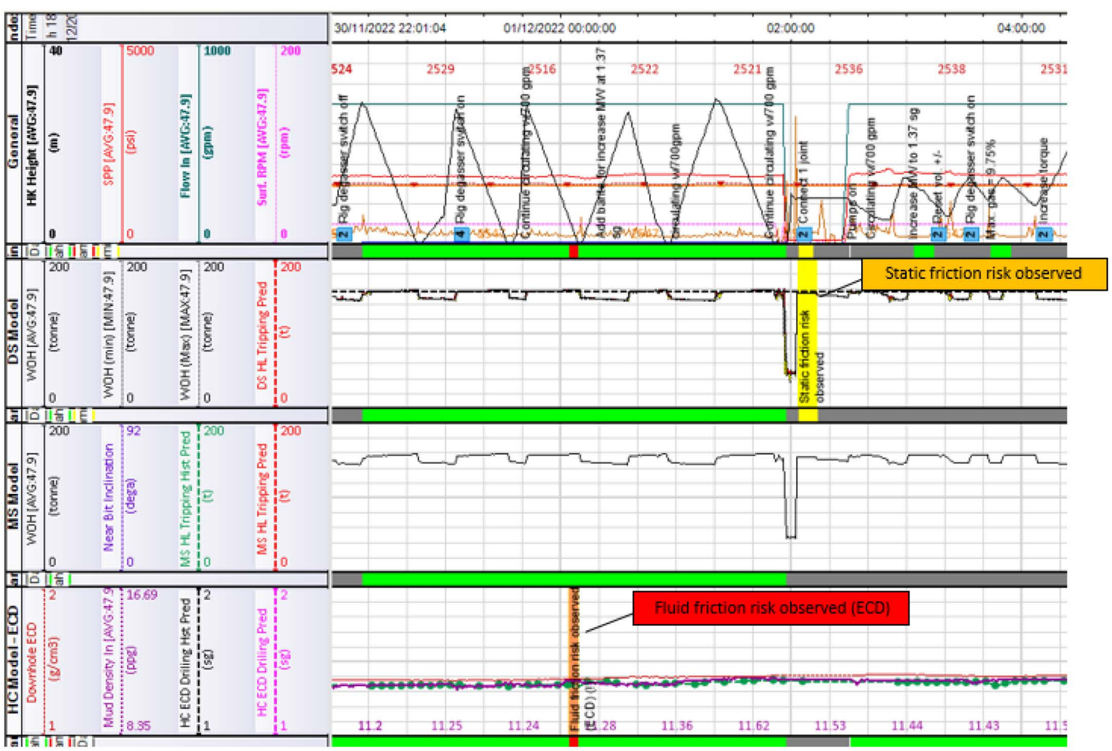

Figure 5—Case 2: A scenario where the DS agent raised a warning due to a predicted increase in static friction, and the HC agent raised an alert based on forecasted increase in fluid friction.

Well 2

The operation took 66 days and the well was drilled to 2625 mMD, shallower than initially planned. Although there were stuck pipe occurrences, they were overcome and the decision of stopping the well before the originally planned depth was based on management strategic decisions, not due to technical challenges. Throughout the entire operation, the risk detection system maintained high uptime and delivered real-time, reliable outputs with minimal false warnings. The KPI's are detailed in Table 3 for reference.

Table 3—Risk detector system performance for well 2. A newer software version, containing features for detecting short-timescale SPP and torque symptoms, was tested retrospectively to assess whether it could have provided early warnings for the missed cases, and thus increased recall and precision.

Performance Parameter	Metric
SPRDS operational time	66 days
SPRDS uptime	100%
WITSML server uptime	99%
SPRDS Average False Warnings per day	0.27 per day (18 false warnings)
SPRDS Recall	0.57 (*increased to 1.0 with new torque/SPP risk detectors*)
SPRDS Precision	0.74 (*increased to 0.82 with new torque/SPP risk detectors*)

Table 4—Cases for Well 2

Relevant observations			
Date	**BHA**	**Operational Details**	**SPRDS output**
5/21/2023 15:30-16:40	17.5in BHA	POOH from 2338 m to 2192 m Up with 311 k, down with 315 k	DS and MS agent provided warnings due to static and dynamic friction increase. See output in ***Case 3***
		Observed intermittent drags to 20 k from 2265 m, wiped and observed weight drop off.	
		Attempted to move string following the connection at 2192, observed weight being taken. Attempted to wipe area – no go max weight pulled 45 klbs.	
		Attempted to apply torque and free string, staged up from 15/20/25/30 klb.ft whilst lowering string to 270 klbs, pumping at 500 gpm.	
5/21/202323:00	17.5in BHA	Attempted to pump out of the hole with 300 gpm /240 psi. Observed tight spot at 2179 m (30 klbs overpull). Attempted to recover rotation – string stalled with 25 kft.lbs torque. Worked the string free by jarring down with 210 klbs hookload (SOW = 296 klbs). Recovered rotation (50 rpm/4 kft.lbs)	MS agent provided warnings due to overpulls detected. See output in ***Case 4***
5/23/2023 1:00 -7:00	17.5in BHA	Washed down / reamed down from 2165 m to TD at 2353 m, working through tight spots as required. At 2315 m observed weight being taken and signs of packing off with pressure fluctuations of 150 psi. Increased flow rate to 750 gpm,1380 psi and reamed in hole with 80 rpm, 2 / 14 k ft lbs torque. Tagged bottom.	MS agent detected some of the overpulls and 6 warnings in the interval See output in ***Case 5***
		Note: – Tight spots at 2165 m, 2194 m, 2204 m, 2237 m, 2256 m. – Wash down from 2165 m to 2173 m, ream down from 2173 m to 2193 m, washdown from 2193 m to 2204 m, ream down from 2204 m to 2222 m, wash downfrom 2222 m to 2237 m, ream down from 2237 m to 2250 m, wash down from2250 m to 2256 m, ream down from 2256 m to 2337 m. – Washing down with 600 gpm / 1050 psi.	
5/30/23 12:30 - 5/31/23 23:00	12.25in BHA	**General Description:** String stuck & packed off after LOT inside 13-3/8″ casing shoe. Worked string, recovered rotation. Backreamed out of hole until recovering partial, then full circulation. Circulated hole clean. Washed / reamed down to casing shoe.	HC agent provided 1 alarm when drilling out the shoe track and MS agent provided 2 warnings right before the stuck pipe. See output in **Case 6**

Relevant observations			
Date	**BHA**	**Operational Details**	**SPRDS output**
		Details: Closed Upper Pipe Rams and performed Leak off test. After successful LOT attempted to move string inside casing, no go- overpull of 30 k. Laid out test assembly and installed working single - attempted to circulate No go - string packed off. Worked sting free with 80 /100 rpm, 12- 20 k ft lbs torque, maintained 100 -250 psi below bit. Worked string up from 2303 m to 2285 m. Racked Back stands and continued to back ream 80 / 100 rpm without circulation maintaining 200 psi on string from 2285 m to 2200 m, observed torque levels drop down from 10 - 16 k ft-lbs to 2 - 5 k ft-lbs, increased pulling speed to 1 m/min.	
		Note: – String packed off unable to RIH as string acting like a closed end piston and taking weight. – At 2200 m observed torque drop to 2 K ftlbs and partial returns at flow line. Staged up flow rate in stages to 700 gpm, 1731 psi whilst reciprocating and rotating the string at 80 rpm. Circulated BU at 800 gpm, 2180 psi, ECD 1.37 sg, 60 rpm, 1.5 k ft lbs. No significant ECD increase or cuttings increase observed at shakers.	
5/31/2023 10:00 – 11:00	12.25in BHA	Backreamed single from 2361 m to 2351 m, but unable to progress down with string through drilled section. String packing off and taking weight at 2355 m, 2356 m, 2357 m, 2358 m. Parameters 80 / 100 rpm, 800 gpm, 2350 psi.	No warnings provided. See output in ***Case 7***
		Note: observed 5% blocky mechanical cavings coming over the shakers which reduced to 3% while circulating.	
6/1/2023 19:45 - 21:30	12.25in BHA	Pick up & make up single 5-7/8″ DP. Reamed down from 2353 m to 2361 m with 750-800 gpm / 2050-2200 psi, 80-100 rpm / 2-5 kft.lbs.	No warnings provided. See output in ***Case 8***
		Note: slow progress, string packing off multiple times between 2355 & 2359 m.	
6/2/2023 8:30 - 10:15	12.25in BHA	Increased flow rate to 700 gpm, 1790 psi, 80 rpm, 3 kft.lbs and attempted to wash / ream to bottom.Reamed down from 2404 m to 2410 m with 700-750 gpm / 1790-2050 psi, 80- 100 rpm / 2-13 kft.lbs.	No warnings provided. See output in ***Case 9***
		Note: slow progress, string packing off multiple times between 2404 & 2409 m.	

The following cases provide an overview of the scenarios encountered during the Well 2 drilling operations, wherein the SPRDS identified anomalies related to pipe and fluid drag, indicating potential stuck pipe risks. Some of the risks materialized into stuck incidents, despite good operational practices and mitigation procedures followed correctly.

Case 3: String held up

The DS agent provided warnings due to intermittent drag while pulling out of hole, and the MS agent provided warnings due to an increase in drag before the string got stuck; these are shown in Fig. 6. The operations team managed to free the string by backreaming.

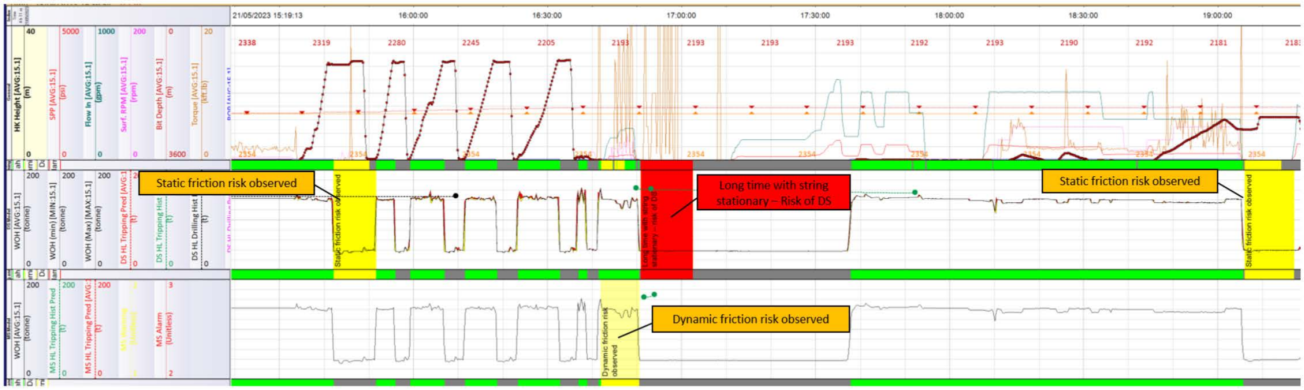

Figure 6—Case 3: DS and MS agents provided warnings due to increase in dynamic and static friction.

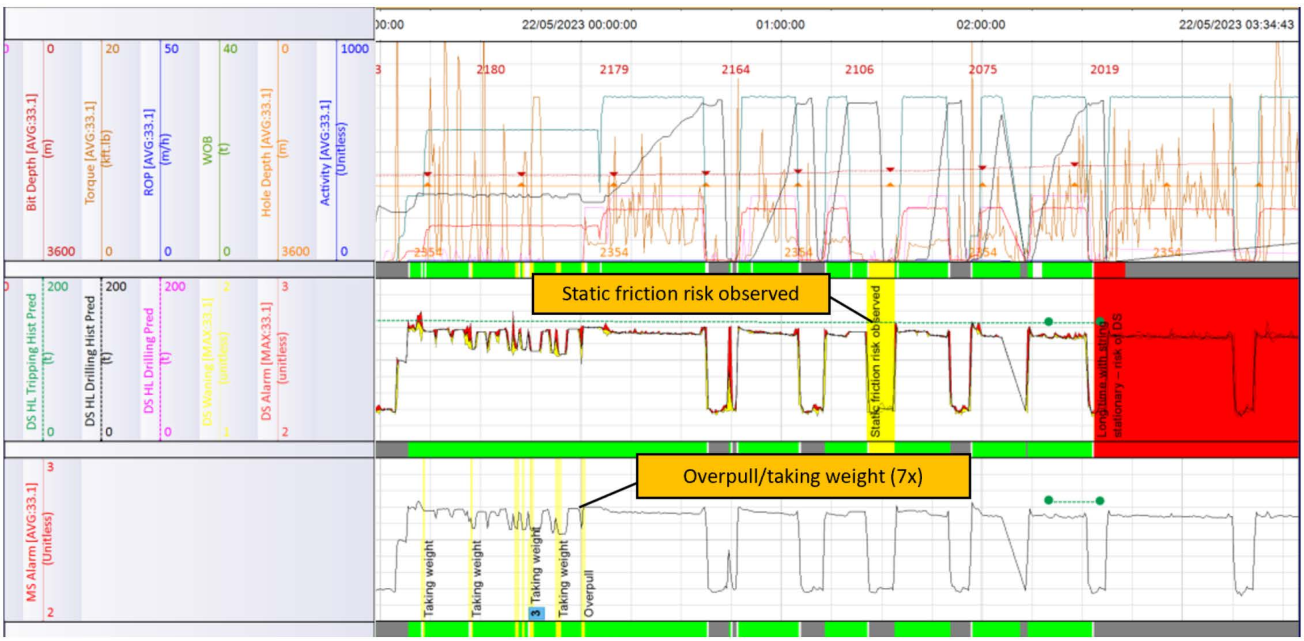

Figure 7—Case 4: MS agent provided warnings due to excessive drag.

Case 4: tight spot

While pumping out of hole, a tight spot was encountered. The MS agent provided warnings due to increased drag. The validity of the warnings is confirmed via the DDR. After jarring, the string was freed and the status became green, thus indicating the risk was mitigated.

Case 5: tight spots

While running in hole with the 17 1/2" BHA, tight spots were encountered. The team washed down/reamed from 2165 m to TD at 2353 m, working through the tight spots as required. From the data, one could observe weight being taken and signs of packing off with pressure fluctuations. The flow rate was increased. At 2193 m, the MS agent provided warnings, indicating that the SPRDS identified this particular zone as carrying the highest risk of stuck pipe. Beyond this point, the status became green, indicating that the risk decreased to an acceptable level. Although the team still experienced some challenges, they were able to overcome these challenges by employing appropriate mitigating actions.

The standard sensitivity for deviated wells was used in this well. As can be seen in Fig. 8, the majority of overpulls were appropriately flagged in this case, although not all. To flag all overpulls, one could increase the sensitivity of the system. However, one should consider that the optimal sensitivity provides a good compromise between identifying relevant risks while keeping a low false warning rate. The overall results for this well show that the standard sensitivity was effective in detecting relevant risks while minimizing false warnings. Therefore, we consider that the sensitivity used was appropriate.

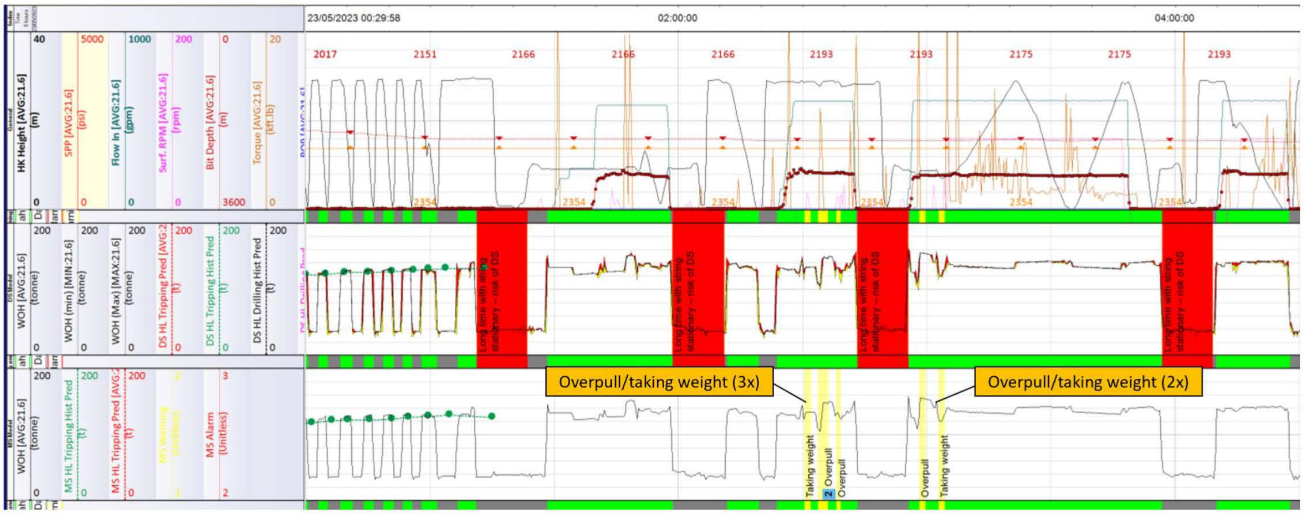

Figure 8—Case 5: Mechanical Sticking module raised warnings relating to a tight spot, due to an increase in drag observed during consecutive stands.

Case 6: Stuck pipe.

A stuck pipe incident occurred inside the casing after a leak-off test (LOT). During the LOT, the surface parameters were behaving as expected with no signs or symptoms of stuck pipe. Furthermore, the risk detector is not expected to provide any warnings during this activity, given the agents focus on activities with string movement. As soon as the string started moving, the MS agent was activated and provided warnings due to observed overpulls, as can be seen in Fig. 9 and reported in the Daily Drilling Report. Very shortly after this stuck pipe symptom was detected, the BHA became stuck; these stuck conditions were evident from the observed overpulls and by the large spikes in rotary torque when attempting to rotate the drillstring and work it free.

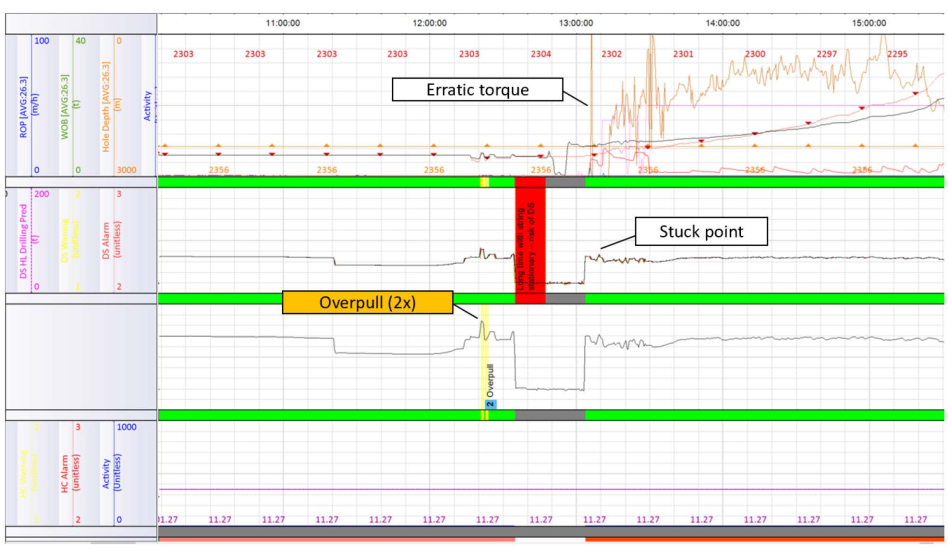

Figure 9—Case 6: Mechanical Sticking risk detection module provided warnings due to observed overpulls before the stuck pipe on May 30th.

The well conditions were good during drilling of the shoe track and in the open hole section. This is confirmed by the risk detector and the analysis. The mechanisms of the stuck pipe inside the casing was unclear in this case, and the data did not show any stuck pipe symptoms in the hours preceding the incident. In Fig. 10, which shows the interval preceding Fig. 9, it can be observed that the conditions appeared to be normal. While drilling the shoe track, there was only 1 HC alarm indicating a temporary increase in fluid friction, but the conditions were quickly normalized.

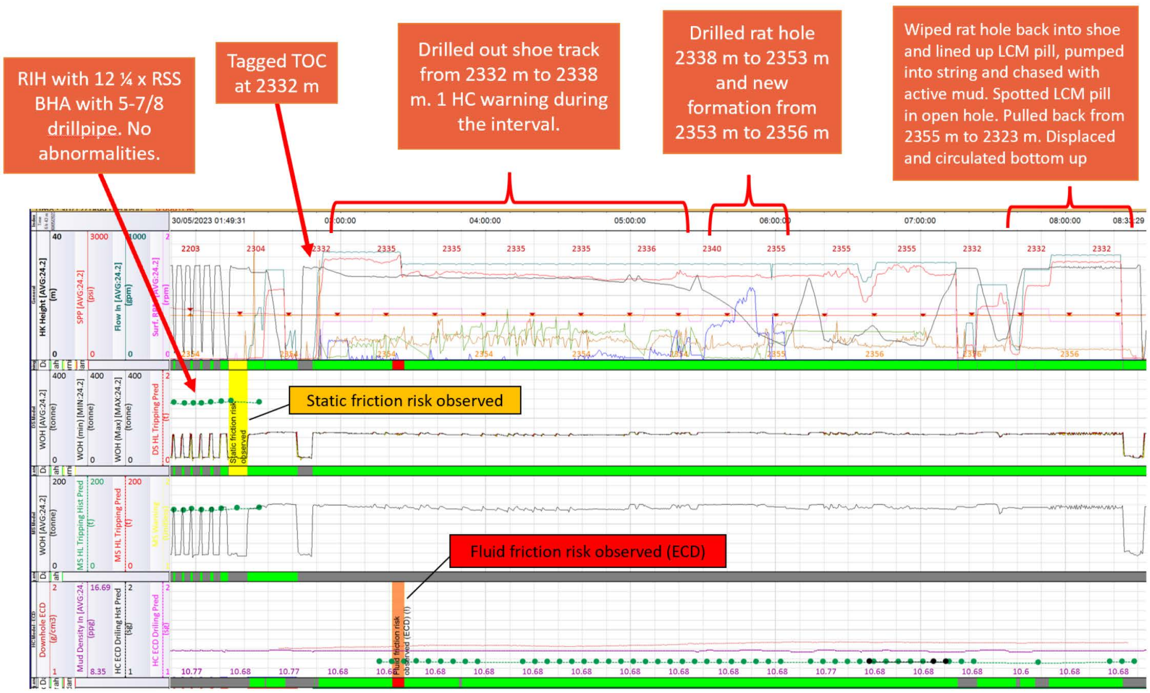

Figure 10—Case 6: Conditions early on May 30th, a few hours preceding the stuck pipe.

The pipe was freed after rotating and working the string up, without being able to pump for several hours due to the pack-off around the BHA. After recovering the BHA at surface some BHA connections and MWD tools showed overheat indications due to the lack of mud circulation while rotation and pulling to free the string. After investigation, one BHA tool had to be scrapped, while another affected tool could be repaired.

As seen in Fig. 9, the torque readings were erratic before the drillstring became stuck; this behavior was not flagged by the software version used during the drilling operations, which did not utilize the surface torque data. An updated version of the SPRDS, which included new modules for detecting real-time risk symptoms in the torque and standpipe pressure measurements (in late-stage development at the time of the field trials), was tested retrospectively using the data from this interval. The new MS agent sub-system was designed to identify torque spikes with stable or falling rotary speeds. This detector identified the sticking signs and raised warnings. These torque risk warnings supplement the overpull warnings in identifying cases relating to mechanical sticking. The results using the newer software release version are shown in Fig. 11.

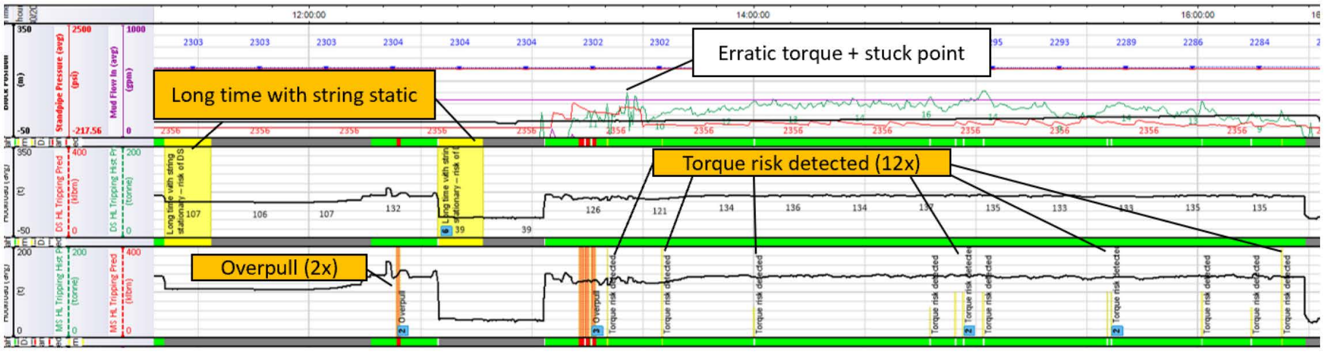

Figure 11—Case 6: The updated SPRDS version's MS agent provided warnings due to increased drag and torque (green curve) – several torque warnings were raised towards the beginning of the second stand by the new torque risk detector. Note that due to the zoom level in the WITSML viewer application, the curves appear to be smoother due to local data aggregations (averaging).

Case 7: Pack-off tendencies.

Pack-off tendencies were reported, evidenced by the SPP spikes and hookload changes as shown in Fig. 12. The changes in the HKL were not substantial enough to trigger any warnings from the risk detector system. Adjusting the sensitivity of the system to detect such minor changes is not an optimal solution either. Doing so would result in frequent warnings being generated for minor instances of increased drag or resistance, overwhelming the user.

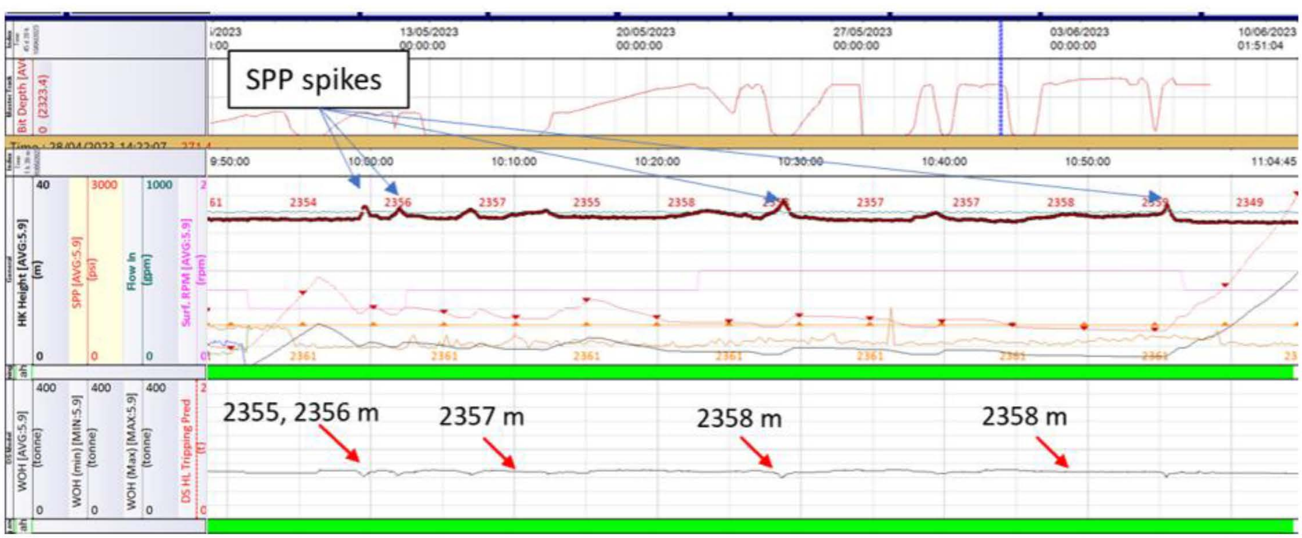

Figure 12—Case 7: Drillstring packing off, evidenced by several SPP spikes.

As mentioned previously, the SPRDS used during Well 2 operations did not incorporate a system for the detection of short-term risks associated with SPP. When testing the new version of the SPRDS, the pressure risk detection system flagged two of the spikes, accompanied by the message "unexpected pressure increase", as seen in Fig. 13. The other spikes were not significant enough to be flagged.

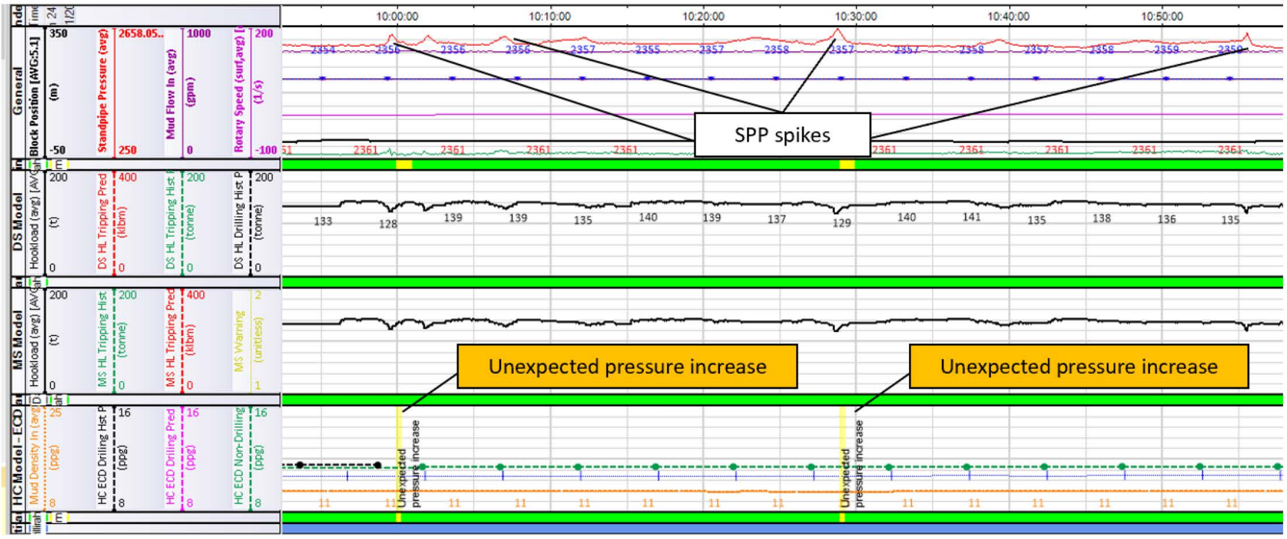

Figure 13—Case 7: Drillstring packing off, evidenced by SPP spikes and flagged by the SPP risk detector (part of the updated software version).

Case 8: Pack-off tendencies.

As shown in Fig. 14, multiple instances of pack-offs were reported, which is substantiated by the presence of pressure spikes. As previously mentioned, the SPRDS used during Well 2 operations did not incorporate a system for detection of risks associated with sudden SPP increases. SPP increases at constant flow rates are indicative of abnormalities, and should prompt an alert from a risk detection system for further investigation. Tests with the updated SPRDS version demonstrated that the new SPP risk detection feature detected these pressure symptoms, and raised warnings as shown in Fig. 15. The standard sensitivity configuration was used for the new SPP and torque risk detectors, determined during the development process using data from wells in other regions; these sensitivities were not tuned for the GoM wells, in order to best imitate use on an exploration well.

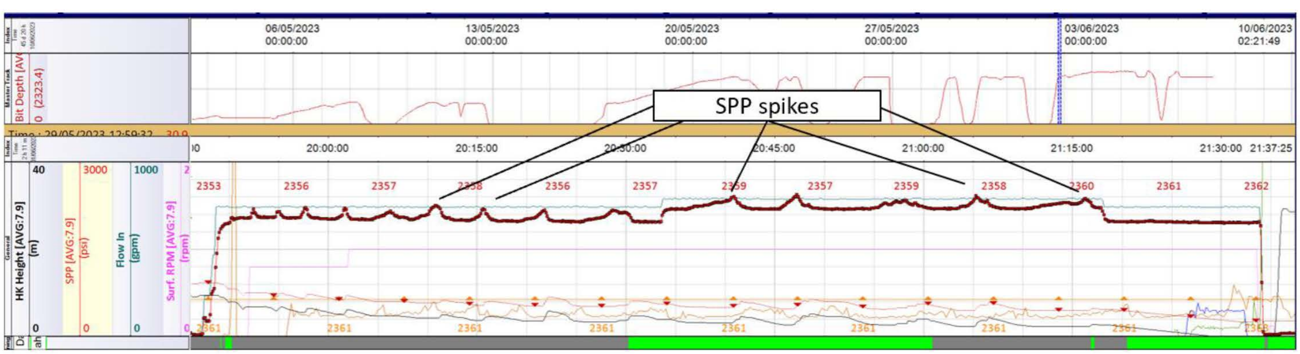

Figure 14—Case 8:Interval with reported pack-offs. SPP spikes are observed in the interval.

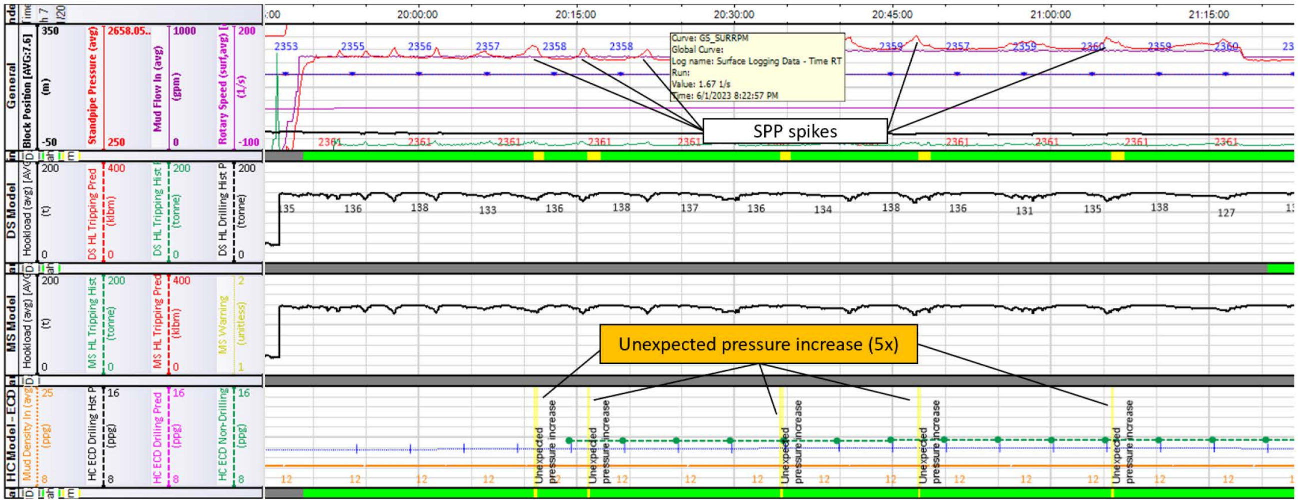

Figure 15—Case 8: Interval with reported pack-offs. SPP spikes are observed in the interval and the updated version of the risk detector raise warnings.

Case 9: Pack-off tendencies.

Similarly to Case 8, multiple instances of pack-offs were reported in the interval shown in Fig. 16, which is substantiated by the presence of several pressure spikes. The new version of the SPRDS, including risk detection features based on pressure and torque spikes, was tested on this case; pressure warnings were raised at multiple points during the interval, shown in Fig. 17.

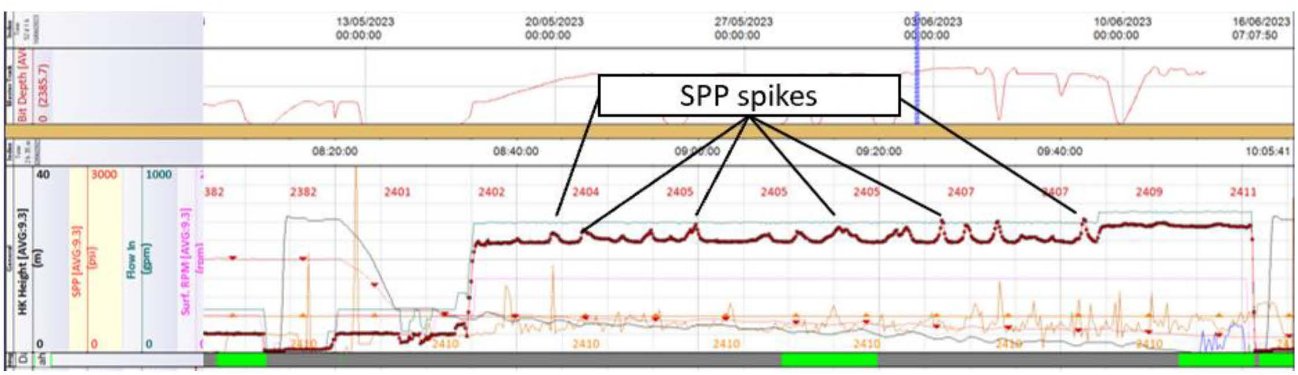

Figure 16—Case 9: Interval with reported pack-offs. SPP spikes are observed in the interval.

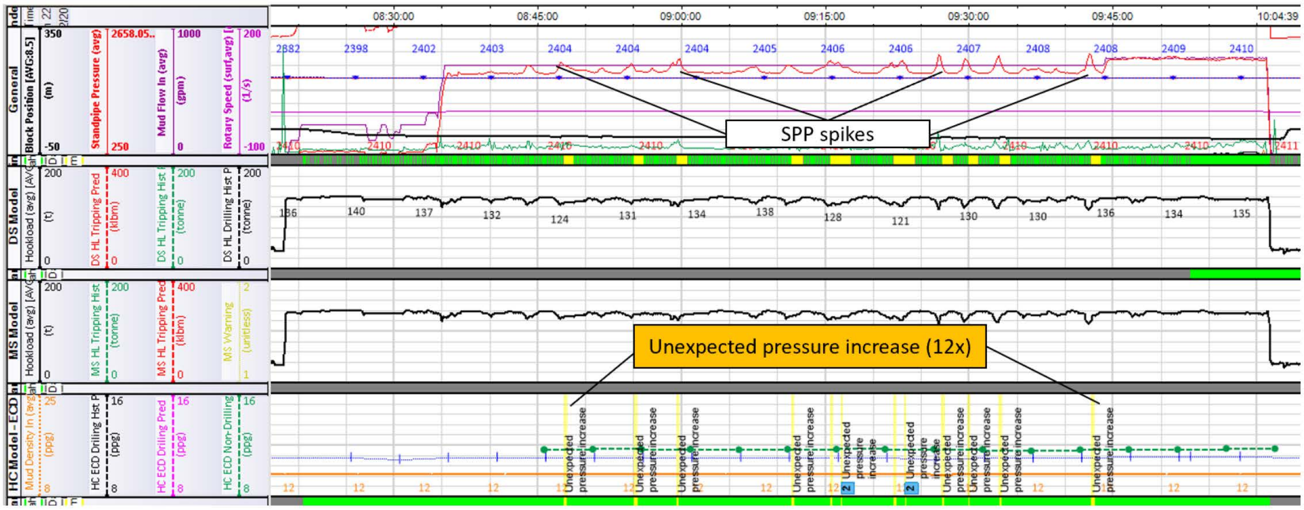

Figure 17—Case 9: Interval with reported pack-offs. SPP spikes are observed on multiple occasions during the interval, and flagged by the pressure risk detector, which is part of the updated software version.

Following the integration of the real-time dynamic torque and standpipe pressure risk detection modules, warnings were issued for Cases 7-9 by the SPRDS, as these transient pressure and torque symptoms were observed. This increased the recall metric for the second well from 0.57 to 1.0, as alerts were issued for all stuck pipe cases when using the updated software release version. These stuck pipe issue scenarios underline some of the challenges associated with stuck pipe risk detection, particularly that risk symptoms are diverse and can manifest on substantially different timescales, ranging from transient spikes in measurements lasting for 5-30 seconds, to more slowly developing drag symptoms observed over the course of many stands during tripping, reaming or drilling operations, which can span tens of minutes to many hours. The original system used during drilling operations was more focused on the slower-building symptoms, and did not cover many transient risk symptoms, except for overpulls and taking weight while moving the drillstring.

Lessons learned and recommendations

The SPRDS worked well out of the box in two exploration wells without any additional or customized training on nearby offset wells. The SPRDS effectively highlighted both potential risks and confirmed their absence, such as when mitigation measures were successful. Product enhancement opportunities were identified and integrated, incorporating the capability to detect torque and pressure anomalies as additional methods for stuck pipe risk symptom identification. These additional modules increased recall to 1.0 for Well 2 (matching Well 1) without tuning sensitivities for these wells, representing best in-class performance. Directly comparing these GoM results to those in the literature can be challenging, due to the limited number of works reporting results from the field, with full sets of statistics not always included. For example, a Middle Eastern national oil company reported a recall of 94% on 38 wells in their domestic fields, without distinguishing between exploration and development wells (Bahlany 2021). Due to the different sample sizes between those 38 wells, and the 2 GoM exploration wells in this paper, it is more instructive to compare the SPRDS mean recall of 98% (average of values observed in each well) achieved on a larger number of wells, as reported by the authors in a previous paper (Payrazyan 2023).

In terms of the SPRDS' business benefit, the main challenge encountered during the drilling campaign was the lack of personnel to monitor the output of the risk detection system. In light of this, the authors recommend the integration of this system into a continuous 24/7 monitoring team or Real Time Operations Center (RTOC). The ability to promptly observe and respond to warnings provides the opportunity to investigate well conditions in real-time and take preventive actions. This approach can potentially offer valuable time before any symptoms escalate into a severe stuck pipe incident, and assist RTOC engineers monitoring several wells concurrently.

The authors advocate for the utilization of technology during the planning phase for exploration wells and propose the use of the SPRDS in historical offset wells to identify potential risks, if suitable offset wells are available. The warnings generated by the system in offset wells data can pinpoint specific risk zones. These risk zones can then be documented in a depth-based map, which can be integrated into the drilling program along with mitigation procedures, in alignment with the company's best practices and guidelines to proactively address these identified risks.

Conclusions

The stuck pipe risk detection system utilized in the operations has proven to be effective in identifying stuck pipe risks while maintaining a low incidence of false warnings. The pre-trained models have great generalization capability and utility for exploration wells. This system operates as an out-of-the-box solution, offering operational monitoring support for exploration wells without the need for pre-training on offset well data. The modular design of the system also proved to be useful following observation of some stuck pipe issues where the symptoms manifested as spikes in pressure and torque measurements; although these cases were initially not flagged by the system version used for live-testing, these symptoms were detected after integrating the real-time torque and pressure risk detection modules, which had been in late-stage development at the time of the drilling operations. The agents' capability of adapting to changes in well condition is helpful in evaluating whether preventive actions were effective.

The company's robust data management and infrastructure were crucial to system stability and high uptime. This underscores the critical importance of having a dedicated team responsible for data management, especially important for data-driven models. To gain the full potential benefits of the risk detection tool, it is strongly recommended to have personnel available for continuous monitoring. This proactive approach ensures that risks are identified as soon as they manifest, allowing immediate responses and mitigation actions.

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Nomenclature

AI	Artificial intelligence
BHA	Bottom hole assembly
DDR	Daily drilling report
DS	Differential sticking
ECD	Equivalent circulation density
GoM	Gulf of Mexico
HC	Hole cleaning
HKL	Hookload
LOT	Leak off test
MD	Measured depth
ML	Machine learning
MS	Mechanical sticking
NPT	Non-productive time
POOH	Pulling out of hole
RIH	Run in hole
RPM	Rotations per minute
SOW	Slack-off weight
SPP	Stand pipe pressure

SPRDS	Stuck pipe risk detection system
TD	Total depth
TVDSS	True vertical depth subsea
WOB	Weight on bit

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