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First 22'' PDC Successful Run On Rotary Steerable System, Optimum Bit Design Selection For Challenging Directional Application

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Abstract

Due to limited surface locations in developed fields, more and more deep well applications are requiring directional work in top sections, still drilling through interbedded challenging formations with severe dynamics issue. With the collaboration of Kuwait Oil Company, this paper introduces a new 22'' PDC bit selection method based on 3D simulations of dual UCS transitions and its impact on a given cutting structure arrangement.

Stability and balancing of the PDC Drill Bit is key to success when drilling a directional section, specially when drilling larger size hole with dynamic events amplified by the inertia of the BHA. Balancing the cutting structure when encountering interbedded soft – hard transition with a variable dip angle is mandatory to achieve planned trajectory together with ensuring a good borehole quality and minimal tortuosity. The design presented in this paper and the optimization made on its cutting structure with an in-house 3D simulation software will demonstrate how these challenges have been solved over a wide range of drilling scenarios, including the proprietary capability to simulate rock transition.

A series of different transition scenarios from soft to hard, hard to soft and with different dip angle have been conducted on a series of targeted 22'' bit designs aimed to be run in an application in North Kuwait. This process has been applied iteratively to estimate the adaptability of the bit design to these scenarios. Bit designs have been ranked with respect to different performance indicators like drillability, steerability, stability and tool face control. The top ranked bit design has been selected, manufactured and successfully run in the field. For the first time worldwide, RSS BHA in 22'' drilled S-Shape section of 1279 ft with inclination up to 10° and back to vertical while reaching 2.5° Dogleg severity. By using a PDC instead of Hybrid Roller cone bit, a 60% gain in ROP was possible and a 44% cost reduction achieved. This unique design configuration allowed an optimum directional behavior with reduced drilling dynamics recorded and enhanced borehole quality for smoother completion operation.

By being the first ever S-Shape section Delivered by RSS worldwide and first 22'' RSS directional run in the Middle East, this success is opening the door to further development of existing field and more complex trajectory achievement. The performance is kept at the heart of the equation with optimized PDC cutting structure to deliver best ROP and lowest cost per foot each and every time.

Introduction

Variability in directional drilling

Rotary steerable systems represent cutting-edge technology within the drilling industry, offering precise and reliable directional control in challenging and deep drilling environments. The complexity of these operations is further heightened when encountering highly interbedded formations sequence.

Directional behavior is influenced by various components of the Bottom Hole Assembly (BHA), such as the drill bit, stabilizers, and drill collars, which interact with the borehole wall, and can also contribute to the variability of the directional response, as discussed in the works of Chen et al. in 2007 and Barton et al. in 2009.

In addition to this, rock formation represents another significant source of variability. While the average lithology of a well may be known, rock characteristics exhibit high variability both across a sedimentary basin and along a drilling section, as indicated by Cuillier et al. in 2017.

One of the most prevalent scenarios encountered during directional drilling is the presence of rock transition intervals, where the formation changes from soft to hard or vice versa. These transitions can have a significant impact on the response of the Bottom Hole Assembly (BHA) and disrupt the cutting action of the drill bit. Consequently, the directional efficiency of the drilling system is diminished. In summary, the success of rotary steerable systems in achieving precise directional goals is influenced by the mechanical responses of BHA components and the inherent variability of the rock formation. Understanding and managing these sources of variability are critical in optimizing drilling operations and ensuring accurate wellbore placement in complex drilling scenarios.

Simulation tools used to optimize the bit design process.

The analysis utilizes a 3D model that considers both the drill bit and the drilled hole as intricately meshed surfaces (Pelfrene et al., 2019a). This simulator employs a versatile computational geometry algorithm, estimating the precise volume of rock removed by each cutter and discerning the contribution of distinct cutter parts, as depicted in Figure 1.

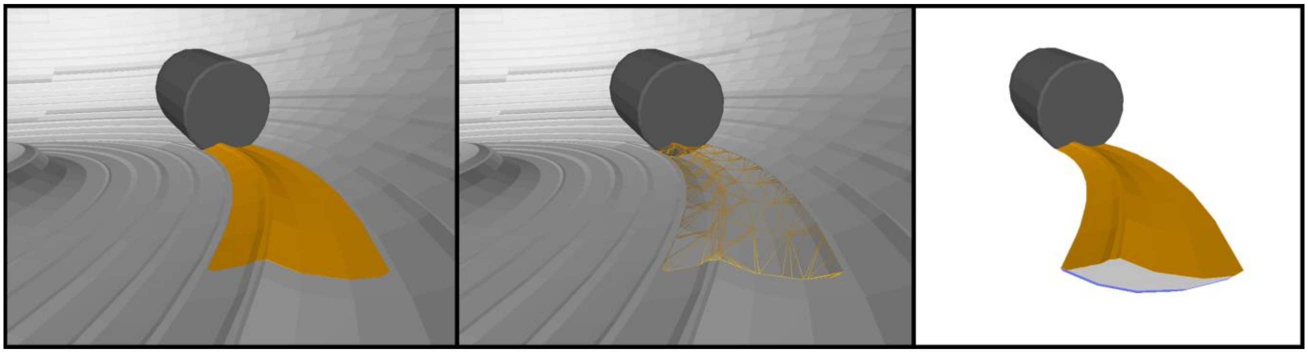


Fig. 1 illustrates the visualization of the rock removal volume (left, depicted in orange), with the wireframe mode shown in the center. On the right, the figure showcases the identification of specific cutter parts contributing to the rock removal (blue denotes the chamfer section, light grey represents the cutting section, and orange indicates the free surface).

This inclusive approach accommodates diverse cutter shapes, as demonstrated in Figure 2.

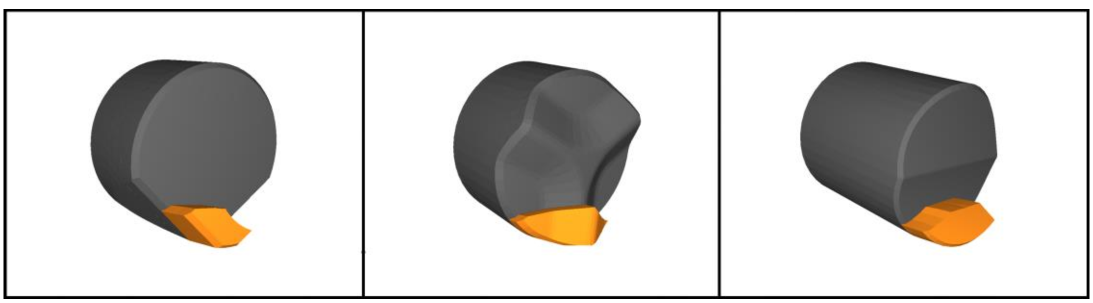


Fig. 2, the algorithm adeptly simulates a variety of 3D cutter shapes, each distinctly associated with its volume of rock removal (depicted in orange).

It allows as well for transition rock simulations, as showed on Figure 3

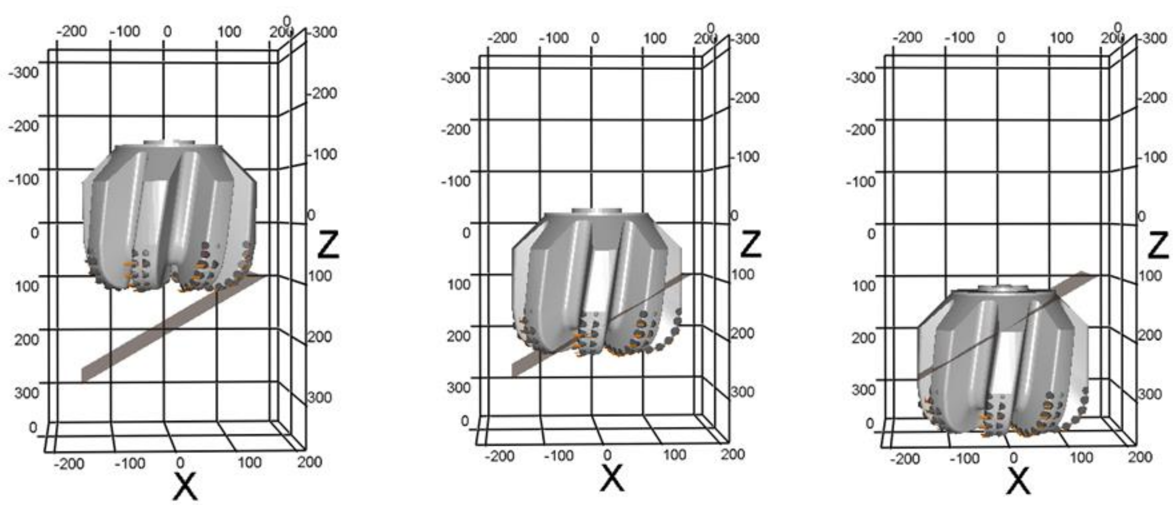


Fig. 3, plane surface is materializing rock transition frontier from Rock 1 above the plan with given properties to Rock 2 below the plan with different properties.

Field Application and Challenges

In Kuwait, the 22'' section is usually drilled Vertically using a Rotary BHA with a PDC drill bit. Due to limited surface location in North Kuwait assets, the need for multi-pad drilling is growing strongly combined with increasing well trajectory complexity in requiring inclination to build in top hole sections.

The trajectory objective is to kick-off from vertical to approximately 8-10° and drop back to vertical with an objective of 1.75°/100ft DLS (Dog Leg Severity) while drilling a 1,400 ft average section from roughly 6,600 ft depth to 8,000 ft TD.

For the first time in the Middle East, an RSS push-the-bit drive system was used to drill this S Shape trajectory. An intensive collaboration was then initiated by a KOC Drilling Engineer, to ensure an optimized match between the drive system and the bit design, together with an adaptability to the challenging environment of hard, abrasive, and interbedded rock to be drilled, see Figure 4, typical UCS & Lithology of a 22’’ KUWAIT deep drilling application.

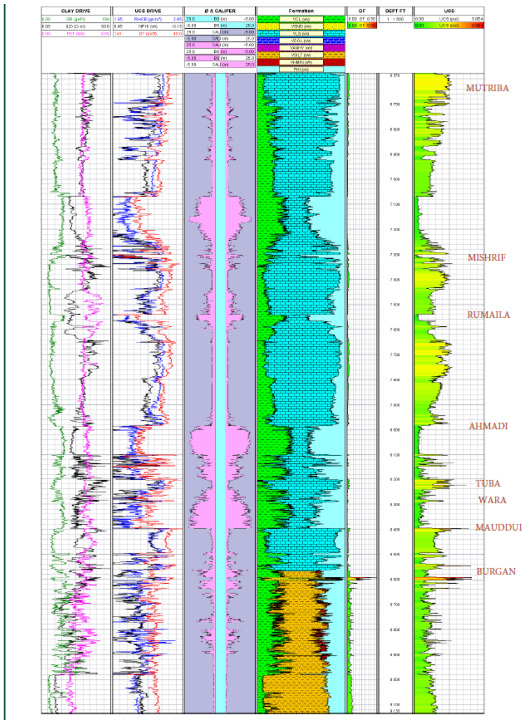


Fig. 4, UCS (Unconfined Compressive Strength) Computation of typical 22’’ section in North Kuwait showing from left to right: Electronic logs (input), Caliper, Lithology, Grinding Factor, Depth, UCS Versus Formations sequence.

Three bits design iterations have been looked at to address dynamic issues on the RSS drive system when drilling a directional build-up section and improve the steerability of the bit. The aim was to reduce the overall imbalance force, especially while going through interbedded formation layers.

In the first section of this paper, the context and the results of the iterative simulations analysis are presented, leading to the final bit design selection for the field run. In the second section, the review of the performance achieved, and further design optimization steps are presented.

Bit Design Evolution

General Characteristics

Based on the existing track record of the bit manufacturer in the area, several design iterations have been conducted over the years for the vertical application market. To tackle the use of new directional objectives and drive system combinations, a further design iteration was developed based on the process described hereafter to improve directional response, tool face control and bit efficiency, focusing on drilling interbedded formation sequence.

The three PDC designs have been selected for their ability to meet the primary goal of the application which is performance and durability into this challenging environment from Mutriba formation to Zubair formation. The main design characteristics of the three 22”-in. PDC’s are presented in Table 1, from the original version (A22670) to the new version (V23026) and to the latest improved version (V23026-2).

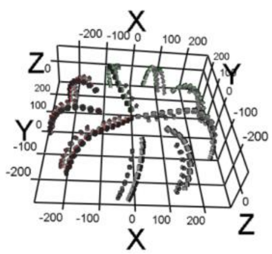
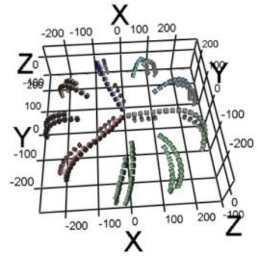
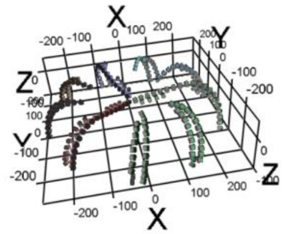
A22670	V23026	V23026-2
		
		
9 blades 19mm cutters Track-set lay-out Dual UCS	9 blades 16mm cutters Single-set lay-out Dual UCS	9 blades 16mm cutters Track-set lay-out Dual UCS
Gage pad Full gage 5'' Length 1.2'' Trimmer Length	Gage pad Full gage 6'' Length 1.2'' Trimmer Length	Gage pad Full gage 6'' Length 1.2'' Trimmer Length
Straight blade design Spiral Pitch 0.04°/mm	Straight blade design Spiral Pitch 0.04°/mm	Straight blade Design Spiral Pitch 0.04°/mm
Steel body 12 nozzles Make-Up length = 21.4in. Open Face Volume ratio = 52.0%	Steel body 12 nozzles Make-Up length = 22.0 in. Open Face Volume ratio = 51.9%	Steel Body 12 nozzles Make-Up Length = 22.0 in. Open Face Volume Ratio = 51.9%

Table 1: Comparison of the three PDC designs selected.

Cutting Structure change for Stability and Steerability

Throughout the design iterations, changes in the cutting structure were made to improve bit steerability. When the original design (A22670) featured a 9 bladed with 19mm cutters distribution, the new design (V23026) was updated with 16mm cutters size to generate less Torque and have a better load repartition along the profile, together with using single set lay-out as opposed to the original track-set arrangement. The same cutters size was then applied to the improved design (V23026-2) but with an enhanced track-set cutting structure to minimize lateral displacement and improve overall stability. The 2D cutting structure and their main attributes are shown on figure 5.

Although improving Steerability often mean increasing lateral displacement capability, the approach can be looked at in a different manner, when dealing with large diameter borehole and high vibration sensitive applications: making a drill bit more steerable (and/or more efficient to react to drive system input forces) would be in fact minimizing overall vibrations occurrence which are counteracting directional responses.

This statement is even more critical when drilling through highly interbedded and heterogenous formations which is the case for the 22'' section in Kuwait.

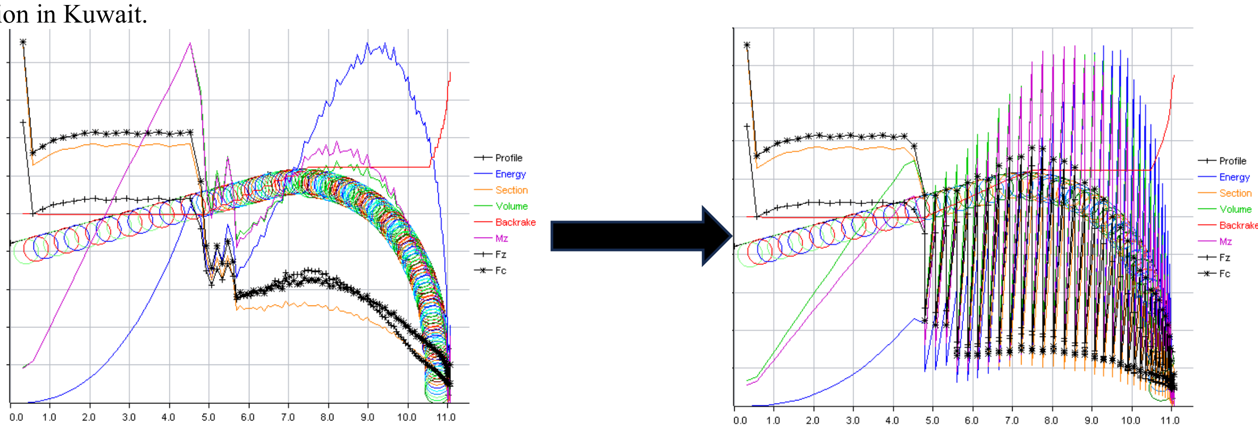


Fig. 5, 2D view of the cutting structure arrange between Single set and track set lay out: V23026 / V23026-2

Therefore, a stable cutting structure, which will have the lowest imbalance force when transitioning from Hard-to Soft or Soft-to-Hard UCS rock becomes a key component to successfully achieving the directional objectives.

Iterative simulations analysis for cutting structure selection.

Parameters Definitions

The iterative analysis is focused on identifying the most directionally stable drill bit from three available options. This is achieved by conducting simulations with a comprehensive and representative set of drilling parameters, carefully chosen to mirror real-world applications. The simulation parameters encompass a wide range of values, and a detailed list of these parameters can be found in Table 2.

	Distribution	Unit	Avg	step	Min	Max
ROP	Fixed	ft/hr	-	-	50	50
UCS Rock1	Discrete	kpsi	-	5-15	5	35
UCS Rock2	Discrete	kpsi	-	5-15	5	35
RPM	Discrete	RPM	-	20-30	80	150
Dip angle	Discrete uniform	°	25	12.5	0	50

Table 2. Simulation parameters used in the Iterative analysis.

These parameters include the rate of penetration (ROP), unconfined compressive strength (UCS) of Rock 1 and 2, revolutions per minute (RPM), and Dip angle of the transition plan from Rock 1 to Rock 2.

Table 2 presents the simulation parameters used in the statistical analysis, including their distributions, units, average values, incremental steps, and minimum and maximum values where applicable.

For the analysis, ROP is being kept constant and since the directional model is inherently influenced by the ROP-to-RPM ratio (resulting into the DOC – Depth of Cut – per revolution), RPM interacts with the ROP in determining the drill bit's directional behavior.

UCS Variability

In this section we will analyze the evolution of the imbalance force evolution during the transition of the cutting structure throughout different UCS layers. Rock 1 and 2 will alternatively take values of soft to hard and hard to soft.
By example, UCS Rock 1 will be set at 15kpsi, UCS Rock 2 at 10kpsi and vice versa, Figure 6.

Drilling parameters selection

	Bit depth	Mud density	Rotary RPM	Motor RPM	ROP	Dip angle	UCS	IFA	Cohesion	Cutting friction angle
Unit	ft	lb/gal	RPM	RPM	ft/h	°	psi	°	psi	°
In	5000	10	120	0	50	n.a.	10000	25	3185.35	10
Out						25	15000	35	3904.25	10

Drilling parameters selection

	Bit depth	Mud density	Rotary RPM	Motor RPM	ROP	Dip angle	UCS	IFA	Cohesion	Cutting friction angle
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In	5000	10	120	0	50	n.a.	15000	35	3904.25	10
Out						25	10000	25	3185.35	10

Fig. 6, Input table for Simulation Software with UCS values varying from hard to soft and soft to hard.

Three case scenarios were simulated with couple of values being [15-10], [20,5], [35-5] (unit kpsi), so that results are validated for a wide range of eventuality in the field. The dip angle was kept constant at 25° as well as the RPM at 120.

Figure 7 is showing typical output plot for the results with explanation as follow:

- Rotation Angle on the X axis represent each step of the simulation. In order to minimize the number of simulations and the time involved, a group of simulations are made every 60 full Rotation of the bit. Each group of simulation is then counting 18 steps to have a results every 20° Rotation Angle. Each vertical data set of points represents one rotation with 18 data points and a moving average is compiled for those 18 data points, example figure 8.
- The Imbalance force on the Y axis is by definition the sum of all the reactive forces vector applied on each cutter, and normalized by the WOB needed to achieve expected ROP input. The lower the imbalance, the better is the stability. Typical

imbalance force into homogeneous rock will target value below 5%, but when going through transition of different rock hardness, this value will increase drastically as can be seen on all the simulations below.
- Depending on the Dip Angle, the extent of the simulation will capture the entrance on the cutting structure into Rock 2 and either the full exit from Rock 1 or only partial exit.

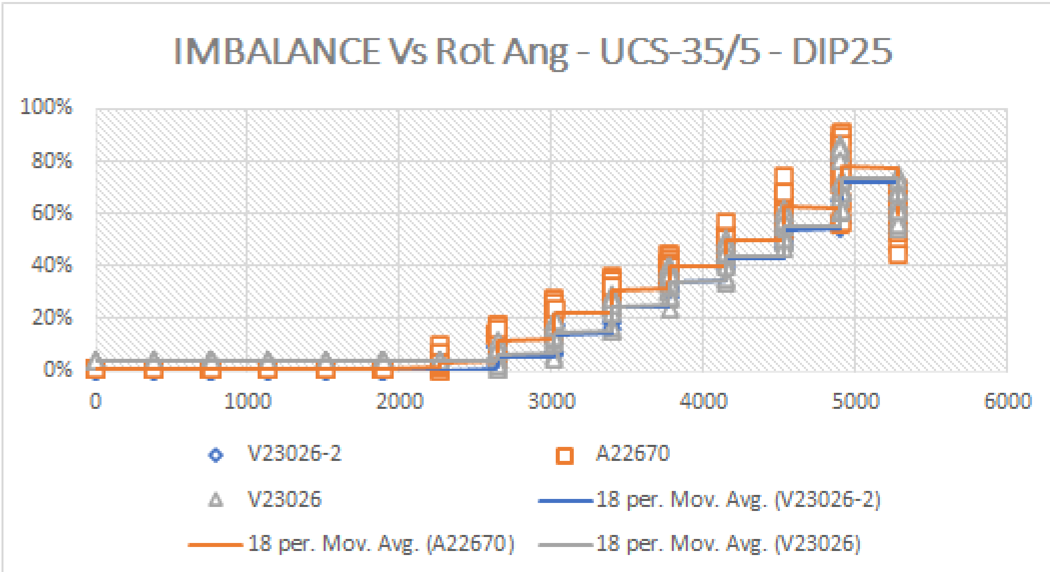

Fig. 7, Simulation results showing Imbalance forces evolution for the three different cutting structure versus Rotation Angle for UCS Rock 1 at 35kpsi and UCS Rock 2 at 5kpsi for a Dip angle at 25°

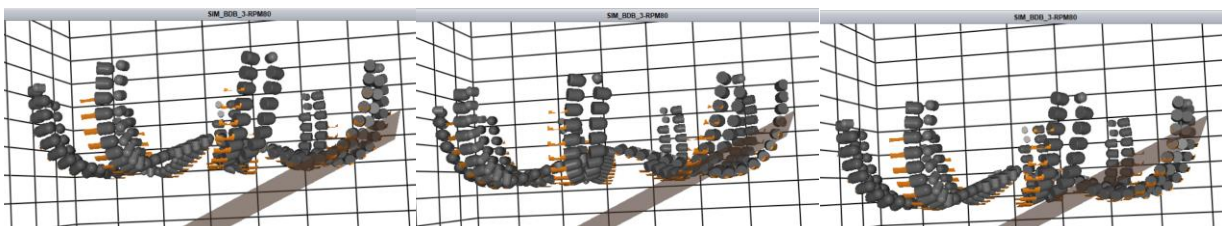

Fig. 8, for each group of simulations performed, bit cutting structure is gradually entering the transition plane.

Results for the 3 different case scenarios are shown below in Figure 9 & 10. The V23056-2 cutting structure design shows an overall lower Imbalance force compared to V23056 and A22670. Especially when entering the new formation layer and exiting it we can see a few percentages less on the V23056-2 average value for each group of simulations.

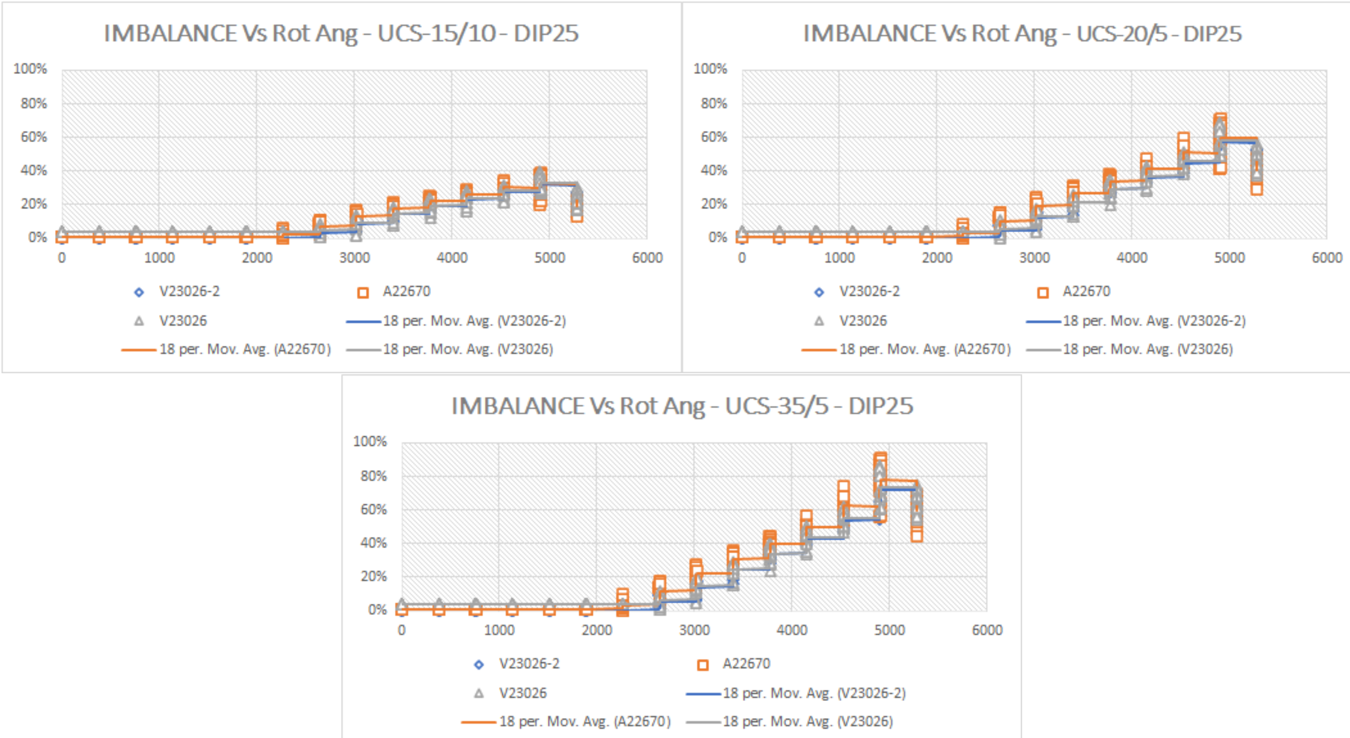

Fig. 9, Simulation results showing Imbalance forces evolution for the three different cutting structure versus Rotation Angle for variable UCS from Hard to Soft Formations

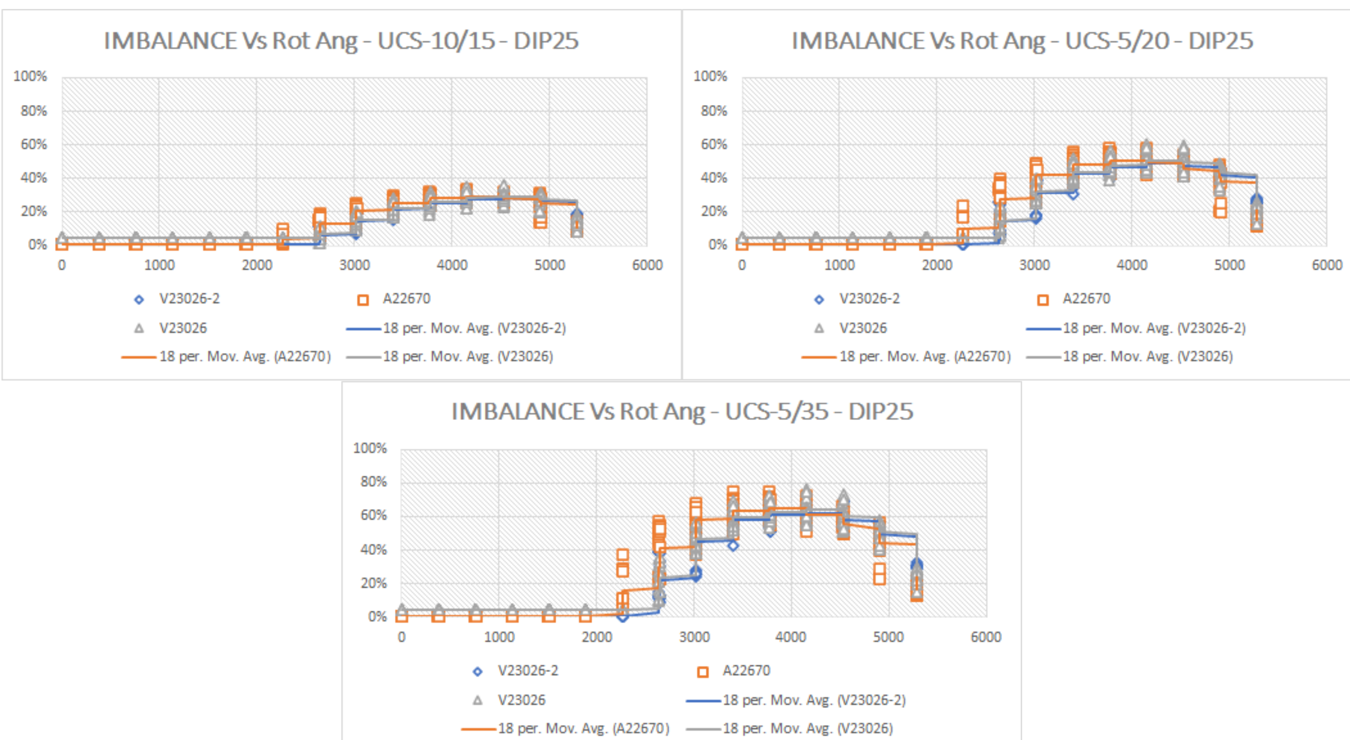

Fig. 10, Simulation results showing Imbalance forces evolution for the three different cutting structure versus Rotation Angle for variable UCS from Soft to Hard Formations

Simulations data clearly show superiority in terms of stability with lower Imbalance forces for the latest V23026-2 design. A zoom on the plots can be seen in Figure 11.

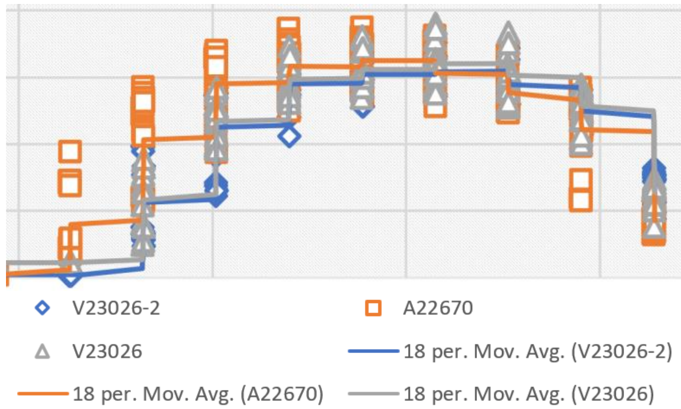

Fig. 11, Zoom on Simulation results showing better Imbalance forces evolution for V23026-2 design (Lozenge shape) especially when entering the new layers with overall lower Average value at each step of the calculation.

Dip Angle Variability

Below in figure 12 is an example view of the different Dip Angle that have been used in the simulation with 0° , 12.5°, 25°, 37.5° and 50° plane used.

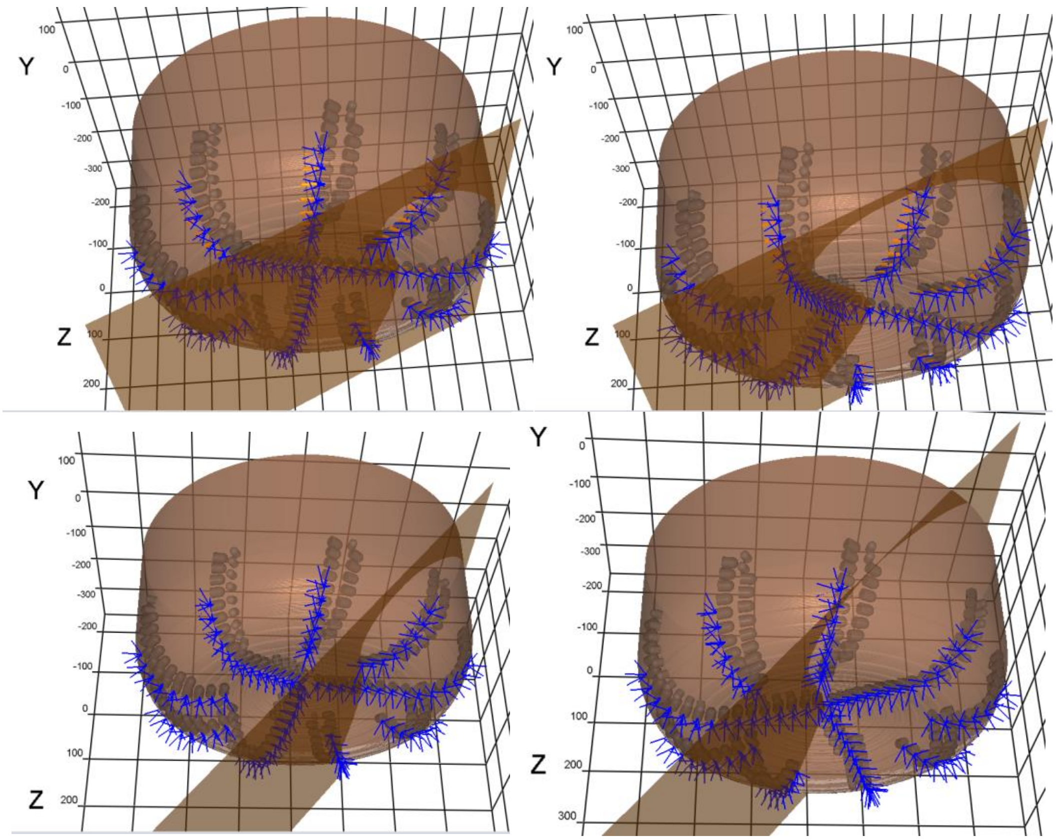

Fig. 12, 3D views of the cutting structure going through 25° and 50° plane of transition between 2 types of rock

Simulations showing the impact of dip angle were done with constant UCS Rock1 and UCS Rock2 but considering 2 case scenarios with soft to hard and hard to soft, Figure 13 & 14.

The couple of UCS values selected for this simulation is [5-20] kpsi and vice versa.

In all the Dip Angle simulated we can see that design V23026-2 shows slightly lower Imbalance forces compared to the other 2 designs. Once again this confirms its stability superiority when going through transition layers of formations hardness from hard to soft or from soft to hard.

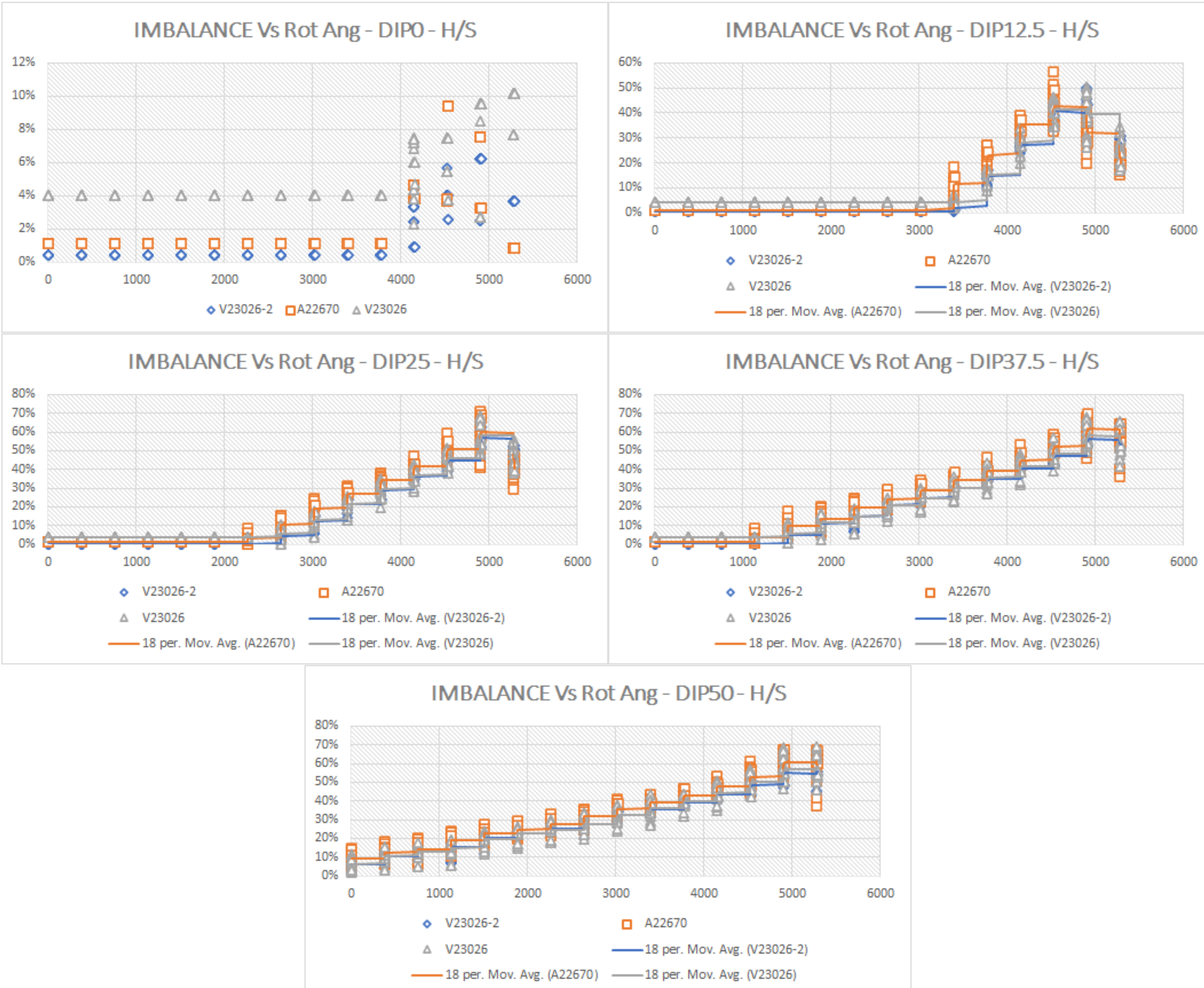

Fig. 13, Simulation results showing Imbalance forces evolution for the three different cutting structure versus Rotation Angle for variable Dip Angle from Hard to Soft Formations

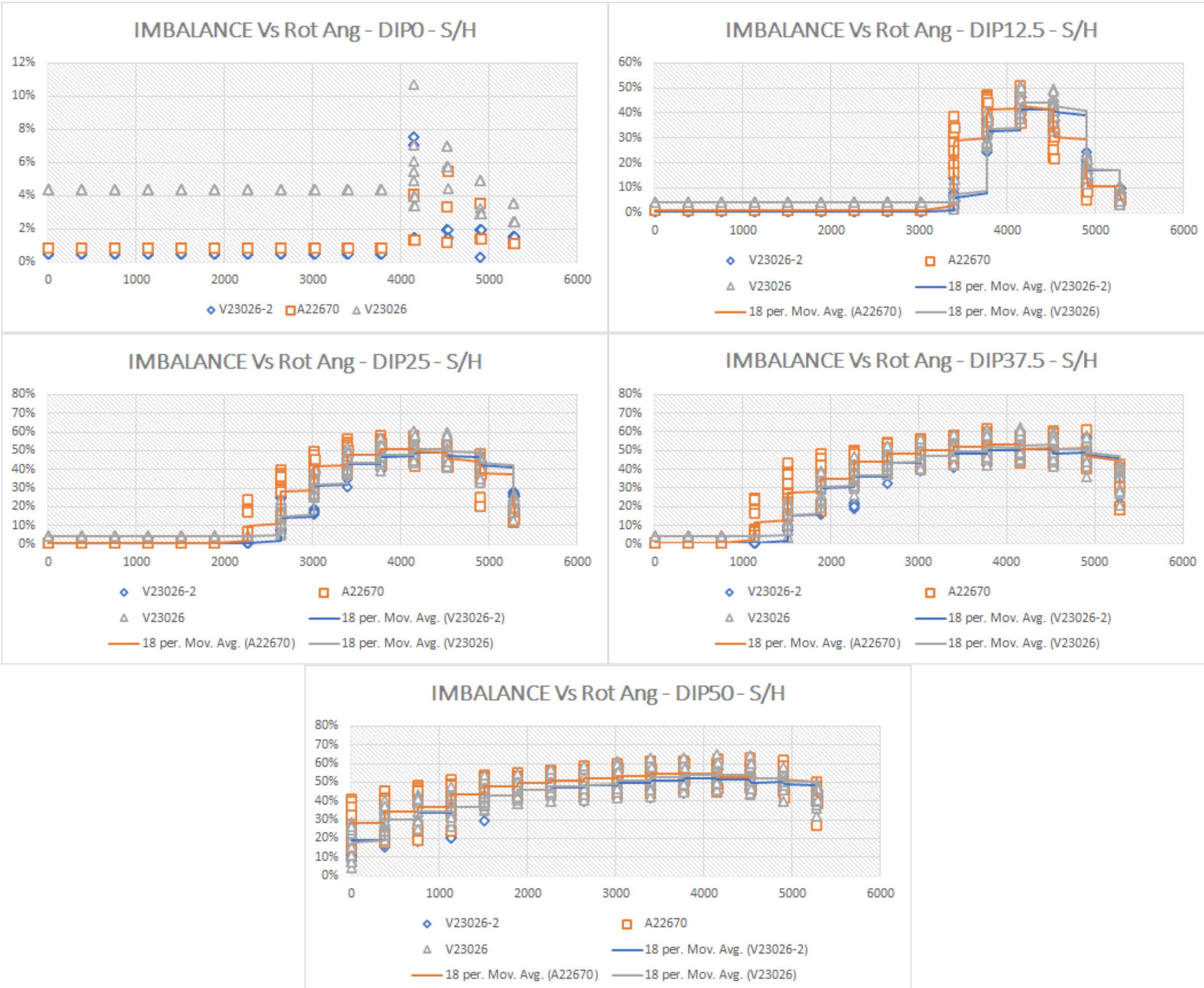

Fig. 14, Simulation results showing Imbalance forces evolution for the three different cutting structure versus Rotation Angle for variable Dip Angle from Soft to Hard Formations

RPM Variability

The three designs were looked at with constant Dip Angle at 25° and UCS transition sequence [20,5] while RPM simulated varied from 80 to 150.

From the plots below in figure 15, we can see that both the average overall value and the dispersion of the Imbalance force is clearly less when simulating V23056-2 track set cutting structure against the other designs and for all different RPM.

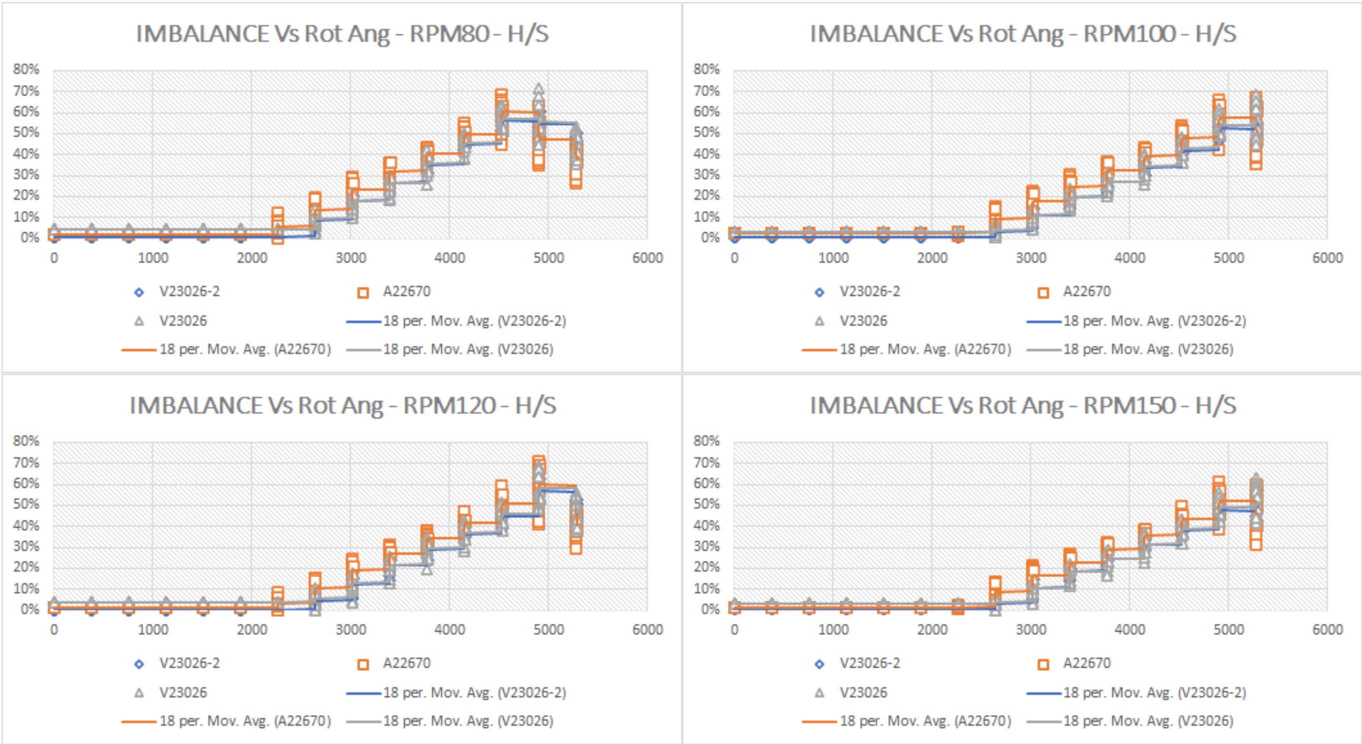

Fig. 15, Simulation results showing Imbalance forces evolution for the three different cutting structure versus Rotation Angle for variable RPM from Hard to Soft Formations

Simulations results conclusion

With all the different simulations above, we have identified that the V23026-2 is a better option to tackle the challenge of this application when considering the Imbalance force evolution especially when crossing a transition layer in the rock hardness and with different Dip Angle. These results allow us to select the newly design cutting structure as the best solution for directional work to be performed in 22'' section of North Kuwait.

Field Results: First 22'' PDC on RSS in Middle East: Kuwait field

Field Application

The 22'' PDC V23026-2 was chosen as a result of the design selection process using the specific simulation and dual UCS model with varying input parameters and used to drill directional top hole section in a North Kuwait field.

The bit was run on a non-motorized RSS Push-the-Bit BHA, with the objective to build from 0 to 10° and drop back to vertical while achieving DLS in the range of 1.75°/100ft. The WOB was between 15 and 35 Klb at approximately 100-110 RPM. Depth In was at 6,510 ft MD and bit was POOH at 7,775 ft MD.

Directional response analysis

The observed directional response of the drill bit is shown in figure 16 with inclination/azimuth and DLS evolution versus measured depth. The bit allowed the achievement of high DLS up to 2.5°/100ft and was able to both build up to 8° and drop back to vertical while turning slightly on the azimuth.

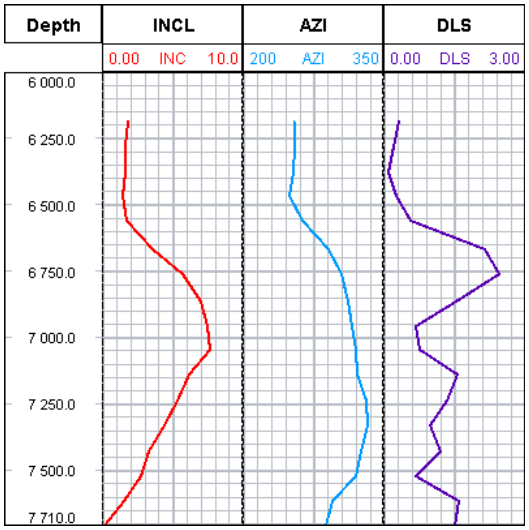

Fig. 16 – BHA directional response

Performance results and comparison

The bit drilled 1279 ft at a very good ROP of 14.9 ft/hr, while building angle from 0° to 8° inclination and drop back to vertical. The bit achieved a 60% ROP improvement compared to the offset average in this application. The dull grade for the bit was 1-1-NO-A-X-I-NO-BHA as can be seen in the pictures below figure 17 – 22” PDC bit picture after POOH. The bit contributed to efficient drilling coupled with excellent directional control resulting in a new ROP benchmark for the area, together with 44% reduction in Rig days and 30% reduction in overall cost per foot, see figure 18.


Fig. 17 – 22’’ PDC Bit picture after RSS run

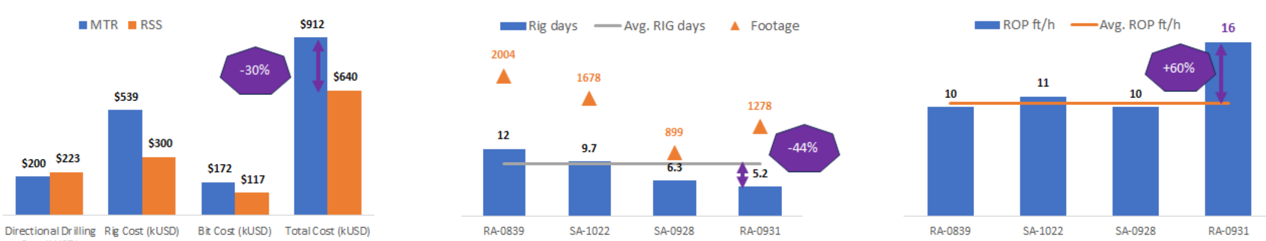

Fig. 18 – performance chart comparison 22’’in. section

Conclusion

This groundbreaking achievement marks a significant milestone as it represents the inaugural implementation of an S-Shape section using RSS technology on a global scale and the first-ever directional run of a 22” RSS system in the Middle East. The success of this endeavor paves the way for future advancements in existing fields and the pursuit of more intricate drilling trajectories. With an unwavering focus on performance, the optimization of the PDC cutting structure lies at the core, ensuring the attainment of optimal Rate of Penetration (ROP) and the most cost-effective drilling operations on a consistent basis.

Simulation tools, including the 3D model discussed in this paper and the dual UCS transitional capability, are of paramount importance in achieving these significant milestones in drilling evolution. By accurately reproducing the real-world conditions that drill bits encounter, these simulation tools enable a deeper understanding of the drilling environment. They play a crucial role in advancing drilling technologies and pushing the boundaries of what can be achieved in terms of performance and innovation.

Acknowledgments

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