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Mitigating Stick-Slip Vibrations Using Surface Control Software

A Validation of SoftSpeed II™ Using High-Speed Along-String Dynamics Measurements in a Norwegian Offshore Field

Universitetet
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Abstract

Stick-slip is a well known drilling related problem that causes damage and delays, often resulting in an overall more expensive well. These problems have traditionally been remedied by reducing WOB or increasing RPM when possible and most often the ROP is reduced as a consequence. In some cases, it is not possible to compensate for the vibrations as it would stop any progress, and stick-slip must then be tolerated with the potential damages that follows.

Remedial processes for stick-slip has been an important field of study. A recent development is the SoftSpeed II™ application by NOV which calculates the downhole bit speed and torque values and implements remedial string rotation to cease several modes of stick-slip vibrations. This way it is not necessary to reduce WOB to cope with the oscillations, and ROP can be maintained.

Bit wear will be reduced as a result of mitigating stick-slip, which in a well may mean the difference between continued progress or an expensive bit trip. Other side effects may include reducing lateral and axial vibrations, reducing wear on BHA and drillstring, and improving borehole quality.

This Thesis will study the use of SoftSpeed in one field located in the Norwegian North Sea. The reservoir contains hard conglomerates which has created high level of vibrations in previous wells. SoftSpeed has been implemented on the last two reservoir sections, and these two will be compared to the previous four sections drilled in the same reservoir.

By using data from along-string dynamic sensors, the effects of SoftSpeed on drillstring vibrations and locally induced stick-slip can be analyzed at different intervals in the well in high resolution. Performance parameters, such as Rate of Penetration (ROP) and Mechanical Specific Energy (MSE) alongside with a derived Stick-Slip Severity index (SSS), will ensure equal comparison between the wells.

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I want to extend gratitude towards all my previous colleagues offshore. My experience working in the North Sea has taught me more about well conditions and interpreting well log data than schooling ever could.

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Nomenclature

ASM Along-String Measurements.

BHA Bottom Hole Assembly.

bps bits per second.

DP Drill Pipe.

IBOP Inside Blow Out Preventer: Control valves used in the top drive system.

kPa Kilo-Pascal.

ksi Kilopound per square inch = psi$\cdot 10^3$.

LWD Logging While Drilling.

MSE Mechanical Specific Energy.

MWD Measuring While Drilling.

NCS Norwegian Continental Shelf.

NPT non-productive time.

PDC Polycrystalline Diamond Compact.

PLC Programmable Logic Controller.

ROP Rate of Penetration.

RPM Rounds per Minute.

SS SoftSpeed.

SSS Stick-slip severity index.

WDP Wired Drill Pipe.

WOB Weight on Bit.

1 Introduction

For a drilling operation to be successful, there are a thousand pieces coming together. Optimizing the time usage is of utmost importance for costs and bringing the project in on budget. One of the cost drivers in drilling operation is to trip out of hole due to tool failure, bit failure or string failure. The use of time as well as the cost of the equipment are all adding up.

Many of these failures are due to the extreme conditions that exist in the hole during drilling operations, especially drilling vibrations. Extreme and continuous oscillating torsional vibrations caused by the bit being stuck to the formation while drilling is called stick-slip and is very damaging to drilling equipment and the bit. This is common when using PDC bits, and especially when drilling long and deviated wells. As the name implies, the bit sticks to the formation and then slips when the buildup of energy is high enough. This leads to the bit going from a standstill up to two or three times the initial string speed in a short period of time, causing extreme acceleration and deceleration rates. When conditions are unchanged, stick-slip is self-sustained which causes oscillations to go through the drillstring and all the way to the surface. The bit and BHA are the most susceptible parts to damage, as the vibrations are most violent near the source, but the continuous oscillations can also be weakening to the drilling tubulars and connections over time. In addition, the drilling vibrations are often coupled, and lateral vibrations that cause damage by impacts and wear to the BHA and tubulars are also common when experiencing stick-slip.

The traditional way of mitigating said vibrations have been to reduce WOB or increase RPM, or both. Increasing RPM may induce whirl as a consequence, which is a lateral vibrations mode, and most often the WOB needs to be decreased which will result in a reduced ROP. For some formations, it is not feasible to reduce the WOB and still maintain progress, stick-slip must then be tolerated and the consequences taken when they emerge.

An alternative solution for this problem has been researched for many years, and a promising method has been to actively dampen the bit speed with the top drive speed. Many methods of achieving this have been developed and also applied into commercially available products.

SoftSpeed was introduced in 2009, offering a method to mitigate these vibrations with minimal changes to existing systems. By using already available input from the top drive and a simple model of the drillstring, the system can calculate the efficient bit speed and torque and adjust the top drive rotation speed to match same and thus mitigate the stick-slip oscillations.

SoftSpeed is now delivered in second generation, also dampening higher modes of stick-slip. The benefits of using this technology, besides curing stick-slip, is allegedly improved bore hole quality, improved ROP, reduced axial and torsional vibrations, reduced bit wear, less drillstring fatigue, and in total a decreased drilling cost [16]. Throughout the thesis, SoftSpeed II™ will be known as only SoftSpeed.

1.1 Thesis Objectives

One recently developed field on the Norwegian Continental Shelf (NCS) will be studied in this thesis. The drilling campaign uses state of the art technology, such as Wired Drill Pipe (WDP) and SoftSpeed. The latter have been applied for the latest two wells which both are featured in this thesis.

The effects of the SoftSpeed system while drilling will be analyzed using traditional efficiency parameters such as ROP and MSE through surface measurements. The SoftSpeed software also comes with a stick-slip severity index (SSS) that gives a calculated value of the amount of stick-slip at the bit (Section 2.2.1). This value is calculated from surface measurements and inputs in the software, and is given at all times as a readable output and as an aid in when to start the application. It will be used as reference in stick-slip analyses where the application is featured.

Effects of the SoftSpeed application will also be studied downhole. The WDP network offers a unique method to deliver measurements along the drillstring. By having dynamic measurement subs at strategic intervals, it is possible to measure the condition of the drillstring locally in the well. Along-String Measurements (ASM) subs delivers, amongst others, drilling vibration readings in all three directions and string RPM, which will be used to describe borehole conditions in this thesis. By using the string RPM, it is possible to derive a SSS index locally in the well which is also possible to use as a stick-slip indicator for all wells, even those which does not feature SoftSpeed.

The first objective of the thesis is simply to see if SoftSpeed actually reduces stick-slip, and if possible to what degree. The aim is to find areas where stick-slip vibrations are recurrent and where SoftSpeed is activated to see if the application reduces stick-slip during drilling operations. Is it possible to maintain WOB and RPM as they were and simply just activate SoftSpeed to mitigate the vibrations?

The second objective is to prove the alleged side-effects of stick-slip mitigation, such as increased ROP and reduced wear on bit. Will drilling vibrations be reduced as a consequence of mitigating stick-slip? What are the economic upsides to implementing the application? Hole quality and string fatigue will not be touched upon in this thesis, but potential reduced wear on bit may indicate reduced wear on string.

The data available will limit the conclusion, but by comparing similar sections with and without the use of SoftSpeed, it will be possible to discuss the performance value of the system, and most importantly to study the effects of the application.

1.2 General field data

The field that will be studied in this thesis is located in the central Norwegian North Sea. It consists of an alluvial to shallow marine conglomerate and sandstone reservoir from Upper Triassic to Lower Cretaceous.

Out of respect for the operator, only approximate values and a general overview of the field data can be given. All length data given in Table 1.1, and elsewhere, are rounded to the nearest 50 meters.

Table 1.1: Basic info surrounding the different wells

	Well TD	Well TVD	8.5" section
Well 1.1	3550m	1950m	1400m
Well 1.1T2	3700m	1950m	500m
Well 1.2	3900m	1950m	1100m
Well 1.2T2	4550m	1950m	700m
Well 1.3	4850m	1950m	1450m
Well 1.4	5700m	1950m	1750m

All wells penetrates the same reservoir in horizontal sections drilled by an 8 1/2" PDC drill bit. The different wellpaths are shown in Figure 1.1. But even though they penetrate the same reservoir and therefore should be ideal for comparison, local differences from one wellpath to another are inevitable.

A short explanation of the lithology encountered will be given in the beginning of each well section presented in Section 4 and compared in Section 4.7.1.

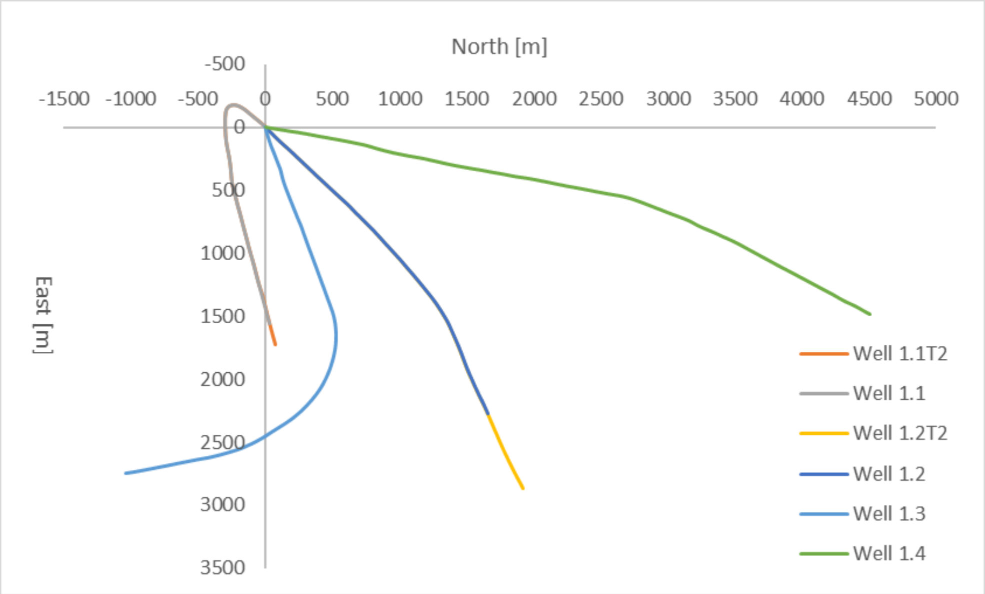

Figure 1.1: Wellpaths for the different wells

1.3 Wired Drill Pipe

The Wired Drill Pipe Network started as a commercial product back in 2007. The product is capable of delivering a very high bandwidth telemetry from the BHA tools, as well as being capable of providing sensors for measurements along the drillstring. The signal is bi-directional and works as long as the drillstring is connected to the top drive, regardless of flow or mud composition. Since its start up, it has been deployed in over 100 drilling campaigns round the world, and over 1 million feet of formation has been drilled [5].

Explained very shortly, the drillstring is connected through all joints and parts by a wire and two coils in each component all the way to the topside. The surface system is also wired through the top drive and up the service loop before the signal enters the computer interface. To be able to send a signal over longer distances, booster subs are placed at regular intervals to clear and enhance the signal. The system can provide a bandwidth of up to 57000 bps, over a thousand times faster than the traditional mudpulse telemetry system. A visual overview of the network is shown in Figure 1.2.

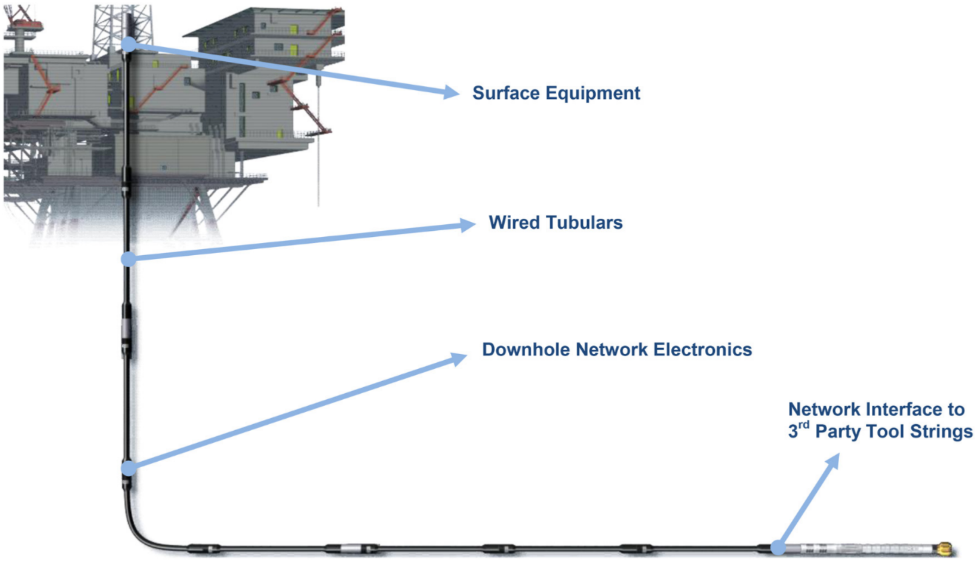

Figure 1.2: Overview of the Wired Pipe system [18]

1.3.1 System Components

All downhole components contain an armored coaxial data cable that travels along the inside of the pipe wall and through the fishneck where it is connected in each end to an inductive coil that lies inside a groove in double shouldered connections of the pipe. The drilling tubulars are conventional double shouldered tubulars that have been modified to incorporate the data cable through the length of each joint. The coaxial cable is encapsulated in a stainless steel and pressurized conduit that is in tension inside the pipe and is designed to minimize interference of mudflow and tools that are being run through the assembly.

The coils are positioned within the secondary torque shoulder and consists of a gold-plated copper wire encapsulated in a protective material which also includes ferrite to enhance the electromagnetic signal, as shown in Figure 1.3. The transmission between two components is by close-proximity electromagnetic induction, where the transmitting side energizes the coil on the receiving side and thus transmitting the signal. The close proximity induction with round coils enables a good signal regardless of the pipe orientation and can transmit signals in the MHz range without substantial attenuation [12].

To maintain the signal strength over longer distances, booster subs are positioned at regular intervals along the drillstring. These subs receives the acoustic signal, decodes it digitally, adds more data if required and retransmits the expanded

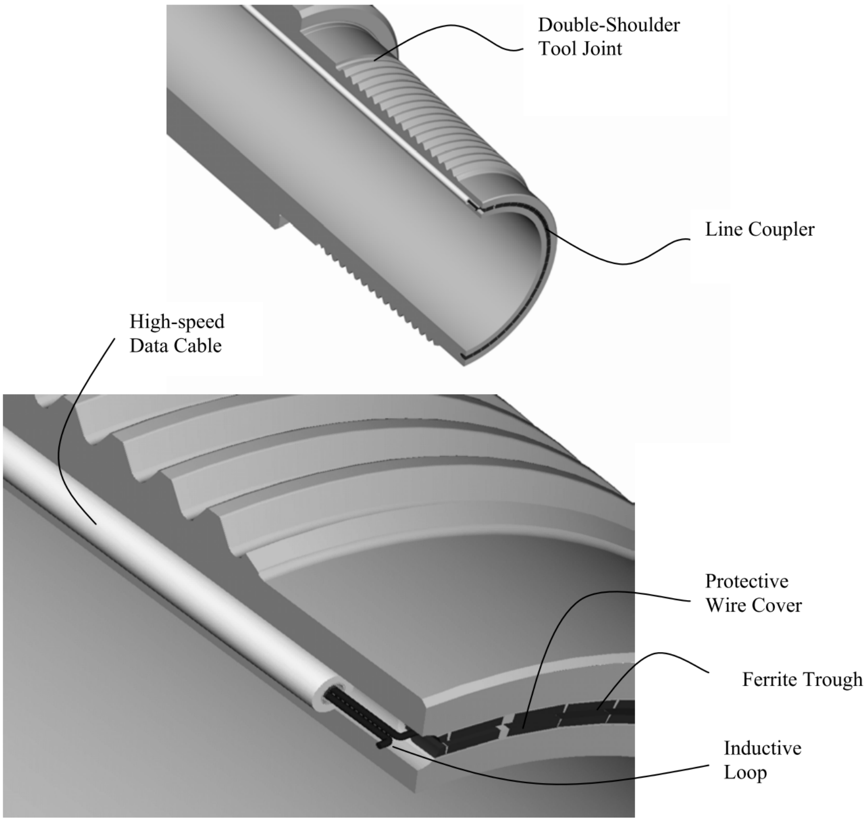

Figure 1.3: Cross section overview of the coil in pin end connection [12]

data set as an acoustic signal to the next booster sub or surface [19].

At the surface, the signal goes from rotating to static through a top drive sub, also known as a data swivel. A sub of typically 1-2 feet, where a static connector is attached to the rotating part, is installed in the top drive. Ideally it would be located straight above the saver sub, as no other top drive components would then need to be wired, but this was found to be unfeasible for development with BP. The sub was then installed above the IBOPs in the top drive, which then also needed to be wired [7]. From the data swivel, the signal is sent through a sturdy cable through the surface loop to the surface interface.

The MWD tools are connected to the WDP network through an interface sub that sits on top of the BHA. The sub can me modified to fit different companies' telemetry. For a cooperation project with Baker Hughes INTEQ, this was achieved by creating a simple protocol conversion at the BHA interface sub and again at surface. This gave a full advantage of the drillstring high speed capabilities without interference with the MWD tool capabilities, enabling mud pulse telemetry to be run in parallel with the drillstring network [18].

1.3.2 Along-String Measurements

The WDP network has enabled sensors to be placed at any location along the drill-string which will give readings as long as the drillstring is connected to the top drive. The ASM's were developed to give pressure and vibration readings in addition to be a fully functioning booster sub for the network.

The sensors included are a temperature sensor, external and internal pressure sensors, one RPM sensor by gyroscope, one axial accelerometer, two tangential accelerometers and two radial accelerometers that measures lateral vibrations.

The ASM tool has a 256 Hz sampling rate and a 0.5 Hz output rate [17]. This gives a reporting period of two seconds where up to 25 channels can be transmitted. For the accelerometers and RPM sensor, three values are transmitted per sensor for better statistical knowledge from the 512 samples that are sampled over the two seconds. For the RPM sensor, the maximum, mean and minimum value sampled are transmitted, while for the accelerometers, the maximum, mean and standard deviation are transmitted.

Visually it looks almost exactly the same as a booster sub except for a small hole in the body where the external pressure sensor sits. The sub is 71" long for both 5" and 5.5" Drill Pipe (DP).

For more technical ASM specifications, please see appendix B.

1.4 Data management

Field data in time based datasets will be the backbone of this thesis. Therefore, statistical and visual analysis are important tools to acquire insight to the effects of the SoftSpeed application.

1.4.1 Software

For initial preparation of data and statistical analysis, Microsoft Excel is the preferred software in this thesis. Excel can read and write a broad reach of formats, and has powerful tools for data compilation and analysis.

For visualization analysis, TIBCO Spotfire™ is utilized. It has an easy interface, works fast and gives many options in visual data analysis. The application has a relatively good compatibility with many database files, however it does not support the well logging standard LAS files and the data sets therefore needs to be converted into a compatible file system. This transformation is done in Microsoft Excel.

1.4.2 Statistical Parameters

For the statistical analysis, a few well known parameters will be used. The mean, the maximum and minimum values, and the standard deviation.

The mean is the sum of a list of numbers divided by the number of numbers in that list. The maximum and minimum value are the highest and lowest numbers in that list, respectively. Together they show the average value and the maximum spread in a list of numbers.

Standard deviation is used to quantify the variation from the mean for a list of numbers and is defined as the square root of variance. Variance is the expected deviation of a random number in the list from the mean, squared. This indicates how far the set of numbers are spread from the average. A large number indicates a widespread population, while a small number indicates that most numbers lies close to the mean. In a standard normal distribution, 95% of the numbers in the list would be within two times the standard deviation of either side of the mean.

2 Theory

2.1 Drilling vibrations

There are three basic forms of drilling vibrations: axial, lateral and torsional. Axial vibrations occur along the longitudinal axis of the drillstring, resulting in varying compression and tension of the string. Lateral vibrations are side to side motions of the drillstring, causing flexing and bending of components, and can also lead to shocks when components are hitting the borehole walls. Torsional vibrations are variations in rotational speed caused by resistance of rotation and release of tension. Severe vibrations in the axial direction are called bit bounce, in the lateral direction it is wl hirl, and excessive torsional vibrations are called stick-slip.

Extreme axial vibrations, or bit bounce, normally happens when using roller cone bits in hard formation. Roller cone is not used on any of the wells featured in this thesis, and this exact phenomena is not relevant. Axial vibrations may occur however induced indirectly by other forms of vibrations.

Lateral vibrations are know to be the most destructive type of vibration when the string is in a state of exited backwards whirl. Backward whirl is when the drillstring is in contact with the borehole and rotates laterally in the opposite direction of the string rotation, causing large shocks as the BHA impacts the borehole wall. Often stick-slip and backward whirl occur in combination, exciting one another [4].

2.1.1 Stick-Slip

Stick-slip is a common problem when drilling with PDC bits in long and deviated wells. It is created when the bit is exposed to a surface with a static friction larger than the initial kinetic friction of the bit, where the bit will "stick". This creates a buildup of potential energy in the drillstring which eventually will overcome the static friction and the bit will "slip". The buildup of energy in the string can lead to BHA rotation speeds typically two to three times the initial string speed when the bit slips. Besides the bit type, other factors, such as the type of formation drilled, the condition and twisting of the well path and the lubrication properties of the drilling mud can all contribute to the stick-slip occurrence [23].

Especially in deviated wellbores, torsional torque may be induced at multiple locations along the wellpath where the drillstring is in contact with the formation.

The torsional wave travels to the top drive, which is considered a fixed point, and is reflected back into the drillstring. Almost 100% of the wave energy i echoed back to the BHA, which in turn can lead to a kinetic friction lower than the static friction of the formation drilled, causing a sticking phase of the bit [8]. The torsional wave from the sticking of the bit is then transmitted to the top drive where it is again echoed back to the bit.

The stick-slip vibrations are thus self-sustaining when started and the parameters stays unchanged. The torsional vibrations can also be coupled with axial and lateral vibrations which will aggravate the potential damage. Reduced ROP, tool failure, bit wear and drillstring fatigue are all potential consequences of this phenomenon [22]. These failures can in turn lead to non-productive time (NPT) and added costs to the well.

At the surface, stick-slip is detected primarily by fluctuations in surface torque. The oscillating nature of the phenomenon will results in several large spikes that is easily recognizable. In addition to this, the MWD tools might have a stick-slip indicator and downhole rotations sensors measuring fluctuations of downhole RPM. The oscillations can last for several minutes and are damaging to drilling equipment, therefore it is important to immediately start with countermeasures.

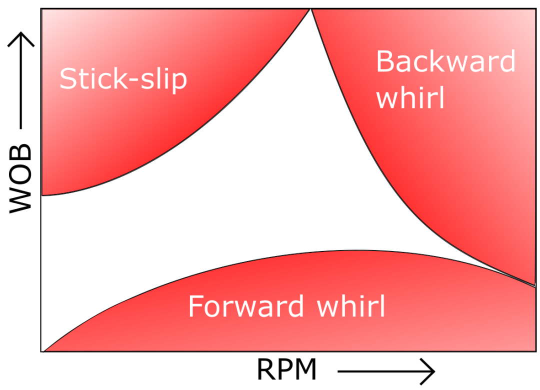

Figure 2.1: Stick-slip relations to ROP and RPM [6]

To stop stick-slip, the drilling parameters needs to be changed to break the trend. WOB and RPM can be manipulated to create a different drilling environment and stop the vibrations. Figure 2.1 shows regions of possible drillstring vibrations marked in red, and the safe drilling envelope would be in the white area. The parameters doesn't necessarily need to be changed much, but the driller needs to be careful not to induce backwards or forwards whirl that could make the situation worse. By increasing the RPM, stick-slip might be mitigated, but this is at the risk of inducing backwards whirl. The most effective solution is to reduce the WOB which will in turn reduce the overall ROP and delaying the drilling process. Sometimes it is not feasible to manipulate said parameters and still have progress. Then stick-slip needs to be tolerated and consequences needs to be taken when they emerge.

Alternative means of countermeasures for stick-slip has been researched for a long time, and the suggestion of dampening the vibrations by adjusting the top drive speed was tried and tested already in 1988 [10]. This principle has been built on since and will be discussed further in Section 2.2.

2.2 SoftSpeed

SoftSpeed is a software system that can detect and efficiently dampen the stick-slip oscillations by adjusting the top drive rotation. When the torsional wave caused by the sticking of the bit reaches the surface, it no longer gets reflected back into the string and bit, but is efficiently prevented. By adjusting the top drive rotation speed to absorb the energy of the torque peaks, SoftSpeed is able to break the trend of torsional vibrations and thus preventing stick-slip. This is done by theoretically matching the top drive rotation speed to the bit rotation speed, without the use of any down hole measurement tools. The bit rotation speed and torque is calculated by combining drillstring geometry and surface readings of the same variables [13].

A very efficient calculation model for bit rotation and bit torque has been derived and applied for the SoftSpeed software system. Inputs for the mathematical model are the top drive speed and torque, a simple model of the drillstring and the inertia of the mechanical system. Values for downhole rotation and torque can be calculated at any location in the well this way [13]. The advantage of this calculation model is that it is only dependent on drillstring dynamics and ignores non-linear effects such as lithology, hydraulics and drag in the wellbore [22].

As the torque readings at surface are noisy due to a combination of torsional and axial forces and several other influences by frictions in the well, the mathematical model aims to filter out the noise in order to be able to calculate what actually happens on bottom. The drillstring is seen as a linear transmission line for torsional waves, where the torque is proportional to the twist rate. Contact friction between the drillstring and the walls of the well is not linear, but is estimated to be linear around the mean of the rotation speed as long as it is above zero. Same approximation is made to the contact friction of the well fluids, except in the case of zero rotation speed where the friction will vanish [13]. By using this more advanced model, the higher order stick-slip oscillations can be filtered out to give a better approximation of the bit torque and give better feedback to the software and in turn the top-drive.

The software is simply put a tuned PI controller for the top drive rotation speed where the P and I factors are chosen to efficiently dampen the stick-slip oscillations. The P-factor controls the angular momentum, or rotational impedance, of the drive and the I-factor controls the torque, normally given indirectly by dividing the P-factor with a time integration constant. The speed controller of the top drive is normally set to keep a steady RPM at any cost, achieved by setting the P-factor high, causing the drive to act rigidly. In order to incur damping of stick-slip oscillations, the top drive impedance must be set closer to the impedance of the drillstring which is normally much lower. In an example of typical top drive settings and 5 inch drill pipe, the drillstring impedance was only 2.4% of the top drive impedance [14].

The activation of the software results in stepped changes of the P and I factors of the speed controller, which in turn is causing a dynamic variation of top drive speed. The variations are intended to be of opposite phase of the torque variations in order to effectively dampen the stick-slip oscillations [13].

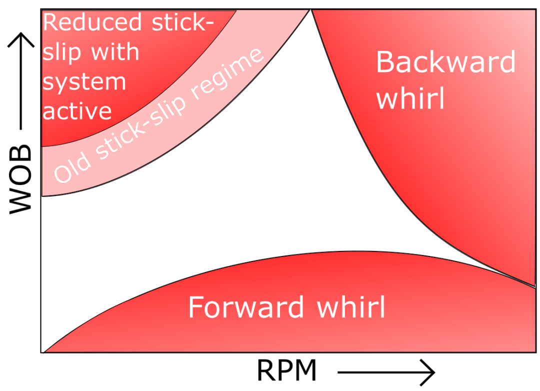

Figure 2.2: Stick-slip relations to ROP and RPM with SoftSpeed active [6, 8]

SoftSpeed effectively extends the possible operational window for drilling, making it possible to drill with a higher WOB and RPM than without the application, as illustrated in Figure 2.2, which results in a higher ROP.

2.2.1 Stick-slip severity index

The stick-slip severity index (SSS) is an output value from the SoftSpeed system which indicates the degree of stick-slip at the bit. Having this parameter makes it easier to determine the severity of stick-slip downhole and make appropriate actions.

The equation for SSS (1) uses the downhole bit speed calculated by the advanced mathematical model and relates it to the mean surface rotation speed. More oscillations downhole leads to a higher stick-slip index. 100% is defined as full stick-slip, meaning that the bit oscillates between 0 and 200 RPM, while having a mean RPM at surface of 100. In severe cases, the percentage can be up to 200-300%, but for simplicity a maximum of 100% is displayed. The equation uses a running average with a 30 seconds recursive window for the surface RPM [9].

$$SSS = \frac{\sqrt{2LP \cdot (\Delta RPM^2)}}{RPM_{avg}} 100\% \tag{1}$$

SSS Stick-Slip Severity index: 0-100%

2LP Low pass filter, ignoring higher modes of vibration

ΔRPM Downhole delta speed (= maximum peak − mean average speed)

RPM_{avg} Average surface RPM over last 30 seconds

2.2.2 System operation

SoftSpeed can be installed on many drilling rigs, depending on their top drive specifications. The system requires accurate and fast feedback of the top drive rotation speed and torque and the possibility of controlling them. It can be installed either as a standalone interface, as an integrated part of the PLC in a NOV top drive with a separate operator screen, or completely integrated into the top drive system such as Cyberbase and Amphion with full control from the drillers screen [16]

The system has two operation modes; The analyzer mode, which is on all the time, and the prevention module which is activated on demand. By activating the prevention module, the system can use the input data and modulates the top drive to effectively dampen the stick-slip oscillations.

The drillers screen may be equipped with a stick-slip indicator to alert the driller of stick-slip. The screen consists of a stick-slip severity plot to see how the stick-slip has developed over time, the instant bit speed estimate to give an impression of the downhole stick-slip motion, and a traffic light to give a quick indicator of the severity. When the stick-slip severity index is below 30%, a green light will show to indicate smooth drilling state. When it is over 70%, the traffic light will become red and an alarm will go to the driller. In between 30 and 70% is the yellow light [14].

For more specifications of the stick-slip system, please see Appendix A.

2.3 Performance parameters

To be able to see the efficiency of the SoftSpeed application, certain parameters will be looked into more closely. A typical parameter of drilling efficiency is the ROP, which will show how fast the drilling is progressing. However, this parameter does not look into the amount of energy that goes into the progress and therefore has limited usage in terms of displaying a difference in drilling efficiency. Another parameter that will be looked into is the MSE, which takes into consideration more factors regarding the amount of energy that goes into drilling a hole.

2.3.1 Rate of Penetration

A common value used for drilling efficiency is ROP and it is normally given in meters per hour or feet per hour. Basically, it is the speed of the drilling operations that is given and it is often the most used performance factor in reporting of wells.

Technically, ROP is the partial derivation of time over drilling depth (2) and can either be derived based on depth increments or time increments.

$$ROP = \frac{\delta z}{\delta t} \tag{2}$$

The accuracy of the output value depends of the depth or timespan over which it is derived, as well as the accuracy of the data and type of data sets. The output value may be adjusted further for presentation- or calculation purposes. More on this in Section 3.2.

ROP Rate of Penetration $[m/hr]$

z Depth $[m]$

t Time $[hr]$

2.3.2 Mechanical Specific Energy

MSE is a better measurement of drilling efficiency. It is a measure of how much progress you get from all your input energy. Most often ROP is limited to a certain limit in drilling operations due to factors such as hole cleaning, log quality or decision making time for geo-steering operations. Thus, ROP is not a good performance factor when the drilling is easy, as it will be limited to the maximum allowable speed. MSE takes all the input factors into account and gives a value of how efficient the drilling really is in all types of conditions.

$$\text{Specific Energy} = \frac{\text{Input Work}}{\text{Volume Excavated}} \tag{3}$$

The definition of MSE was derived by Teale in 1965 [21]. He defined specific energy for a bit as the work required for the bit to move rock divided by the volume of rock excavated (3). The work is done by the thrust and torque, in the axial and torsional direction respectively, which can be written as the pushing force times the penetration rate, in axial direction, plus the rotational energy in torsional direction ($Fu + 2\pi NT$). The volume of rock excavated can be written as the area of the bit times the penetration rate ($A_b u$).

The accepted industry standard is an output in psi or ksi while using the factors as described below (4). 120π is a simple unit conversion which includes 60 minutes/hour and 2π radians/revolution [1].

$$MSE = \frac{F}{A_b} + \frac{120\pi NT}{A_b u} \tag{4}$$

MSE	Mechanical Specific Energy [psi]
F	Weight on Bit [lbf]
A_b	Area of bit [in^2]
N	Rotation speed [1/min]
T	Torque [ft-lbf]
u	Penetration rate [ft/hr]

The input factors in the available datasets are not equal to those used for the equation (4). Therefore, the formula needs to be adjusted accordingly:

Table 2.1: Conversion factors for MSE calculations

Parameter	Input unit	Output unit
MSE	1 psi =	$\frac{1}{1000}$ ksi
F≡WOB	1 tonne =	2205 lbf
T	1 kNm =	737.6 ft-lbf
u≡ROP	1 m/hr =	3.28 ft/hr

After all the transposing factors have been taken into account, the equation will look like the equation below (5).

$$MSE = \frac{2.20 \cdot \text{WOB}}{A_b} + \frac{27.0\pi \cdot \text{RPM} \cdot T}{A_b \cdot \text{ROP}} \tag{5}$$

MSE	ksi
WOB	tonne
A_b	in^2
RPM	min^{-1}
T	kNm
ROP	m/hr

2.4 Bit grading

The drill bit is an excellent indicator of how the hole condition has been. Stick-slip and excessive drilling vibrations are impact drivers for wear on the drill bit, in addition to the formation and force subjected from above.

After every run, the bit is graded when it arrives the surface. The grading tells how worn the bit is, where it is worn, what kind of wear and what the reason for the bit being pulled up is.

A standard for classifying drill bits has been developed by the International Association of Drilling Contractors (IADC) in conjunction with the Society of Petroleum Engineers (SPE). Roller cone and PDC bits are differentiated by separate classification systems. The standard provides a uniform way of systematically evaluating and describing the bit after each run, assessing if it is fit for further service or not.

All bits used in this thesis are PDC bits, and the IADC dull grading for fixed cutter bits are explained in this section based on the revision from 1992 [2].

CUTTING STRUCTURE				B	G	REMARKS	
INNER ROWS	OUTER ROWS	DULL CHAR.	LOCATION	BEARINGS / SEALS	GAUGE 1/16"	OTHER CHAR.	REASON PULLED
				X			

Figure 2.3: The IADC classification system for fixed cutters bit [2]

The first four categories describe the cutting structure of the bit and main location of wear. There are multiple rows of cutters on a PDC bit, and the first column represent the amount of wear on the inner rows of cutters. The scale is linear and goes from 0-8 measured across the cutters surface. 0 means no wear and 8 means no usable cutters left, while 4 means 50% wear. The average value from all cutters is recorded. Same type of grading goes for the outer rows of cutters.

The dull characteristic depicts the main physical change of the bit. Two letters are written in this box, chosen from the following characteristics:

BF Bond Failure
BT Broken Teeth/Cutters
BU Balled Up
CR Cored
CT Chipped Teeth/Cutters
DL Delaminated Cutters
ER Erosion
HC Heat Checking
JD Junk Damage
LM Lost Matrix
LN Lost Nozzle
LT Lost Teeth/Cutters
NO No Dull Characteristics
NR Not Rerunnable
PN Plugged Nozzle/Flow Passage
RO Ring Out
RR Rerunnable
WO Washed Out
WT Worn Teeth/Cutters

Location describes the area of the main physical change on the bit, and may include:

A All Areas
C Cone
G Gauge
N Nose
S Shoulder
T Taper

All fixed cutter bits are denoted by an "X" in the bearings and seals section. For roller cone bits, this section would describe a 0-8 scale for the wear on non sealed bearings or, for sealed bearings, "E" for effective seal and "F" for failed seal.

The gauge space is used to record the condition of the bit circumference. If the bit is the same size as when it entered the well, "I" is recorded for "in gauge". Otherwise, the amount of undergauge is recorded down to the nearest 1/16". "1" is denoted for 1/16" undergauge, "2" for 2/16", etc.

Other dull characteristics may be used to record secondary evidence of bit wear and the same list as primary dull characteristics is used. This section may be used to describe the bit as a whole, such as using "erosion", or it may describe the cause of the primary physical change of the bit.

The last space is used to record the reason why the bit was pulled out of hole:

BHA	Change Bottomhole Assembly
CM	Condition Mud
CP	Core Point
DMF	Downhole Motor Failure
DP	Drill Plug
DSF	Drill String Failure
DST	Drill Stem Test
DTF	Downhole Tool Failure
FM	Formation Change
HP	Hole Problems
HR	Hours on Bit
LIH	Left in Hole
LOG	Run Logs
PP	Pump Pressure
PR	Penetration Rate
RIG	Rig Repair
TD	Total Depth/Casing Depth
TQ	Torque
TW	Twist Off
WC	Weather Conditions
WO	Washout - Drill String

3 Data handling

The data sets used in this thesis are time-based data with one second intervals delivered in the well log standard LAS, version 3. Both surface data and downhole data are represented in the same log. There are several known challenges to handling time based data sets, such as null values and outliers, which will be remedied and explained in this section. Performance parameters will be calculated in order to study the effect of the SoftSpeed application. The ultimate goal is to achieve accurate and user friendly data that represents the reality of the drilling environment.

3.1 Preparation of data

In order to open the data in the visualization software, the data sets needs to be converted into a readable format. The LAS file can be converted into a CSV file by using Microsoft Excel. The difference in the presentation is easily mitigated by assigning the top cell of each column with the curve information found in the LAS header. The top row needs to be the title of the curve in CSV file format, and therefore the rest of the data in the LAS header needs to be deleted.

The data sets are limited to a certain size when using Microsoft Excel, with a maximum of 1048576 rows by 16384 columns. Each row represents one second, and therefore one data set is limited to contain roughly twelve days. Each column represents a curve, so there should be no problems in exceeding the allowable limit in that aspect.

The units of each curve is defined in the curve information

3.1.1 Removing "null" values and outliers

A null value is a value used to signify that a specific data-point does not have a valid measurement. Normally, the two values -999.25 (for floating numbers) and -999.00 (for integer numbers) are used [15]. Where null values occur in the data-set, the visualization of the curve will be seriously disturbed and it is therefore better to remove them altogether.

Several large spikes in the curves, known as outliers, were present in all the data sets. These are false reading and needs to be removed. The values are unrealistically high and surpasses all other data-points in the entire data set and can therefore be easily deleted by setting an upper limit to the data-set and deleting all values over the threshold. Cleansing the data in this way removes about 80% of the wrong values [11].

It is important to utilize the appropriate techniques when handling such large amount of data in Microsoft Excel. In order to remove the null values and outliers, the software needs to go through over 100 million data points in the largest data sets and delete up to several million cells. The integrated search function in Excel is not capable of deleting cells above a threshold and is slow and cumbersome to boot. In order to successfully filtering out undesirable values within an acceptable time frame, two macro scripts were programmed. The script utilizes arrays and goes through all cells within a set range and replaces all cells equal to or larger than a set value [20].

As the null value was predefined, the aim of the script was to delete all values equal to -999.25. However, the threshold for the outliers needed to be found and analyzed before deciding upon a value. Most outliers had a reading surrounding 45000, but some extended up to 150000. The highest real values in the datasets were found to be pressure readings in kPa up to 27000. A limit of 30000 were then set, deleting all values exceeding that limit.

The macro scripts can be found in the Appendix C.

3.1.2 Drilled depth check

The depth is a very important factor in analyzes and therefore it is important to check that the depth is correct. There are two depth references in each data set; the current bit depth and the total accumulated depth.

First and foremost, the accumulated depth must never decrease when drilling in the same section. Any values of decreasing depth will lead to negative ROP values and must therefore be fixed. One instance of decreasing depth was found and corrected in the data handling.

Holes in the depth data must be filled. Due to a unit shutdown during drilling of one of the wells, there was a 2 hour hole in the drilling data. As a consequence of the shutdown, 2 meters of formation was drilled ahead before the driller was notified and could pull off bottom. This was fixed by filling in 2 meters of roughly the same ROP as the previous data had.

Another issue was a sudden jump in the depth that occurred during a connection. Sometimes during drilling, the depth is set to match the pipe tally as the depth sensor rarely is exactly accurate. The depth may be set to the wrong stand, or more commonly the depth is set at a bad time, typically when the block is moving during connection and the system has not been set into in slips mode. The depth was changed back by the data operator, but it was not fixed in the data set. The sudden increase and decrease of depth led to huge spikes in the ROP calculations, and the false depth readings were replaced by the correct depth.

3.2 ROP calculations

ROP is a good performance value for drilling and is also a necessary factor in the MSE calculation (4). The aim for this section is to find the best possible ROP estimation for the time-based datasets. Well 1.3 comes with a ROP curve included in the dataset which will be used for comparison.

The calculations are all done in Microsoft Excel where a new column is added, making it possible to both present it visually and to further use it in analyses and MSE calculations. As the datasets are time based in one second interval, the ROP will also be updated every second.

3.2.1 Formulas for time based and depth based ROP

The formula for calculating ROP is given in equation (2) in Section 2.3.1. There are two parameters, time and depth, and both can be used as basis in the derivation in order to achieve an estimation of the ROP.

Creating a basic formula for time-based ROP is quite simple in a time based data set. Deriving the depth increment over a set time interval Δt will give a calculated ROP (6). As the dataset is based on seconds, the equation needs to be multiplied with 3600 to make it hour based.

$$\mathrm{ROP}(t) = \frac{z(t) - z(t - \Delta t)}{\Delta t} \tag{6}$$

The formula for depth based ROP is very similar in appearance, however now the time increment for a set depth interval needs to be derived (7). In the time based data sets used in this thesis, the depth measurements are not accurate enough to produce a new depth value for every depth increment and it is rarely exactly Δz in between two depths. Therefore the closest value to Δz must be found and used as basis for the calculation. A formula for Excel that accomplishes this is shown in Appendix D.

$$\mathrm{ROP}(z) = \frac{\Delta z}{t(z) - t(z - \Delta z)} \tag{7}$$

Since the depth based ROP only reacts to increased depth, a stop in the drilling process will not be noticed, and the previously calculated value will be broadcast until a new depth value has been reached. When a new depth is registered, the time to the previous depth value over Δz will be long, and subsequently the ROP will be low. This leads to false values after connections and other times the bit is off bottom, and perhaps most importantly it gives a delay in new ROP values until drilled depth has passed Δz after the break.

In well 1.3, the dataset came with a ROP value for the system, which was used as reference to develop the correct formula for ROP in Excel. Figure 3.1 shows the calculated time based ROP derived over 30 seconds and the calculated depth based ROP derived over 1 meter in comparison to the system ROP curve over 10 minutes (600 data points). Different intervals will be explored in later section, but for initial research the time based ROP will be derived over 30 seconds, and the depth based over 1 meter.

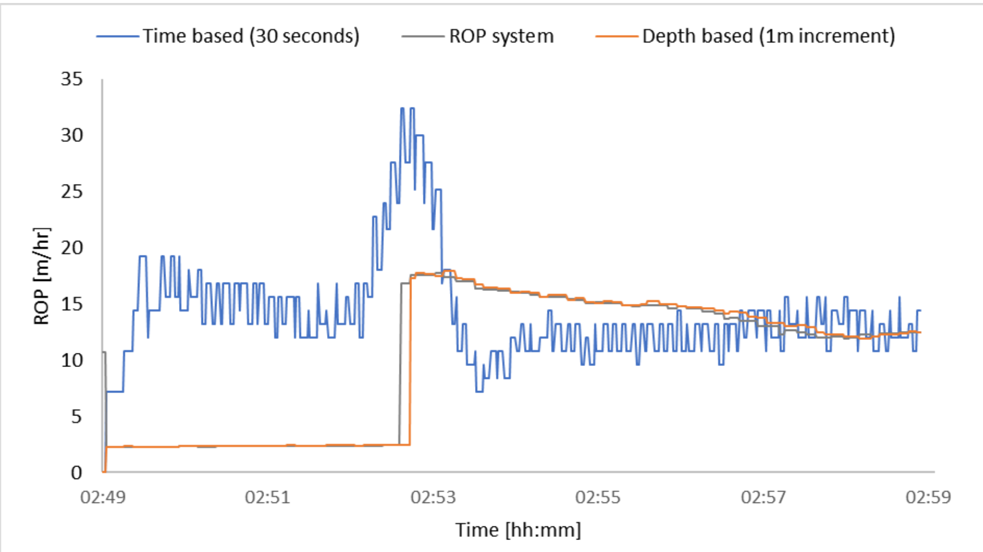

Figure 3.1: ROP calculated over a 10 minutes interval compared with system value

It is obvious that the ROP curve taken by the system is one meter increment depth based, as the calculated curve follows the one from the system closely. The curve starts right after a connection, and the delay in updated ROP values is clearly visible. After 1 meter of new formation is drilled, the depth based curve suddenly jumps to a much higher value.

The calculated depth based ROP is a little bit off the system ROP in Figure 3.1. For the rest of the curve, they are quite similar and the formula shown in Appendix D works well enough for initial analyses.

The time based ROP is clearly more noisy, and it also fluctuates much more. However, the fluctuations may not be such a bad thing if the actual ROP of the time is represented better. The noise in the signal may be mitigated for visual and practical reasons in post processing. After all, the aim of this exercise is to achieve accurate measurements in order to get accurate statistical data and correct MSE calculations.

3.2.2 Exponential smoothing of ROP curve

The values for the calculated time based ROP may be right, but they don't look good visually due the noise in the signal. To smoothen the curve, a good way is to use exponential smoothing which is a common technique for time series data. The calculated smoothened value S_t uses a smoothing factor α to weigh the relevance of the raw time data x_t to the previous value in the new smoothened curve S_{t-1}. A lower value for α gives less weight to the previous recorded value in the raw time series and produces a smoother curve, but with some delay in response to changes. The simplest form of exponential smoothing is given in (8) [3, p.101]. As the exponential smoothing technique always base on the previous value in the smoothened series, the first value in that series shall be the corresponding value in the raw time series; $S_0 = x_0$.

$$S_t(x) = \alpha x_t + (1-\alpha) S_{t-1}(x) \tag{8}$$

The time based ROP calculation made in previous section can be seen in Figure 3.2 with different smoothing factors (α) of 0.2, 0.1 and 0.05. The effects of the exponential smoothing are clearly visible, resulting in a smoother curve. Lower α

results in a smoother curve, but also in a larger time delay caused by changes in trend due to the low weight on previous observations. Higher α results in a shorter time delay, but with more noise visible in the curve.

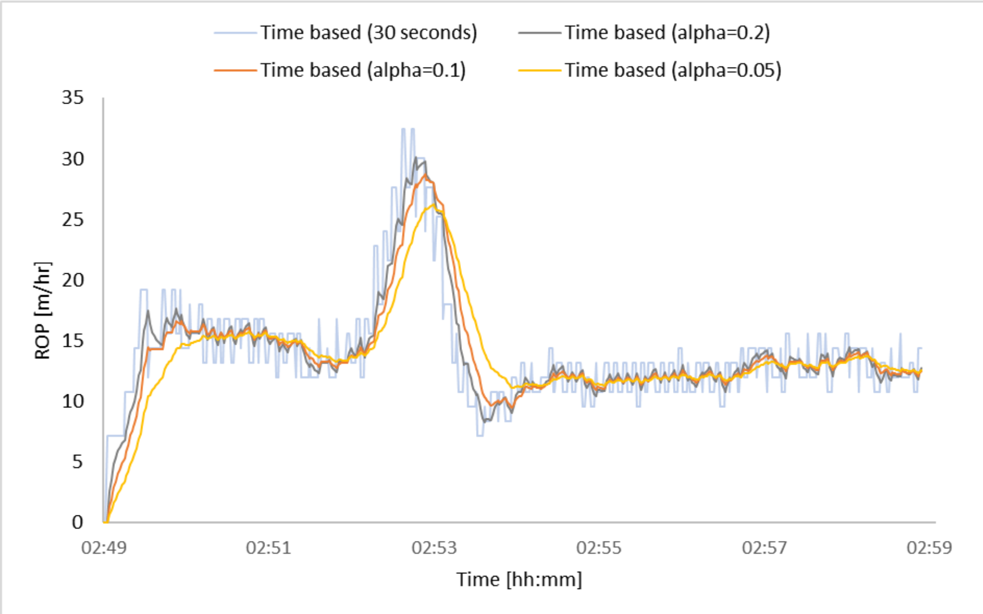

Figure 3.2: Time based ROP with different smoothing factors

3.2.3 Calculate actual ROP and compare

In order to determine which of the depth based and different time based ROP estimations is the best, all the on bottom drilling data from well 1.3 was compiled. Presuming that the depth achieved during the time from start to finish of an on bottom drilling period will provide the actual ROP, an average ROP from each drilling period was calculated by dividing the progress by the time. All in all, 185 different drilling periods were defined, ranging from two minutes to two hours.

Depth based (1m increment), time based (30 seconds) and system ROP were calculated for the entire well in separate columns. From the same time periods as for the actual ROP, the average of these values were extracted to be compared to the actual ROP.

Figure 3.3 shows the distribution of the different ROP calculations and the actual ROP. This way, the different time intervals cannot be compared directly against each other, but it provides an image of how they are distributed. There is a clear anomaly in this comparison, which is the depth based ROP. It contains much more occurrences of lower ROPs than both the actual and the time-based. The distribution of the time-based ROP looks similar to the distribution of the actual ROP.

Figure 3.3: Distribution of different ROP intervals for actual ROP derived, depth based and time based ROPs

In order to compare each drilling period to each other, a relative difference between the actual and the calculated ROP in question was assembled for all drilling time periods. The difference was measured from the actual ROP in percentage deviation. All values were weighted to one hour increments, making the deviation of a small time interval weigh less than the deviation from a large time interval.

The results of the comparison is plotted in Figure 3.4, where the x-axis is the number of drilling segments and the y-axis marks the deviation from the actual ROP. Statistical values of the comparison can be found in Table 3.1.

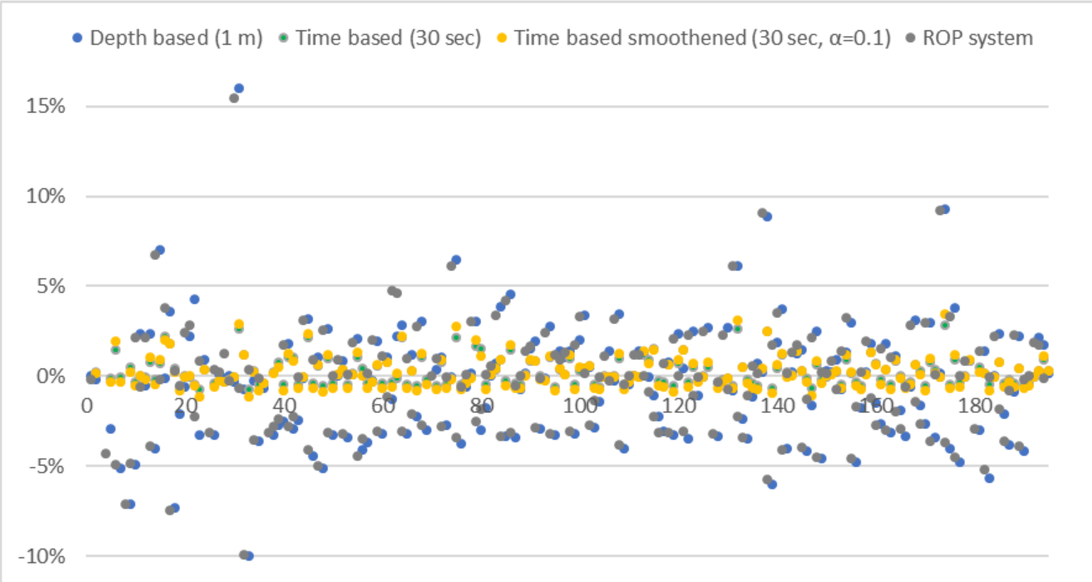

Figure 3.4: The difference from the calculated ROP values to the actual values

Just by looking at the graphical distribution in Figure 3.4 it is clear that the time based estimations lies closest to the actual ROP derived. The depth based estimations are much more widespread, something that is also reflected in the statistical values presented in Table 3.1.

Table 3.1: Statistical values of the ROP comparison

	Depth based (1m increment)	Time based (30 seconds)	Time based smoothened	ROP system
AVG	-0.19 %	0.24 %	0.17 %	-0.14 %
STDEV	3.70 %	0.78 %	0.94 %	3.63 %
MAX	26.71 %	2.90 %	3.53 %	26.33 %
MIN	-9.99 %	-2.23 %	-1.97 %	-9.96 %

AVG Average calculated ROP value compared to actual

STDEV Standard Deviation of the ROP values compared to actual

MAX Highest positive deviation from calculated values to actual

MIN Lowest negative deviation from calculated values to actual

3.2.4 Exploring different intervals for time based ROP

For all time based ROP calculations in the earlier sections, an interval of 30 seconds has been applied. In this sections, other time intervals will be explored to see if there is a better approximation than the initial approach. By using smoothing techniques in post processing, there are opportunities to experiment with input factors that would not be possible in real time.

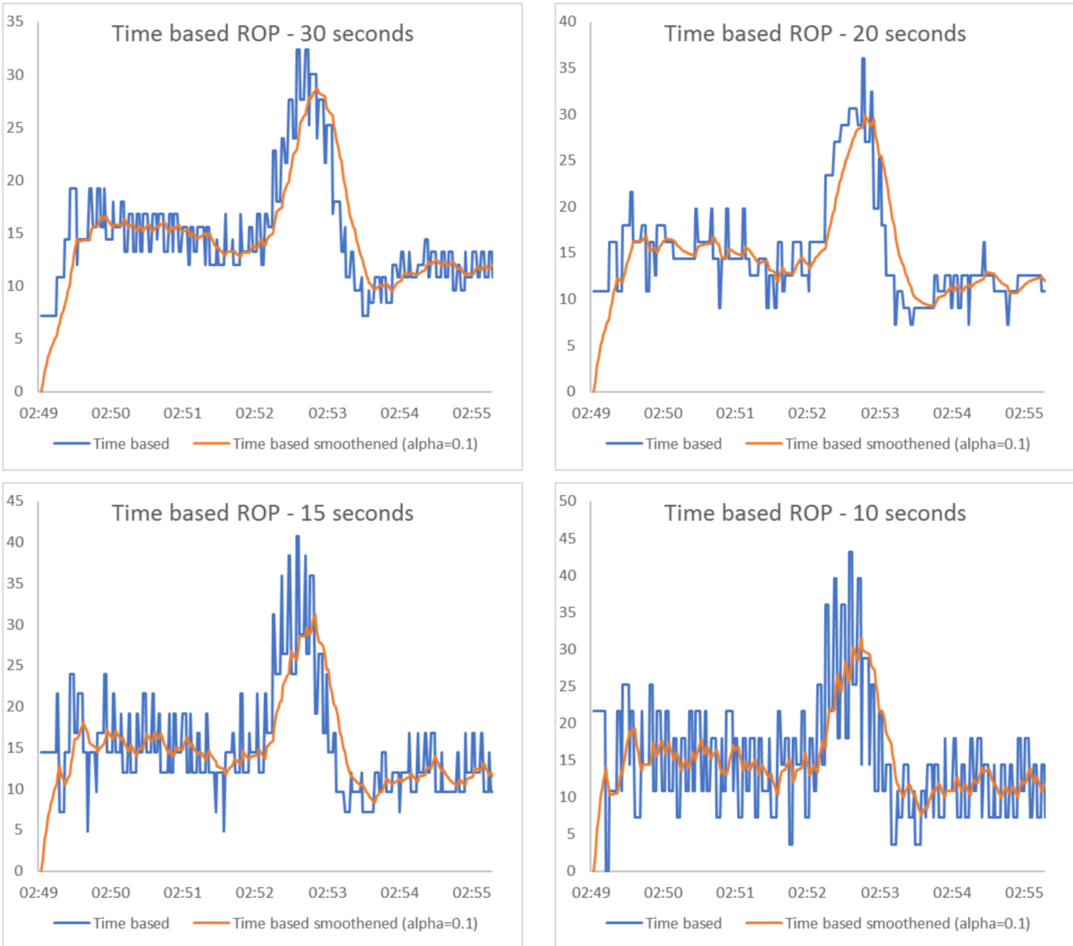

Figure 3.5: Time based ROP curves of 10, 15, 20 and 30 seconds interval with smoothing factor 0.1

Figure 3.5 shows four different time intervals for the time based ROP and the corresponding smoothened curve with a smoothing factor of 0.1. Notice how the noise levels goes up when the time interval gets shortened. However, the smoothened curve seems to diminish the differences and creates similar looking trajectories.

Table 3.2 shows the statistical values for the different time based calculated ROP values compared to the actual values that was obtained in Section 3.2.3. The differences between the intervals are small, but it may be noted that even if the average value escalates slightly as the time interval decrease, the standard deviation and variance declines by shorter time intervals. The difference, however, is not large by any means, and all approximations seems good by looking at the statistical data.

Table 3.2: Statistical data from different increments in time based ROP compared to actual ROP

	AVG	STDEV	MAX	MIN
Time based ROP				
10 seconds	0.33 %	0.65 %	2.50 %	-2.53 %
15 seconds	0.30 %	0.68 %	2.50 %	-2.47 %
20 seconds	0.27 %	0.71 %	2.59 %	-2.39 %
30 seconds	0.24 %	0.78 %	2.90 %	-2.23 %
Time based smoothened ROP (alpha=0.1)				
10 seconds	0.24 %	0.77 %	2.81 %	-2.27 %
15 seconds	0.22 %	0.81 %	2.97 %	-2.19 %
20 seconds	0.20 %	0.85 %	3.15 %	-2.11 %
30 seconds	0.17 %	0.94 %	3.53 %	-1.97 %

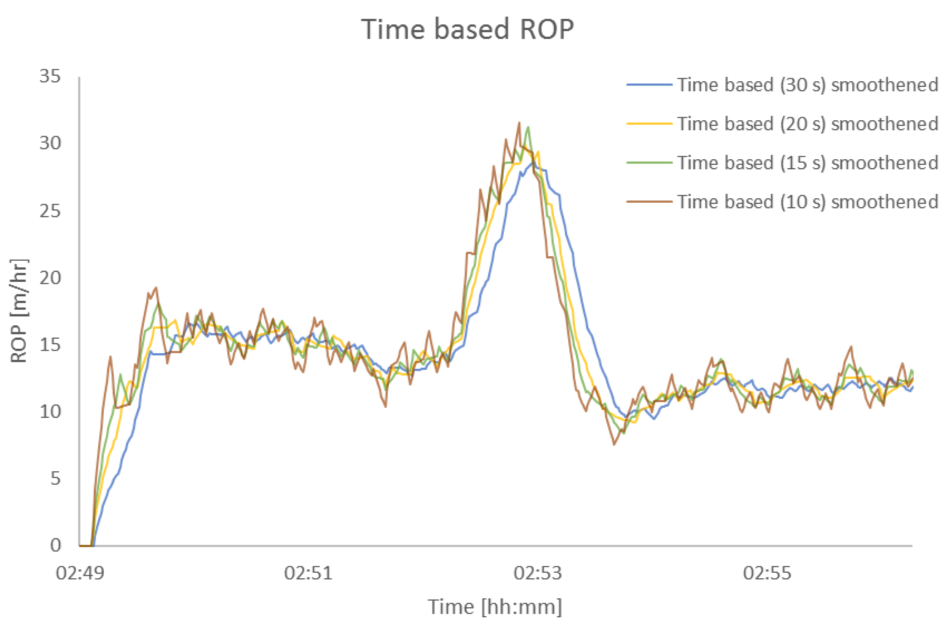

Figure 3.6: Comparison of different intervals for time based ROP

In Figure 3.6 the four different ROP approximations with smoothing factor 0.1

are shown in the same plot. As mentioned earlier, the values will have a slight lag depending on the time interval they have been derived over. There is not much difference when the curve is even, but at periods of increasing and decreasing ROP, the longer time interval is lagging behind.

3.2.5 Exploring different increments for depth based ROP

Depth based ROP gives a smoother representation of the progress, but the 1 meter interval seems to be too much smoothness compared to the time based ROP curve. Figure 3.7 shows the depth based ROP curve for 1, 0.5, 0.2 and 0.1 meter right after a connection on the same time interval as the curves above. It is clear that decreasing the depth increment makes the curve more susceptible of changes in depth, and it seems to get closer to the time based curve. However, there is still a lag in the beginning of the stand, only shorter, and the curves are crude.

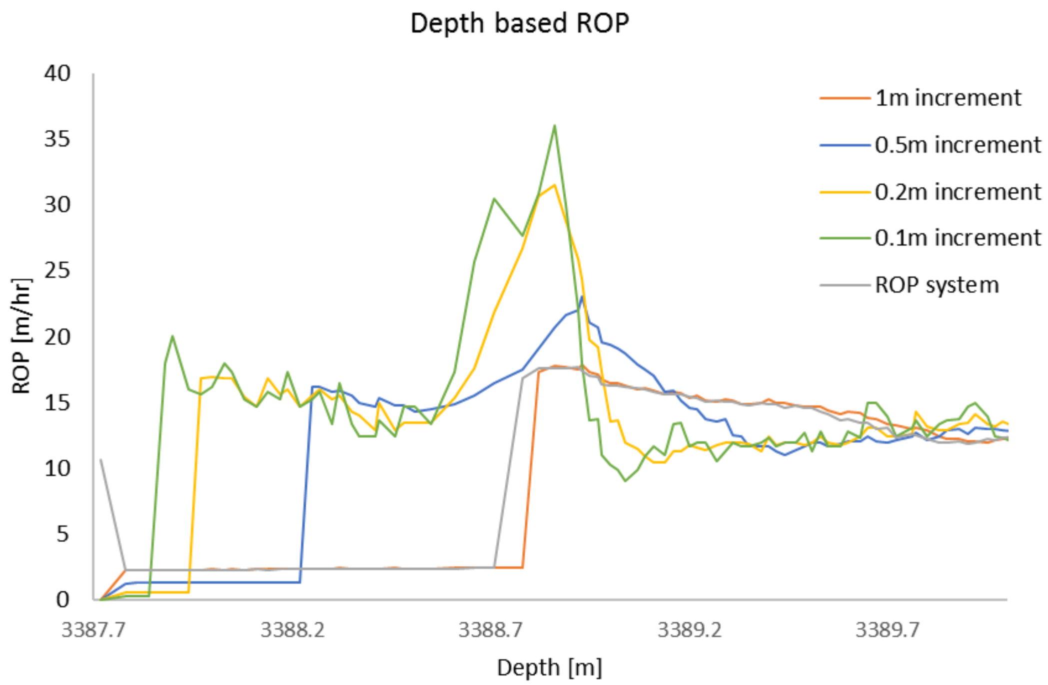

Figure 3.7: Comparison of different depth based ROP intervals

Same statistical analysis as above was conducted on different depth based ROP calculations. All drilling intervals were compiled and the actual ROP from each time interval was compared with the average value of the depth based ROP for the same interval. The difference was then listed and statistical values from that list of

185 drilling periods can be found in Table 3.3.

Table 3.3: Statistical values of depth based ROP compared to System ROP

	ROP system	Depth increments 0.1m	0.2m	0.5m	1m
AVG	-0.14 %	2.34 %	1.40 %	0.62 %	-0.19 %
STDEV	3.63 %	3.87 %	3.11 %	3.26 %	3.70 %
MAX	26.33 %	42.06 %	29.87 %	28.77 %	26.71 %
MIN	-9.96 %	-1.12 %	-1.82 %	-5.25 %	-9.99 %

3.2.6 Discussion around best ROP estimation

Time based ROP may not look as good on a graph, and it may be noisy due to the nature of the data set, but it is not because of the presentation the ROP needs to be calculated. It is primarily for analyses and the MSE calculation that an accurate ROP needs to be calculated. And the ROP needs to be exact in order to trust it as a performance factor in itself. Regarding the presentation of the curve, the worst noise can be fixed in a data set post processing by exponential smoothing or a longer time interval can be chosen.

Analyses above show that the time based ROP is a much better representation of actual ROP than depth based. The average values are much closer to the actual value in the time based calculations than they are in the depth based. The standard deviation from the actual ROP are also much lower, as well as the total deviation.

The depth based ROP system has serious flaws. One is that it cannot recognize zero values if the bit stands still, as the value will only update if there is any depth increment, and thus the ROP will be stuck on the last value before the bit stopped. These false values may be removed by an off-bottom filter, but that requires one extra step. The next flaw is a big one, namely that there will be a lag in ROP values when drilling finally commences after a break. This will occur at least every connection and if drilling needs to be stopped mid stand for other purposes. This will create a series of false values, both for ROP and MSE.

The time based ROP calculations are much closer to the actual ROP achieved than the depth based. Even the 30 seconds recursive window for the time based calculation was better than the best depth based approximation. For performance calculations, both in MSE and a performance factor in itself, the time based ROP will be preferred.

For the following analyzes, the 10 second interval ROP will be used. That approximation shows least deviation from the actual ROP and it has the least lag in updating. As the ROP will be used to indicate on-bottom periods in many drilling analyses, it is important to have a short lag. The raw curve will be used in analyses considering average values while a smoothing factor of 0.1 will be applied in a separate column to be used for visual analyses.

3.3 MSE calculations

Mechanical Specific Energy (MSE) is a good way to see drilling efficiency as the calculation (4) takes into account all the input energy in the drilling process. In short, the parameter indicates how much energy goes into creating a hole at any given time.

3.3.1 Set-up in Excel

For simple MSE comparison in Excel, a column needs to be added to implement the calculations based on formula (5). Columns for ROP needs to be added first. As a trial, both depth based and time based calculations were implemented to compare the effects of the different approaches. Depth based over 1 meter and time based over 10 seconds was included in the initial analysis.

Surface measurements from the top drive is used to describe the torque, force and rotation of the bit. These measurements are not equal to the forces experienced at the bit, but it is the only feasible method to use when no special tools are implemented to monitor these parameters.

In order to see the distribution of MSE estimations at different intervals, the values throughout the entire well was compiled in "bins" ordered by magnitude and by SoftSpeed on or off.

3.3.2 Discussion of ROP estimation with MSE calculations

The whole exercise in Section 3.2 was to provide a ROP value to be used in MSE calculations. In this section, the two ROP estimations will be compared in a MSE analysis covering the entire well and compare the average values.

Two columns of calculated MSE values were made in Excel, one with time based ROP and one with depth based, and the average value of MSE with SoftSpeed on and off was calculated for both. The results are shown in Table 3.4.

Table 3.4: The average MSE value for calculations made with depth based and time based ROP

Avg MSE values with	SoftSpeed ON	SoftSpeed OFF
Depth based ROP	328.3 ksi	483.7 ksi
Time based ROP	361.4 ksi	355.6 ksi

When looking at the depth based ROP, it seems like SoftSpeed has a huge impact on the amount of energy used while drilling. By using this approximation, the energy is reduced by over 30% with the application in use. But when time based ROP is applied in the MSE calculation, there is not much difference at all.

By looking closer to the distribution of the MSE with depth based ROP, as shown in Figure 3.8, it looks like there are more high and fewer low values of MSE with SoftSpeed off than it is with the application on. However, when looking at the calculations made on the time-based ROP, that is not the case.

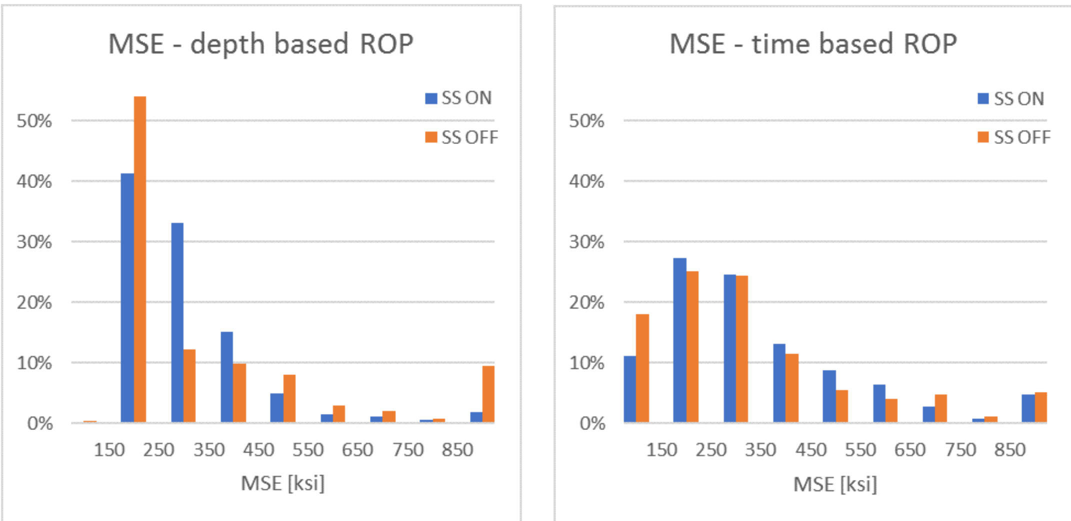

Figure 3.8: MSE values for depth based and time based calculations

The issues with depth based ROP not responding well to starting drilling after a break has been discussed earlier and a low ROP will produce a high MSE value as it is the denominator in the fraction (4). In Figure 3.9 the average ROP values for the given MSE intervals are shown as dots, and for the depth based ROP it is clear that the average value is low when the MSE values are high. However, the time based ROP shows the opposite, that the high MSE values correspond to a relatively high ROP average.

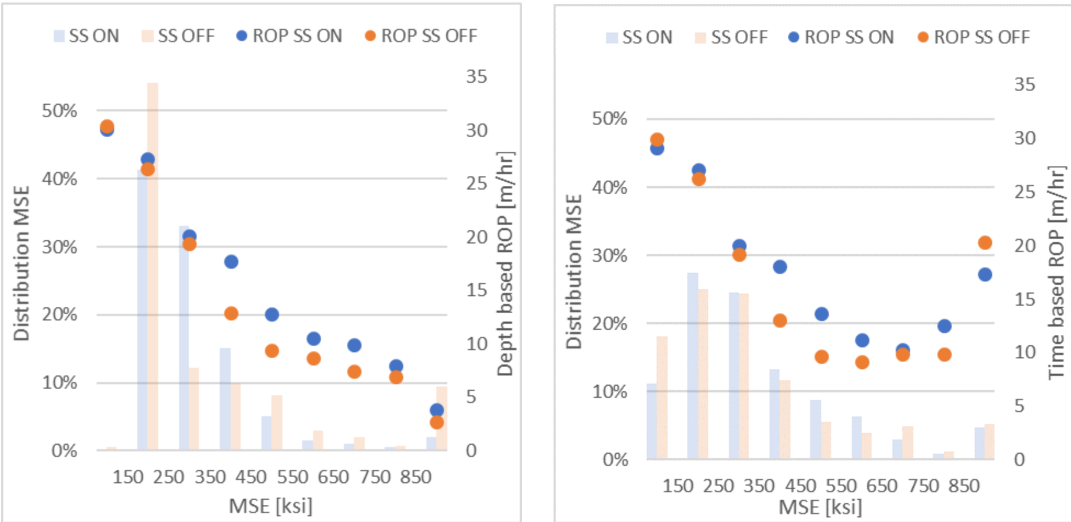

Figure 3.9: MSE values and ROP values for depth based and time based calculations

It was clear from earlier that the time based ROP is the best estimation, but here the consequences of using the supplemented depth based ROP from the data set becomes evident.

3.4 Stick-slip calculations

A way to quantify stick-slip from the ASM measurements should be developed in order to see the effect of the SoftSpeed application locally in the drillstring. Again, the dataset from well 1.3 will be used as this contains values for stick-slip severity. The ASM RPM shall be used as basis for the calculation.

3.4.1 Using ASM RPM to indicate stick-slip

As mentioned in Section 2.1.1, stick-slip can lead to drillstring speeds of two to three times the initial string speed. The RPM data from the ASM can therefore be used as a good stick-slip indicator. As mentioned in Section 1.3.2, there are three output values of RPM data, a max value, a minimum value and a mean value out of the 256 Hz sampling rate within the 2 seconds sampling window. By using these three values, an approximate estimation of how much rotation force the ASM was subjected to at the string location can be made in similar fashion as the stick-slip severity index described in Section 2.2.1.

While equation (1) denotes dRPM as the difference between the mean and maximum reading, both the maximum and minimum reading from the ASM will be used in this equation (9). That means the equation should be divided in two to achieve similar result. The mean from the surface RPM will be used as denominator, also here. There will be no low-pass filter and therefore no square root. All parameters in the equation are average values from a 30 seconds recursive window in same fashion as (1), creating a smoother curve. The equation used in Excel can be found in Appendix D.

$$SSS_{ASM} = \frac{RPM_{Max} - RPM_{Min}}{2 \cdot RPM_{surface}} \cdot 100\% \tag{9}$$

3.4.2 Discussion around validity of ASM stick-slip approximation

An example from Spotfire of the given SSS curve from SoftSpeed with the calculated SSS curve from (9) is given in Figure 3.10. The created equation follows the SSS estimation from SoftSpeed very well on higher values, but are far above on the lower SSS values.

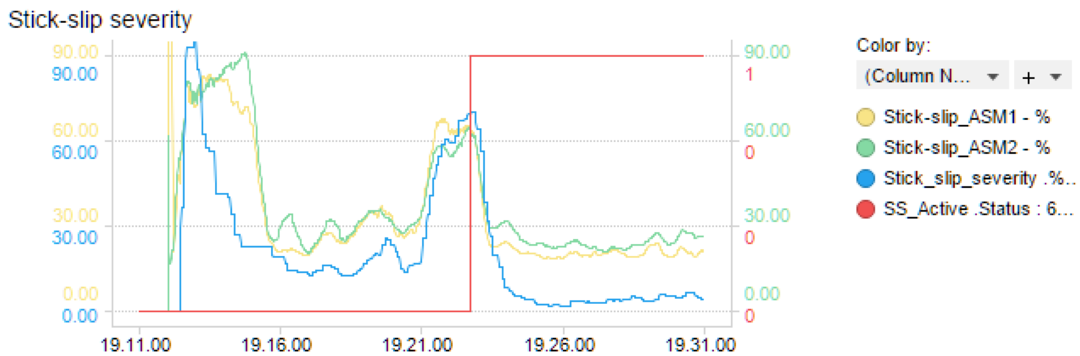

Figure 3.10: Comparison between the SoftSpeed calculated SSS curve and the created ASM SSS curve

In Figure 3.11 the SoftSpeed SSS spectrum from well 1.3 and the calculated

ASM approximations are compared. Below 1% and above 29% is not included in the analysis, but these two intervals only represent 0.9% of the total population. Linear regression is applied in Excel, showing a very good determination coefficient for both approximations.

The bit is the basis for the SoftSpeed calculated stick-slip severity index. ASM1 is only 62 meters behind, while ASM2 is 1050 meters behind. The figure shows a linear relationship between ASM SSS and the SS value with a fairly good confidence. ASM1 shows the best correlation, which is expected since it is located closest to the bit.

The exact relation between the two approximations is not important, but it is important to know that it exist. Having the SSS estimation from the ASMs enables a stick-slip index that can be used in all wells as basis for comparison.

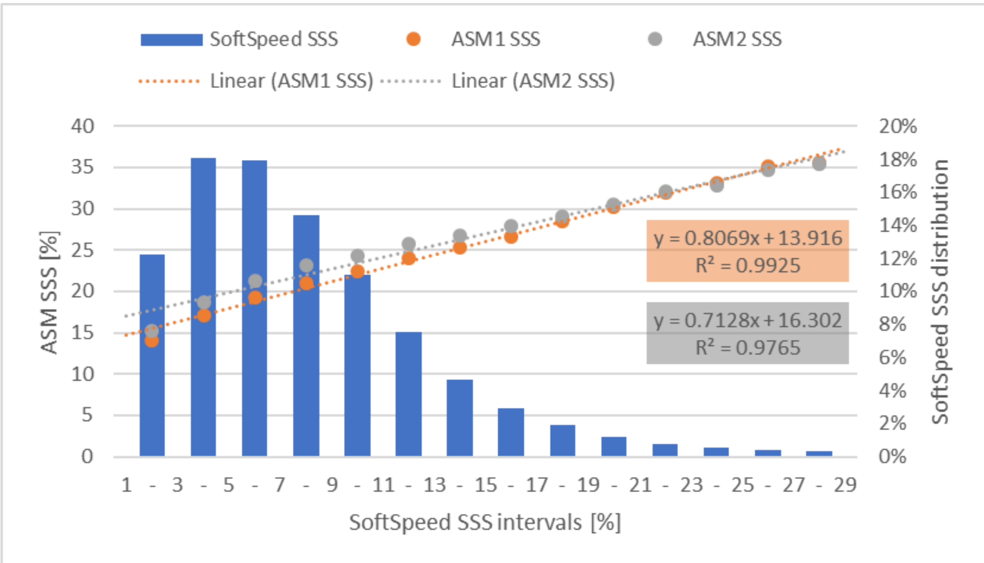

Figure 3.11: The correlation of SoftSpeed SSS with calculated ASM SSS

3.5 Statistical presentations

All statistical presentations will only contain on-bottom values. In time-based datasets, there will be present data while the bit is off bottom which includes weight, rotation, torque and vibrations, amongst others. Rotation is generally started prior to going on bottom with the bit. This leads to vibrations in the string, often substantial, but without weight and therefore with less energy. These vibrations will not be included in this thesis.

All wells will be presented in a similar fashion. First, some general data will be provided from the well. Note the offset of the ASMs, as this indicates the location of the SSS readings. As mentioned earlier, ASM1 is closest to the bit and will represent stick-slip and drilling vibrations which are closest to what is experienced at the bit. Average values of ROP, MSE and SSS indicates the general performance and conditions experienced in the well.

Secondly, surface data and calculated performance values will be presented over the length of the well, where the values plotted are the average values over 50 meters intervals. This is done in order to be able to present the data in an orderly fashion without too much noise. Note that two axes are used and that two types of values are plotted in the same axis on one side.

Next, the distribution of the performance values are presented. This is done in a histogram style where all data has been compiled in bins and the magnitude of each bin represents the percentage of all values that lies within said interval. The bins are denoted on the chart by showing a common upper and lower limit to adjacent bins. The total magnitude of all bins is 100%.

The spectrum of ASM1 SSS will then be divided into a more applicable range if necessary and the influencing parameters for stick-slip (WOB and torque) as well as the consequences of stick-slip (ROP and MSE) will be derived within each interval. The intention of these graphs are to show the relation stick-slip has to these parameters.

Then, the drilling vibrations will be displayed. The graphs shows the average mean value in a 50 meter interval together with the average standard deviation that is delivered by the sensor. The standard deviation gives the magnitude of the vibrations while the mean indicates in which borehole conditions the vibrations are experienced.

Finally, a case study from an interesting section revealed by the previous graphs will be presented. Here, an area from the time based dataset will be plotted in Spotfire with several different factors. First the surface parameters together with the ROP will be plotted. Then there will be a plot showing the stick-slip severity and below a plot of the RPM which the SSS has been derived from. Oscillations are generally represented as noise in the RPM graph. At last the drilling vibrations will be presented by separate plots for mean, standard deviation and maximum values.

4 Results

An overview from all six wells will be given in this section. Well 1.1, 1.1T2, 1.2 and 1.2T2 was drilled without the aid of SoftSpeed, while well 1.3 and 1.4 did use it. The results will be presented for each well in a similar fashion, compared in the end of this section and discussed further in the next section.

All data has been processed as described in Section 3 with time based ROP calculations spanning 10 seconds and application of exponential smoothing with a smoothing factor $\alpha = 0.10$.

4.1 Well 1.1

Well 1.1 was drilled into the reservoir through the caprock while building angle from approximately 67° to 90° while slightly turning. Large amounts of stick-slip and lateral vibrations were encountered when drilling through the hard caprock, which ceased when entering the reservoir.

The reservoir consisted mainly of sandstones with clear to translucent grains which were fine to coarse in size and moderately sorted. Short intervals of conglomerates were penetrated which were poorly sorted and consisted of quartz and feldspar rock fragments. Interbedded layers of siltstone and claystone were encountered halfway through the section and onwards. In total, the section consisted of approximately 10% caprock, 67.5% sandstone, 2.5% conglomerates and 20% siltstone.

The bit penetrated into the caprock at approximately 3500 meters, and it was not possible to steer back into the hard conglomeratic reservoir. It was then attempted to do an openhole sidetrack at 3200 meters, but it was unsuccessful and the bit was pulled to be replaced.

Table 4.1: Basic info surrounding well 1.1

Section length	1400m
Section TD	3550m MD/1950m TVD
Bit hours	73.1 hrs
ASM1 offset	217m
ASM2 offset	1053m
Bit grading	1-3-CT-N-X-I-LT-BHA
Average ROP	19.4 m/hr
Average MSE	447.7 ksi
Average $ASM1_{SSS}$	49.7 %
Average $ASM2_{SSS}$	42.3 %

Table 4.1 shows basic well info and average well performance parameters. It was drilled with a relatively high ROP, but with high SSS and high MSE when compared to the length of the section. The bit grading indicates 40% wear on the outer rim cutters. They were primarily chipped, but some were also lost. The bit was mostly worn on the nose and was still in gauge.

Figure 4.1 shows the development of the surface parameters throughout the well, showing average values from 50 meters intervals of the well length. The plot shows increasing values of torque throughout the well and high WOB early and late in the section.

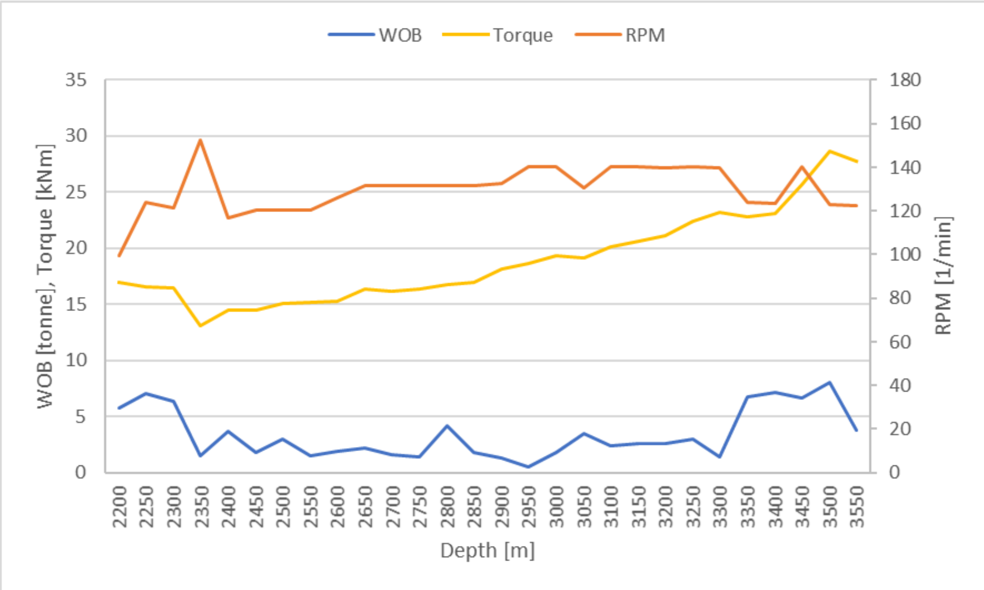

Figure 4.1: Development of surface parameters throughout well 1.1

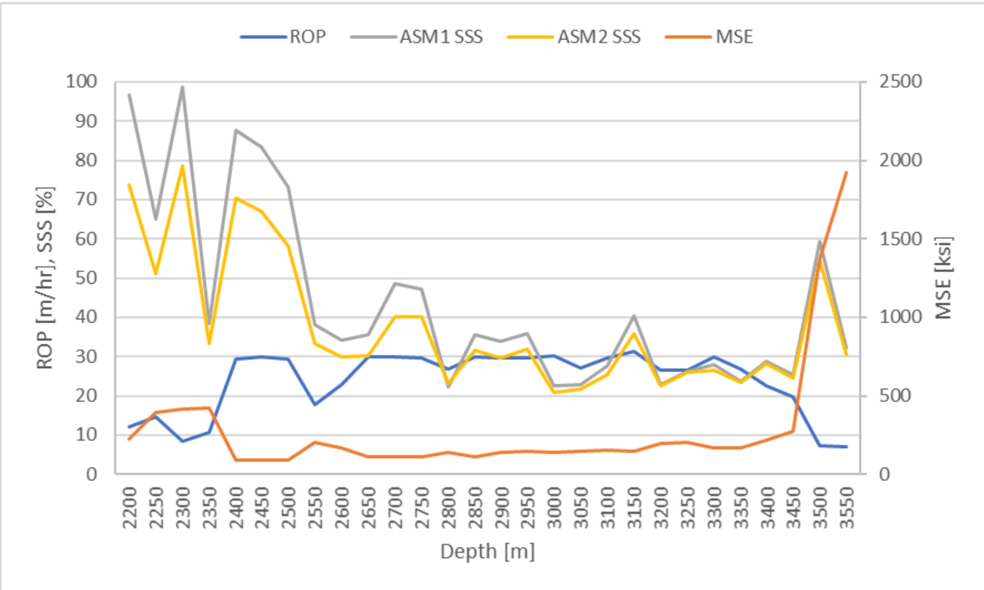

Figure 4.2: Development of performance parameters throughout well 1.1

High values of stick-slip can be observed early in the section when looking at the SSS parameters in Figure 4.2. This corresponds well to the reported stick-slip when going through the caprock. ROP was also low in the beginning, but increased when entering the reservoir. The last 50 meters shows the attempt of steering back into the reservoir after the bit went into the overlying caprock. Low values of ROP combined with high values of torque and WOB provides a very high MSE value.

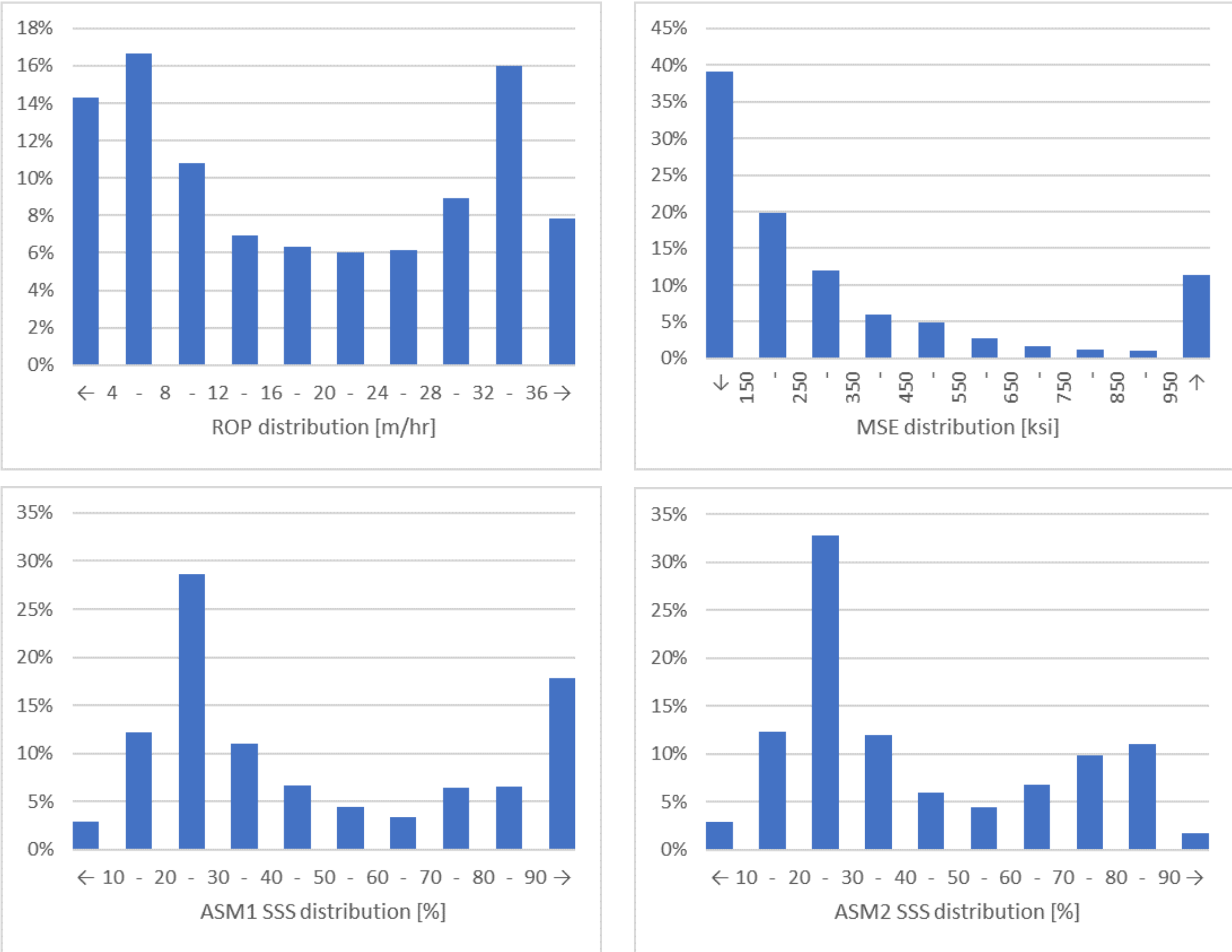

Figure 4.3: Distribution of performance parameters in well 1.1

Distribution of the performance parameters are given in Figure 4.3. These distributions are meant to give an insight in how the parameters are distributed and not only the average value. There are two main peaks for ROP, one low centered in the 4-8 ROP interval, and one high centered around the 32-36 m/hr interval. The MSE distribution is skewed towards the low end of the spectrum, but with a second higher level peak. This high MSE peak undoubtedly coincide with the high MSE seen towards the end of the section. The distribution of SSS shows that the main peak for both ASM1 and 2 lies in the 20-30% stick-slip interval. Higher modes of stick-slip are also present, and especially for ASM1 where 18% of the drilling, that is 250 meters, saw stick-slip above 90%.

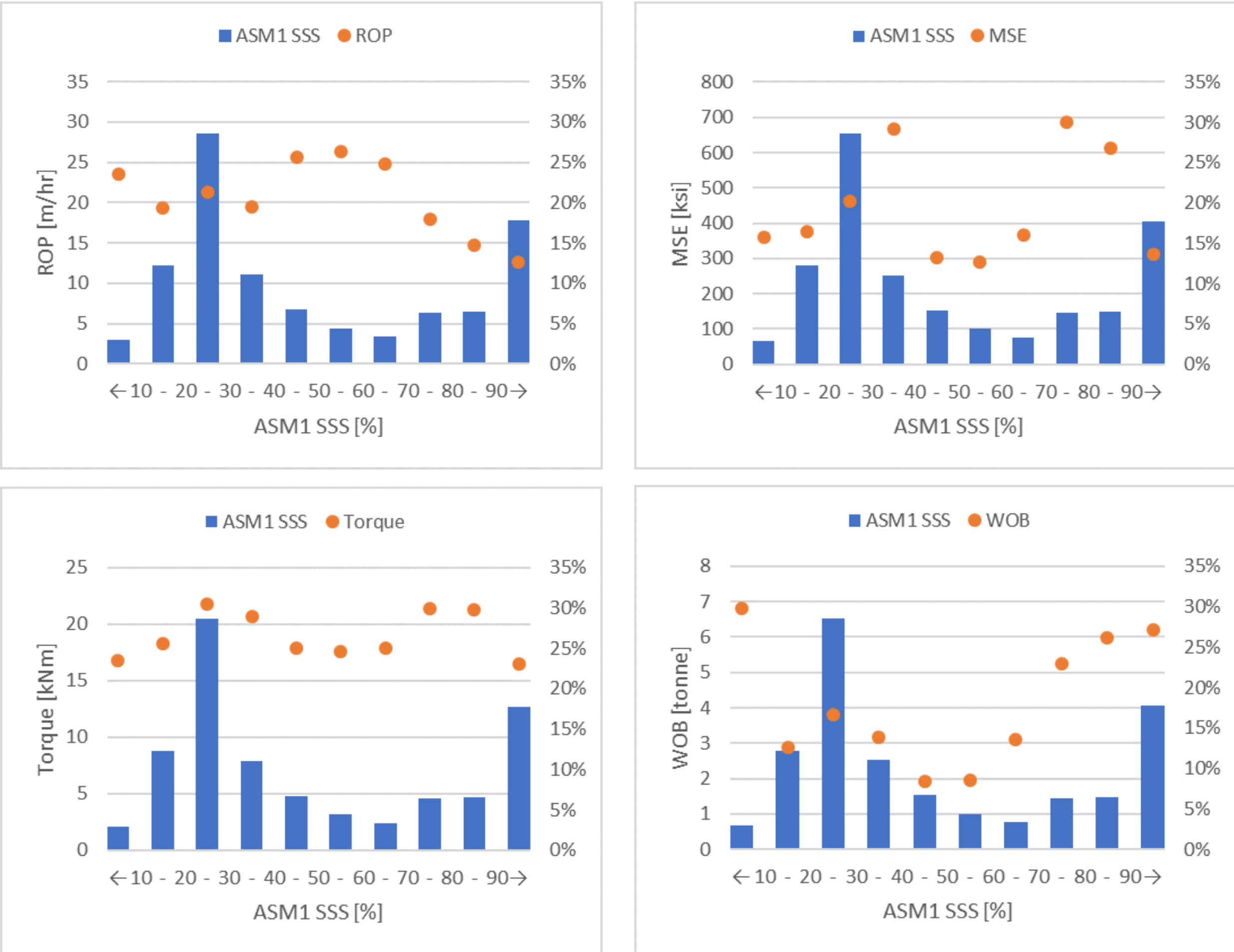

Figure 4.4: Comparison of ASM1 SSS spectrum against ROP, MSE, Torque and WOB in well 1.1

The comparison of parameters with the SSS spectrum in Figure 4.4 is meant to provide an image of how stick-slip is affected by surface parameters and how it affects the calculated performance parameters. The MSE comparison can also give an indication of the relative energy going into the hole at given stick-slip severity. What is interesting from this well is that relatively low energy goes into the hole where stick-slip is most severe. Otherwise there is a clear trend of increasing WOB and decreasing ROP as stick-slip is getting more severe.

Figure 4.5 shows the development of drilling vibrations throughout the well, also here that average values are portrayed within 50 meters intervals. The mean value is shown as a dot and the standard deviation, describing the magnitude of vibrations experienced by the sensor, are shown as error bars in the chart.

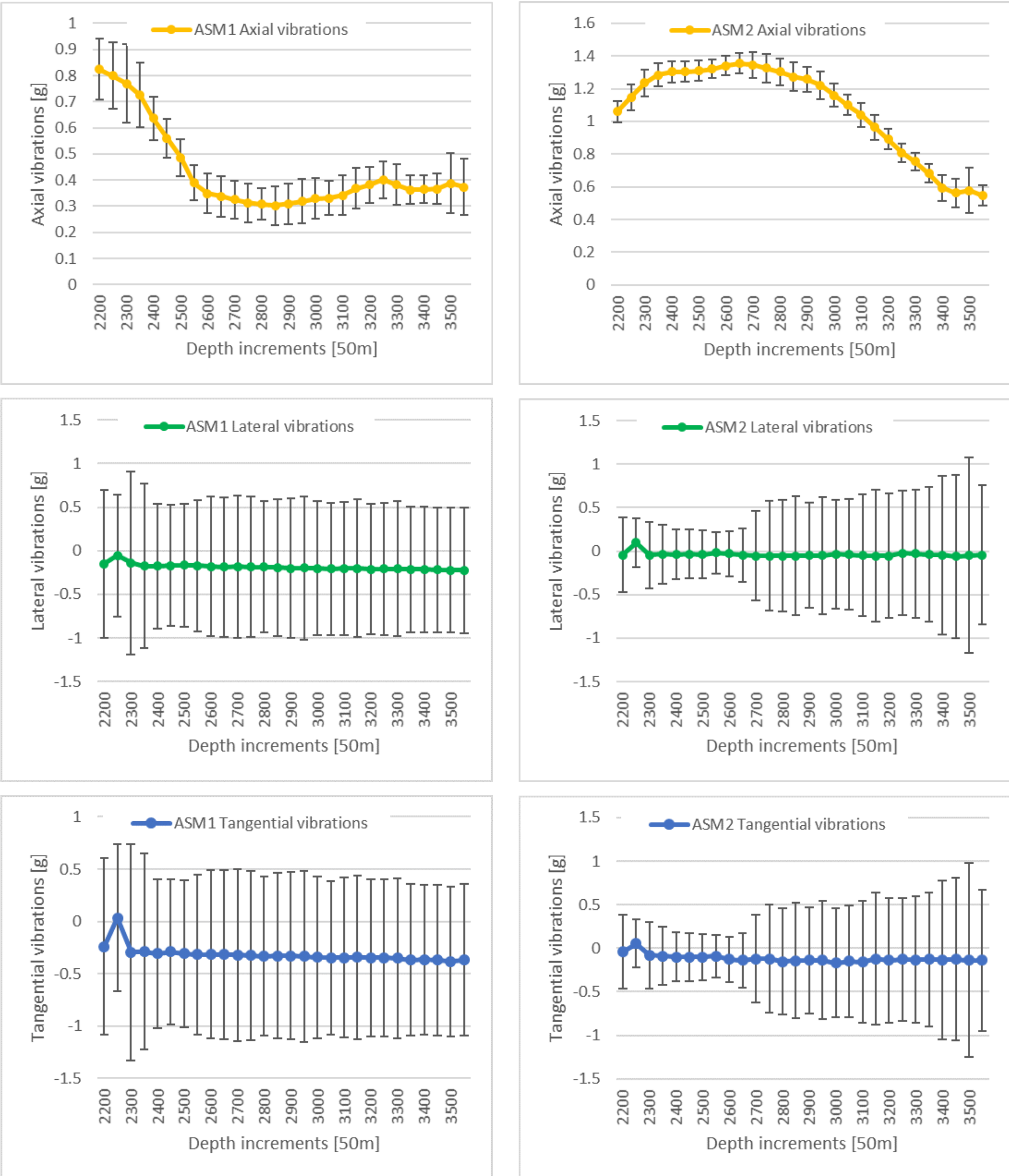

Figure 4.5: Drilling vibrations with standard deviation in well 1.1

The axial vibrations from this well, and others, are changing in magnitude throughout the length of the well. This is probably due to the wellpath experienced by the ASM sensor, and will be discussed further in Section 5.3. The magnitude of the standard deviation of lateral and tangential vibrations from ASM1 in the beginning of the well is related to the stick-slip experienced when going through the caprock. ASM2 is not subjected to these vibrations, but are experiencing larger vibrations at greater depth.

Figure 4.6: Case study from beginning of well 1.1

Figure 4.6 shows a section of time-based data from the worst vibration interval in the beginning of the well. The top plot depicts the surface parameters at this point, and it is clearly visible that there are severe torque oscialltions in the top drive, closely related to the drilling vibrations. The SSS index shows very high values, especially ASM1 which reports over 100% stick-slip. The figure of ASM RPM shows the large deviation in rotation of the string, which is the basis for calculating the ASM SSS.

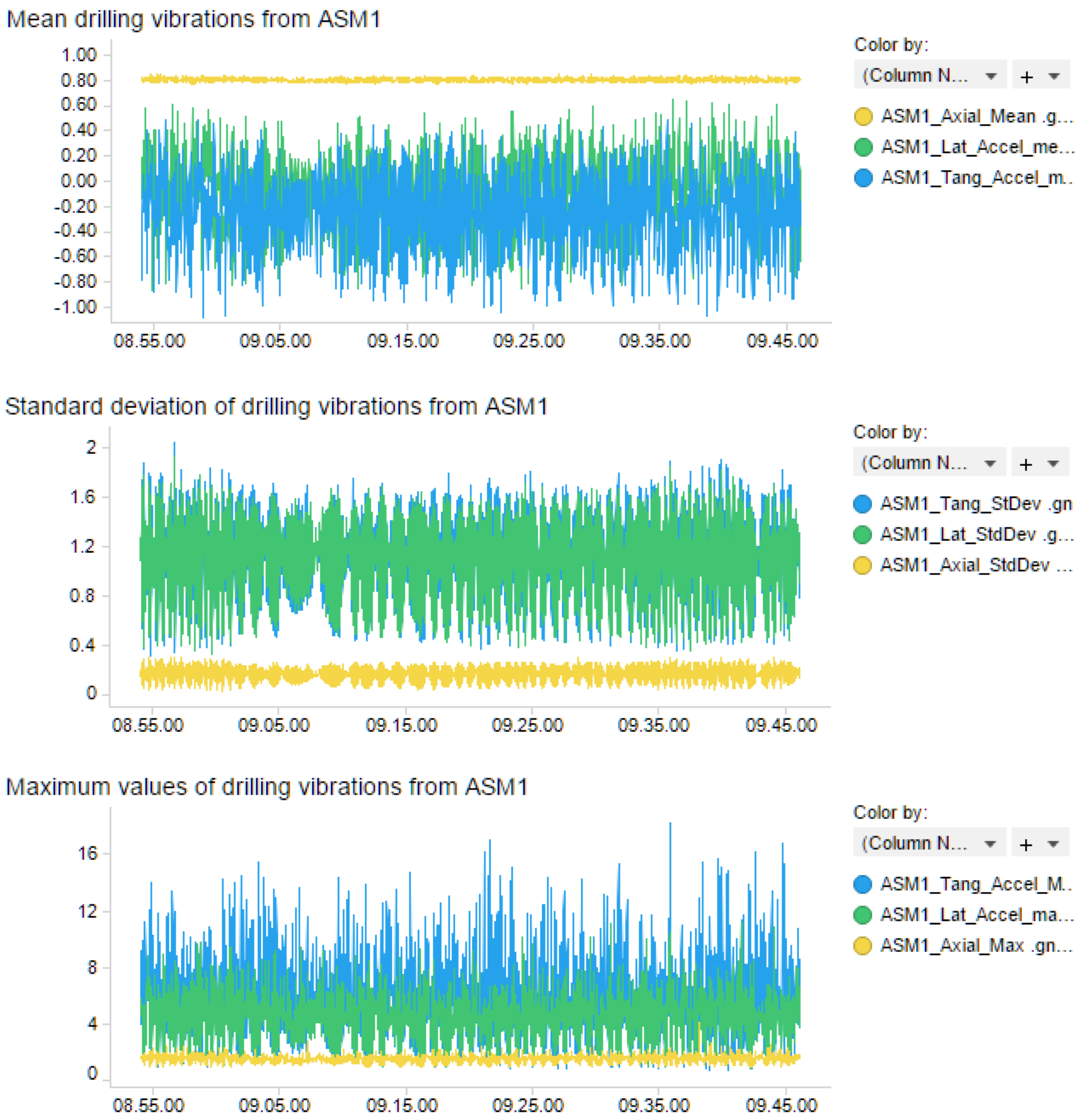

Figure 4.7: Drilling vibrations in case study from beginning of well 1.1

Figure 4.7 shows all directions of drilling vibrations from the ASM1, as this is the closest to the bit and represent the values experienced by the BHA the best. The vibrations are represented by the acceleration value of each direction and the y-axis represent gravitational forces which has the unit g where 1g=9.81 m/s^2. All vibrations oscillate to some degree, but axial vibrations oscillate the least and only shows 0.2g in standard deviation and a little higher for maximum values. Both tangential and lateral vibrations are oscillating much more, following each other closely in the standard deviations but tangential vibrations show higher maximum values.

4.2 Well 1.1T2

Well 1.1T2 is an openhole sidetrack kicked off at 3200 meters measured depth with a new drill bit. The section is horizontal with a stable trajectory without turning.

The lithology in this section consisted of approximately 40% sandstones, 40% siltstone and claystone, and 20% conglomerates. The conglomerates appeared towards the end of the section and proved very hard to drill through, decreasing the ROP and increasing stick-slip along with drilling vibrations. The conglomerate consisted of quartz and feldspar rock fragments with traces of biotite and calcite cemented aggregates. Grain size of the crushed cuttings varied from very fine to very coarse to granular.

Table 4.2: Basic info surrounding well 1.1T2

Section length	500m
Section TD	3700m MD/1950m TVD
Bit hours	30.3 hrs
ASM1 offset	225m
ASM2 offset	1061m
Bit grading	5-3-RO-N-X-0-WT-PR
Average ROP	16.9 m/hr
Average MSE	641.8 ksi
Average $ASM1_{SSS}$	52.9 %
Average $ASM2_{SSS}$	49.3 %

The length of this section is only 500 meters, as seen in Table 4.2, but it has the highest average MSE values of all wells. Average ROP is 3 meters per hour slower than the previous section and the stick-slip is at higher levels overall. The bit from this section explains the low ROPs towards the end as it is very worn. Over 70% wear on the outer rim cutters and 40% on the inner row. The cutters at the nose were completely worn down, and the bit started to be eroded on the metal body, commonly known as ring out. A picture of this bit can be found in the comparison section (Figure 4.71).

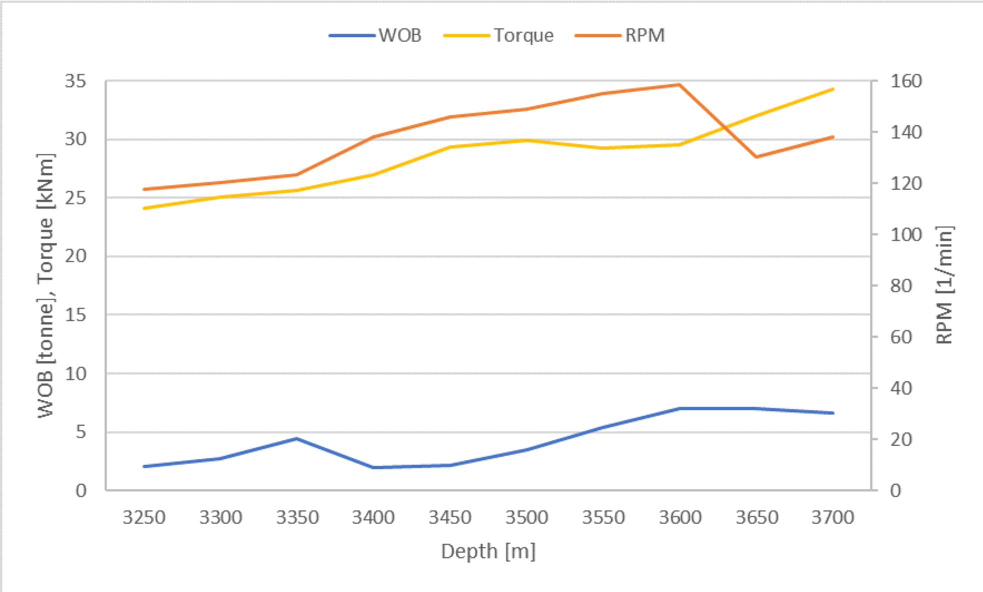

Figure 4.8: Development of surface parameters throughout well 1.1T2

The surface parameters shown in Figure 4.8 shows that very high average torque values were experienced towards the end of the well. WOB also increased when drilling through the conglomerates. The RPM used in this section is higher than what is seen in the other sections, but this doesn't need to mean much as it usually is a personal preference for each directional driller.

Figure 4.9 shows an increasing MSE and stick-slip towards the end of the well. The ROP also decreased, probably due to a combination of hard formation and worn bit. The high MSE in the beginning is most likely due to the kick off procedure as an open hole sidetrack requires slowly grinding down the formation in order to create a new hole.

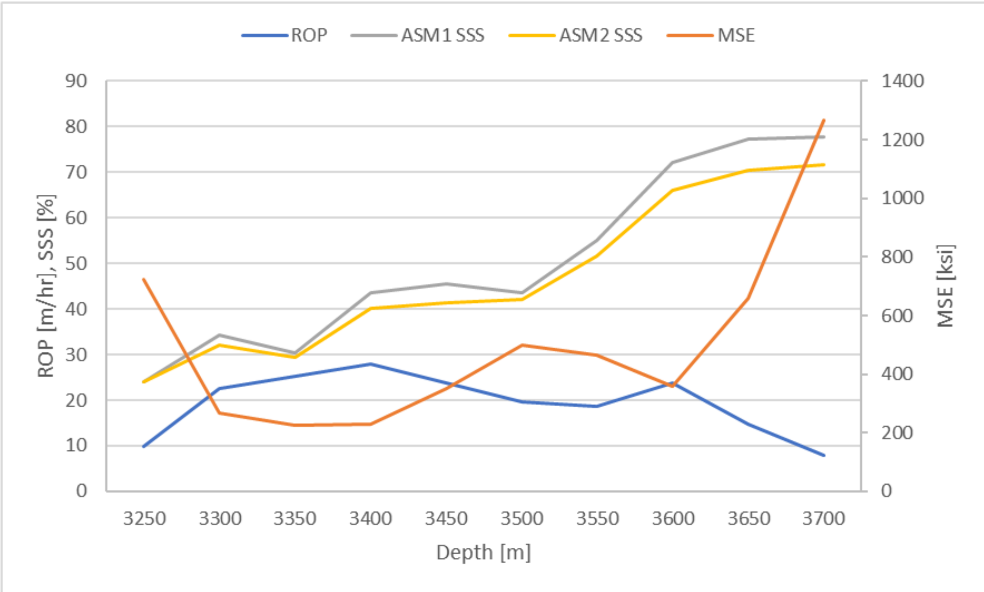

Figure 4.9: Development of performance parameters throughout well 1.1T2

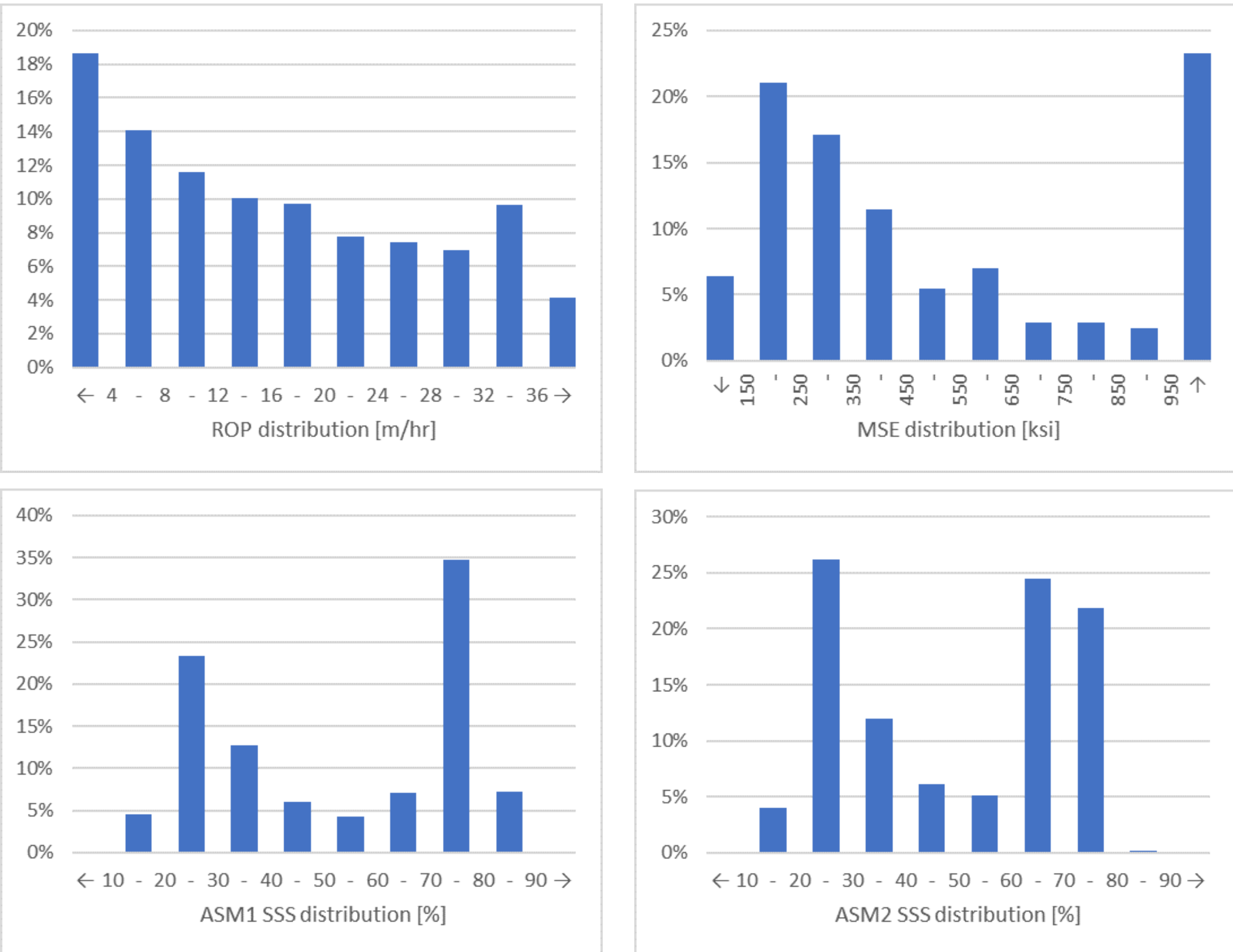

Figure 4.10: Distribution of performance parameters in well 1.1T2

The distribution in Figure 4.10 shows a relatively skewed distribution of ROP towards the low end. This also corresponds well with the peak of high MSE. The stick-slip is again bimodal, and shows higher levels of stick-slip for ASM1. Over 200 meters were drilled with stick-slip above 70%, around 40% of the total section length.

The comparison of parameters in Figure 4.11 shows that stick-slip in this instance is related to high MSE, high WOB, high torque and low ROP, which are all to be expected when drilling a hard formation which is causing stick-slip.

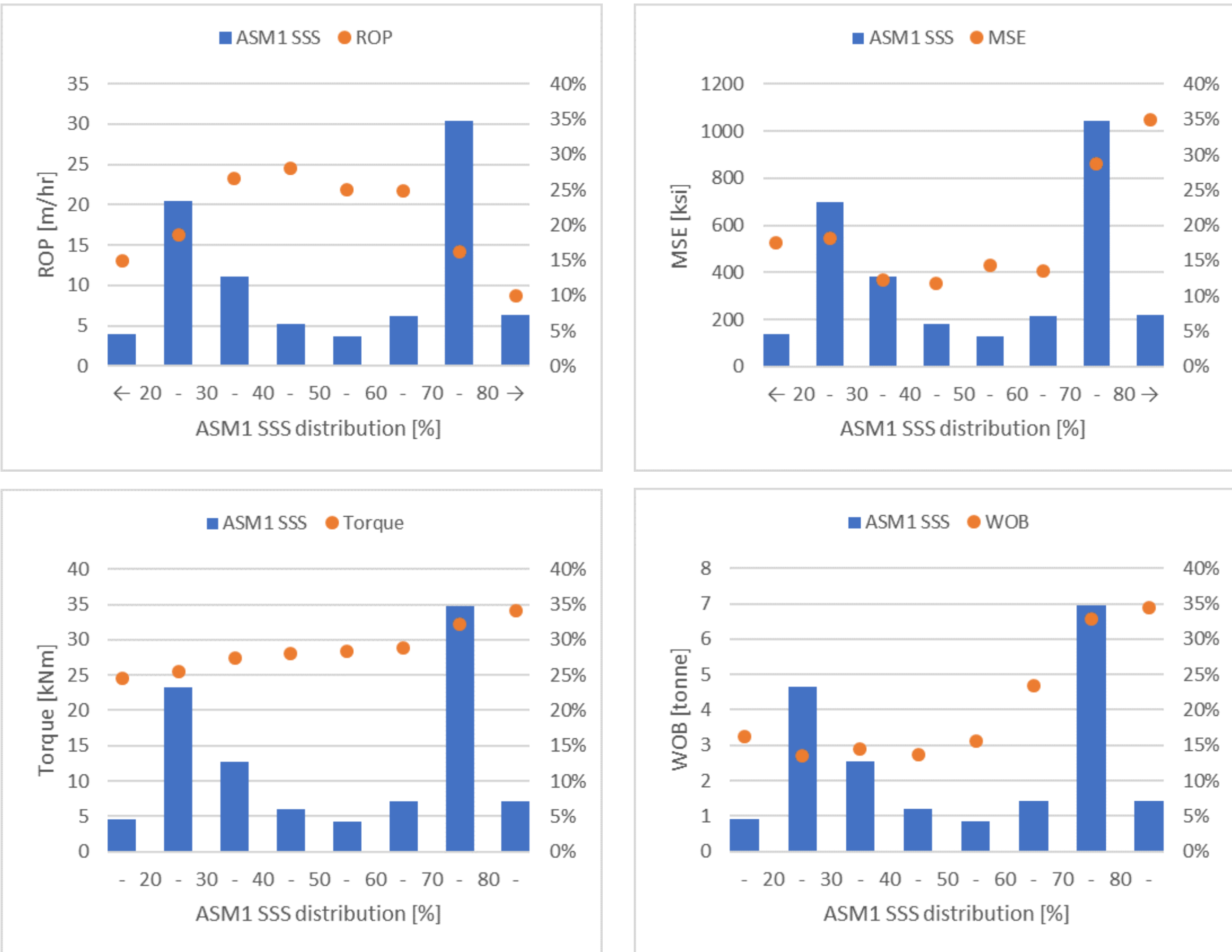

Figure 4.11: Comparison of ASM1 SSS spectrum against ROP, MSE, Torque and WOB in well 1.1T2

Drilling vibrations in Figure 4.12 shows increased vibrations towards the end of the section, similar to the trend of stick-slip. The trend for ASM2 axial vibrations follows closely the same trend in well 1.1 at the same depth. It is interesting that the standard deviation of axial vibrations are increasing also, indicating very rough hole conditions. A case study from the end of the well is presented in Figure 4.13.

Figure 4.12: Drilling vibrations with standard deviation in well 1.1T2

The time based plots in Figure 4.13 shows a drilling period of over seven hours spent on drilling the 11 last meters of formation, which amounts to an average ROP of 1.5 meters per hour. The torque sensor shows large oscillations and RPM is very high. ASM1 vibrations shows violent oscillations, which is reflected in the high stick-slip severity calculated for the well.

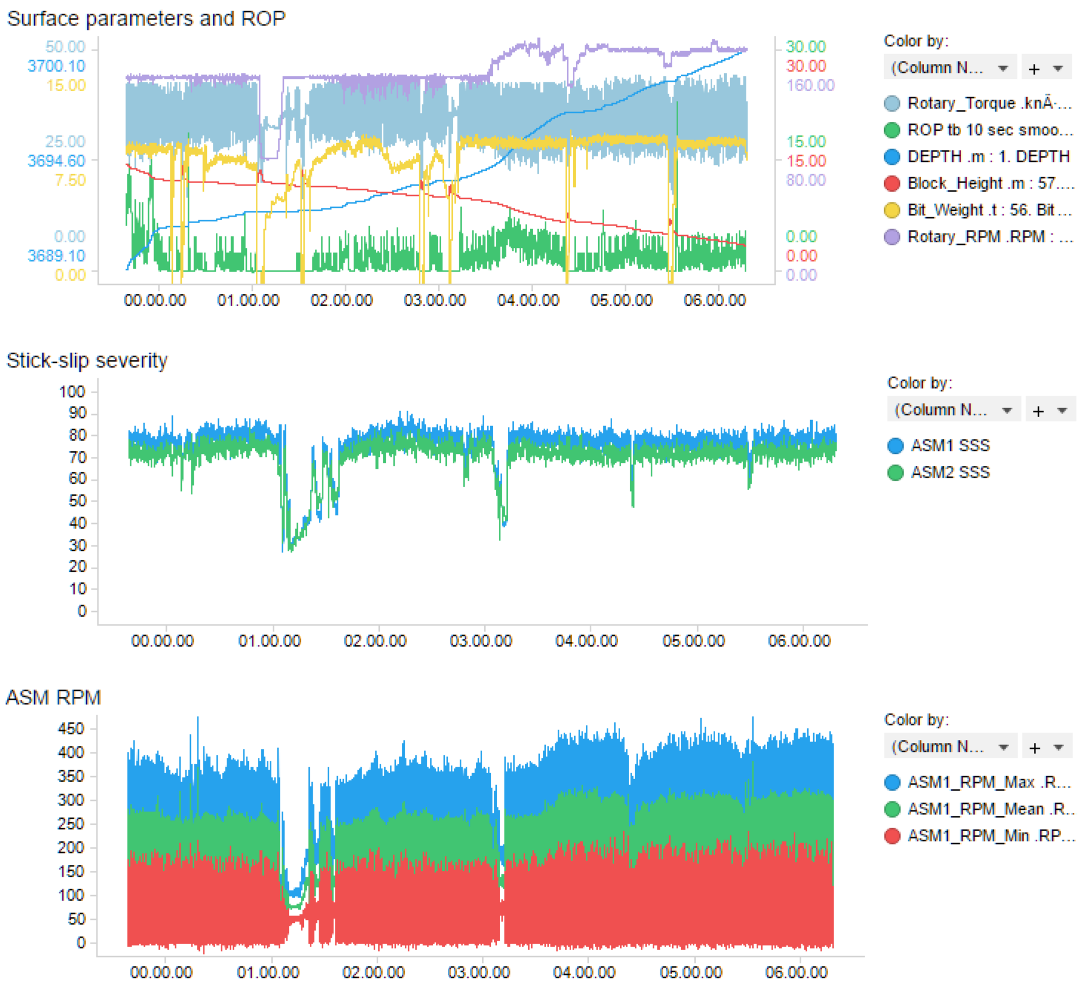

Figure 4.13: Case study from end of well 1.1T2

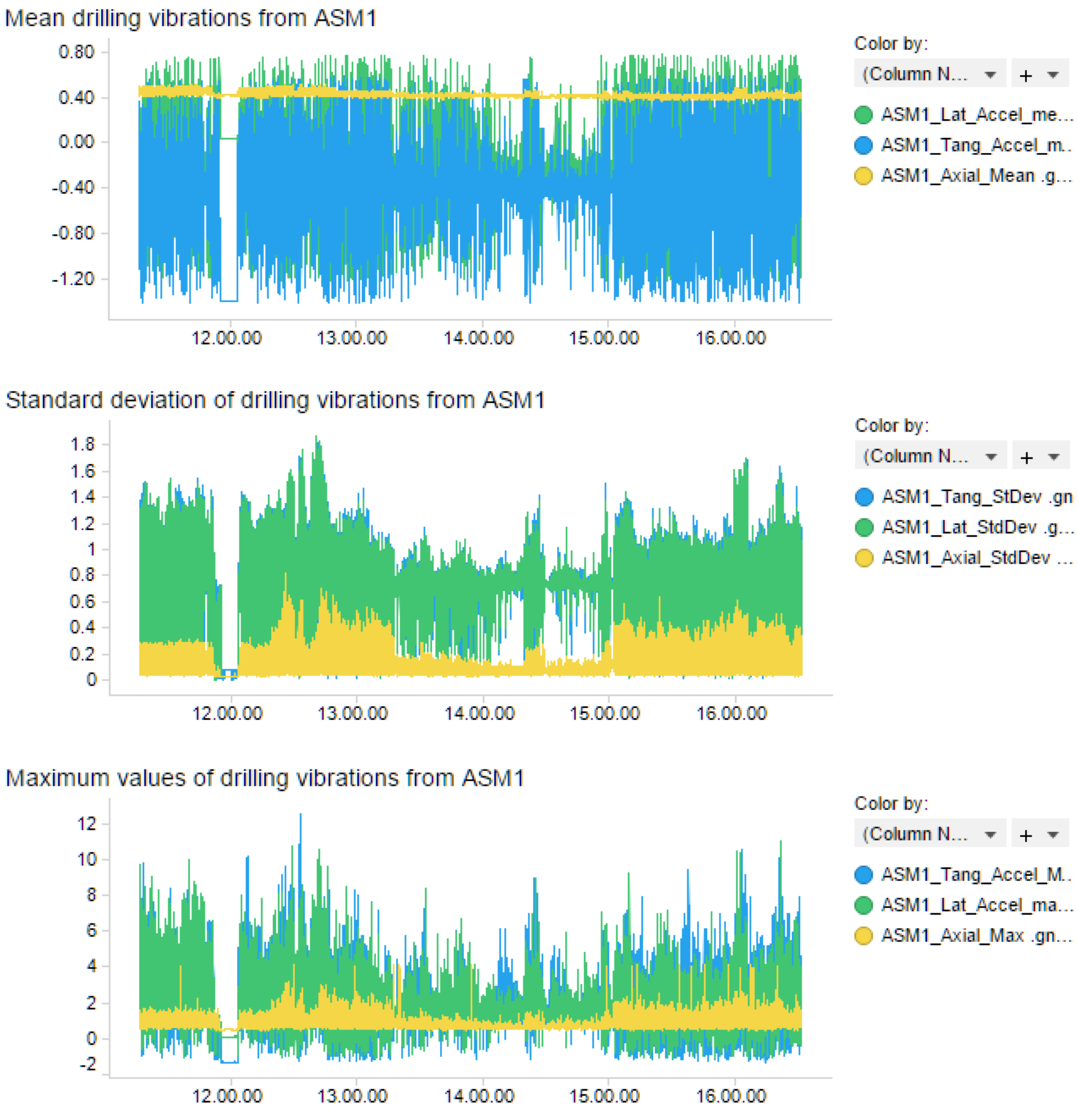

Figure 4.14: Drilling vibrations from case study from end of well 1.1T2

Figure 4.14 shows the drilling vibrations experienced in this high stick-slip interval. The standard deviations of both lateral and tangential vibrations are approximately equal, oscillating between 1.8g and 0. The axial direction experienced more shocks in this section than the earlier example, showing standard deviations up towards 0.8g and spikes of maximum values up to 4g. The mean values of tangential and lateral oscillates ±1g.

4.3 Well 1.2

Well 1.2 was drilled through the cap rock into the reservoir with a target inclination of 90° from approximately 77° while slightly turning 12° north. Stick-slip and drilling vibrations was not experienced while drilling through the cap rock for this well section.

The lithology consisted mainly of interbedded sandstone and conglomerates layers after the cap rock was penetrated. There was approximately 10% caprock, 40% sandstone and 50% conglomerates in this section. The sandstones were locally pebbly containing up to very coarse grains. The conglomerate consisted of siliceous and felsic rock grains, occasionally up to granular in cuttings size.

Table 4.3: Basic info surrounding well 1.2

Section length	1100m
Section TD	3900m MD/1950m TVD
Bit hours	71.4 hrs
ASM1 offset	240m
ASM2 offset	1218m
Bit grading	3-5-BT-A-X-1-CT-BHA
Average ROP	15.7 m/hr
Average MSE	383.8 ksi
Average $ASM1_{SSS}$	36.9 %
Average $ASM2_{SSS}$	31.9 %

This section has been drilled with a relatively low average ROP and moderate SSS and MSE values. The drillstring was pulled out to change bit and a BHA element. From the grading of the bit it was clear that it was ready to be exchanged due to broken and chipped cutters all over the surface in addition to being undergauge by 1/16".

The development of surface parameters in Figure 4.15 shows an increasing torque curve along with a slightly increasing WOB. RPM is decreased at the same time as stick-slip became dominant in Figure 4.16.

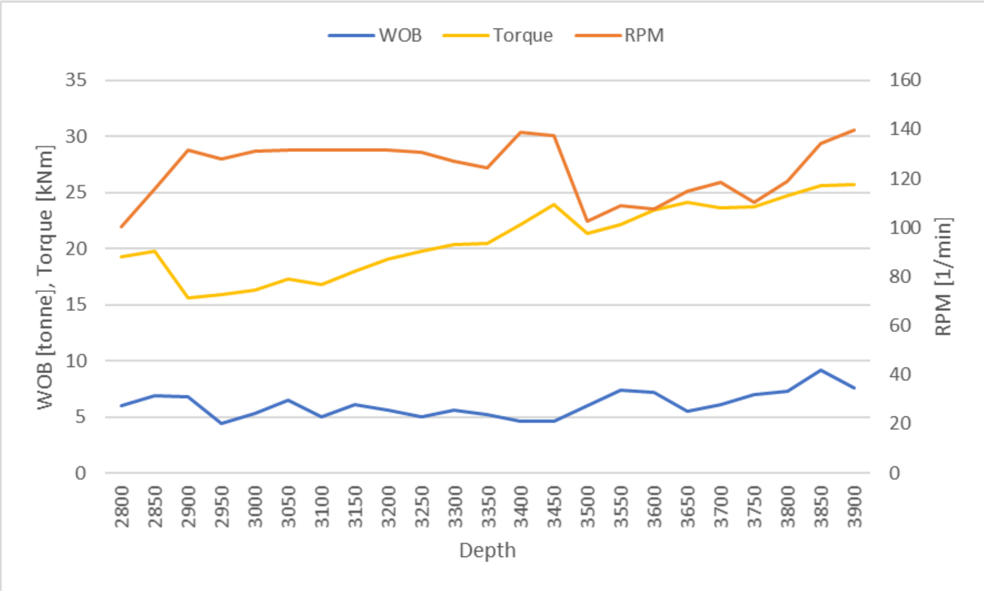

Figure 4.15: Development of surface parameters throughout well 1.2

MSE is high in the beginning of the well, indicating high-energy drilling through the caprock, while stick-slip stays low. ROP increases after entering the reservoir but is decreasing as SSS increase. MSE is building up along with SSS, but is suddenly decreasing at the same depth as RPM was adjusted and subsequently dropping the torque.

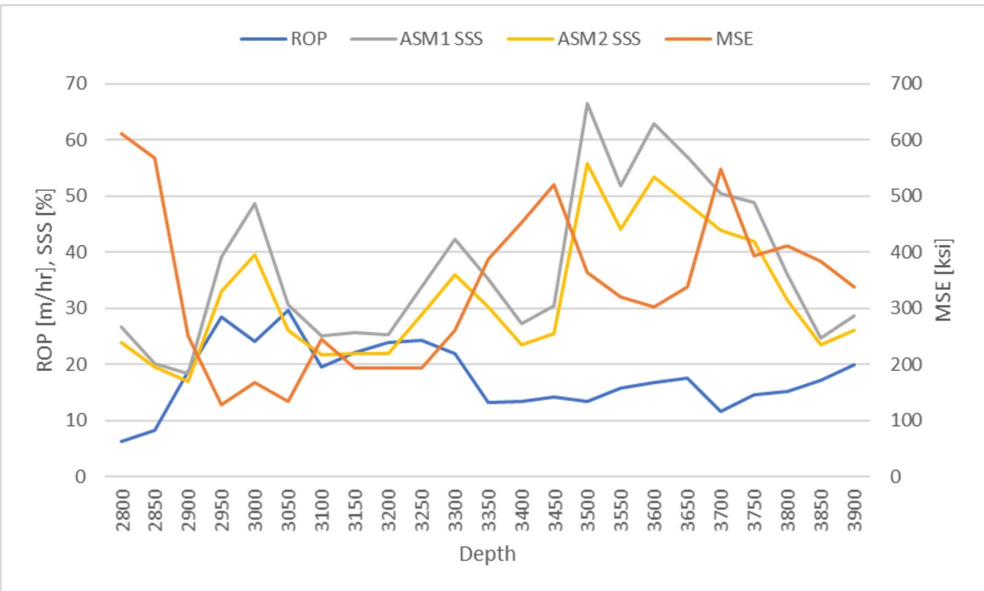

Figure 4.16: Development of performance parameters throughout well 1.2

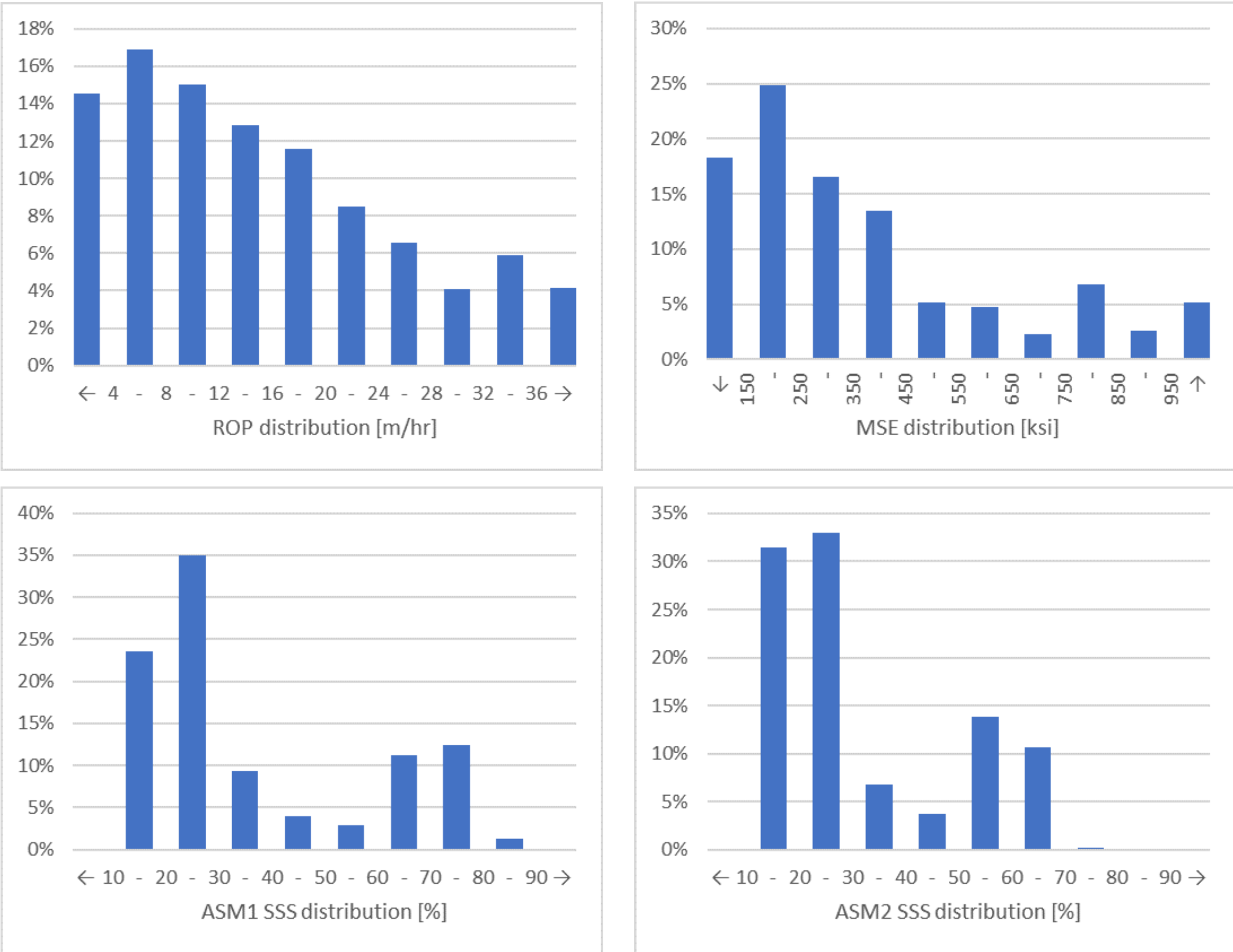

Figure 4.17: Distribution of performance parameters in well 1.2

The distribution of the performance parameters in Figure 4.17 shows that both ROP and MSE stays relatively low, with a peak in the distribution in the 4-8 interval for ROP and 150-250 interval for MSE. SSS for ASM1 and 2 are mainly concentrated around 10-30% stick-slip, but they both portray a peak of higher vibration, more so for ASM1 than 2. 25% of the drilling time was spent above 60% stick-slip.

The comparison in Figure 4.18 shows that the highest level of stick-slip is related to lower values of ROP, WOB and torque, which may indicate that the most severe stick-slip encountered in the well are associated with the SSS peak around 3000 meters. MSE is mirroring the other parameters and reveal that the highest levels of stick-slip are not necessarily drilled with high energy.

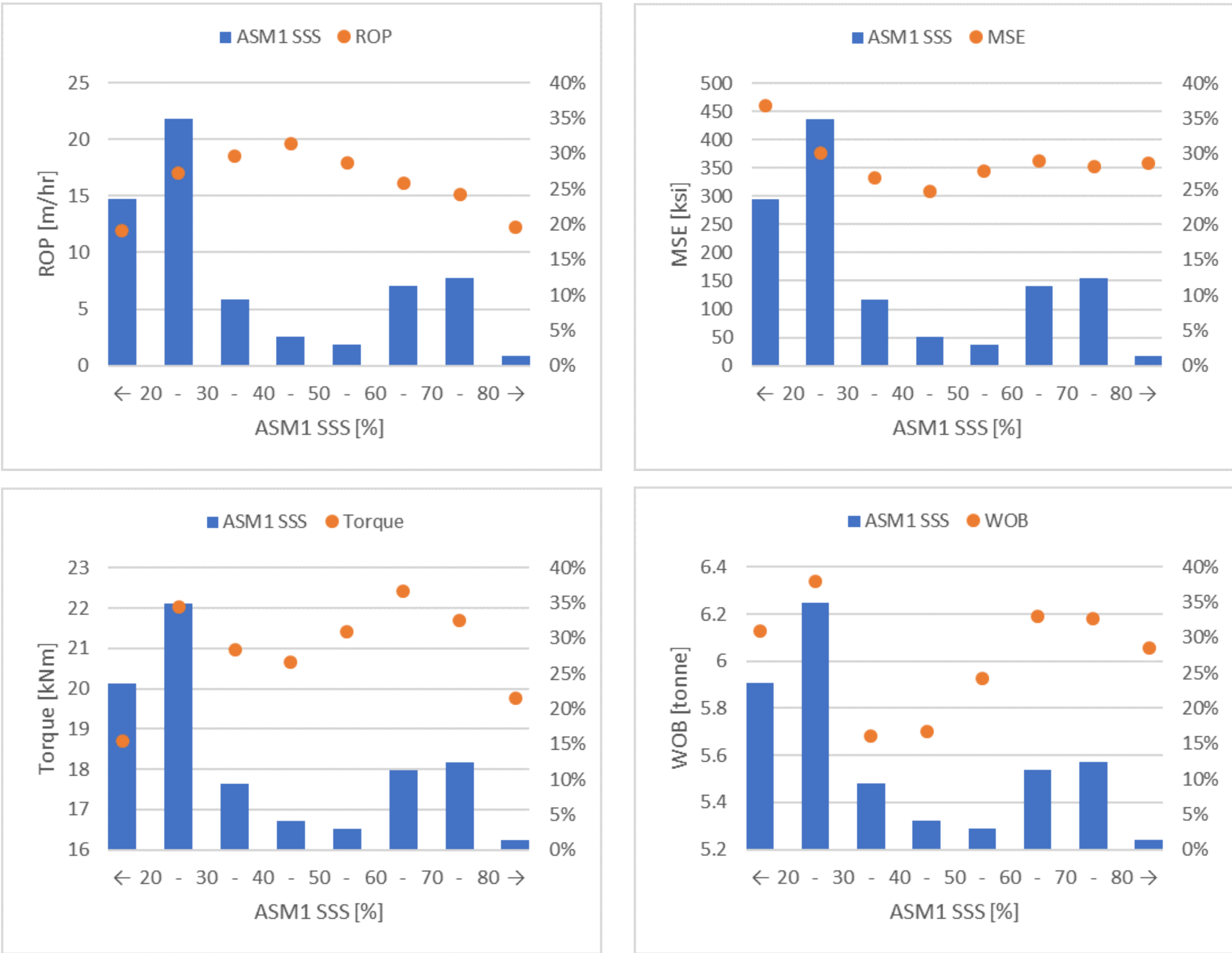

Figure 4.18: Comparison of ASM1 SSS spectrum against ROP, MSE, Torque and WOB in well 1.2

Drilling vibrations shown in Figure 4.19 shows that there were present vibrations throughout the well. Perhaps the most interesting one is the axial vibrations from ASM2 which shows that there were massive vibrations in the axial direction along the drillstring throughout the well. But when comparing data from ASM1, which is the one of most importance, it seems to be an area around 3450 meters with higher than normal vibrations in all directions. This area will be studied in Figure 4.20.

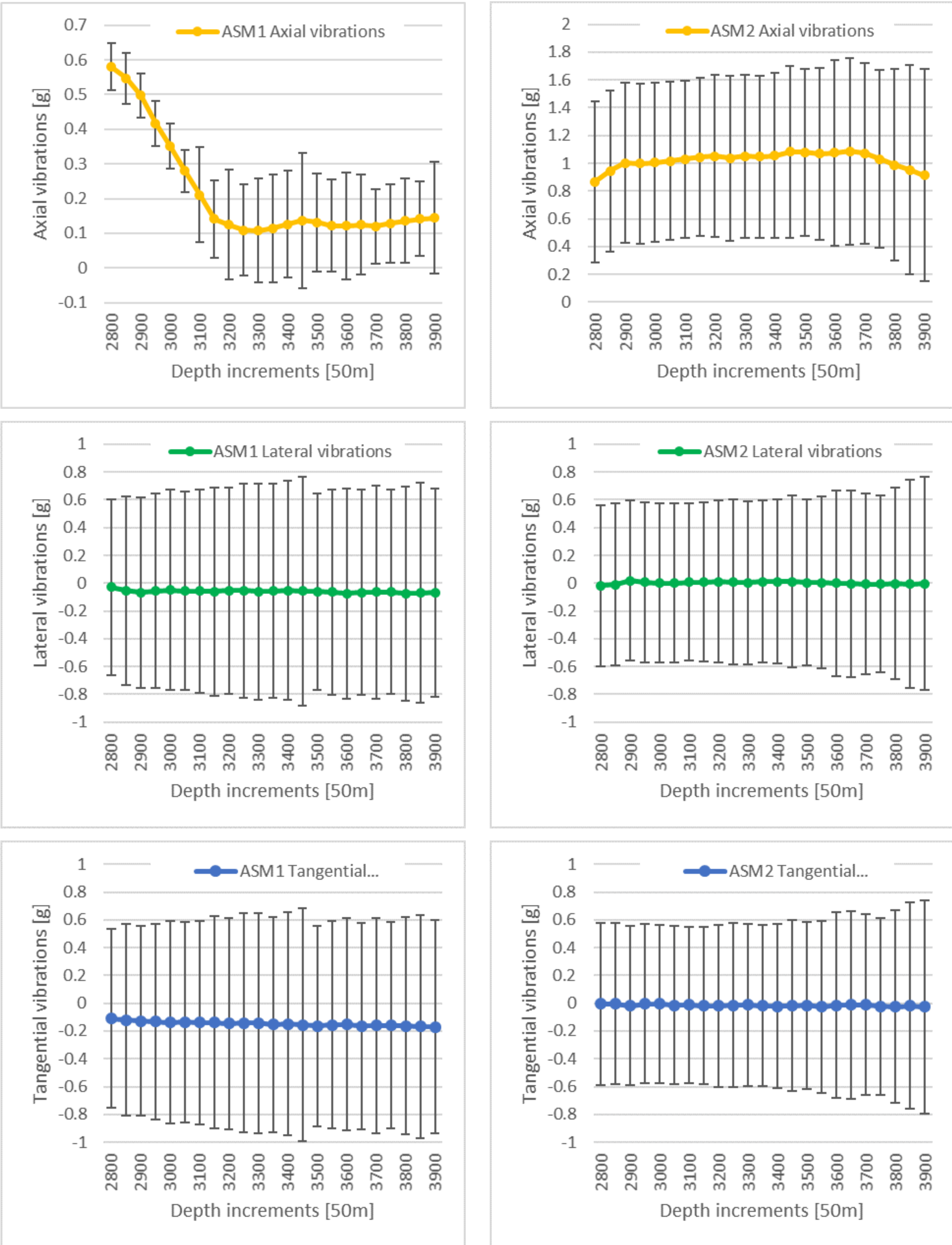

Figure 4.19: Drilling vibrations with standard deviation in well 1.2

Figure 4.20 shows the very spot where stick-slip started to get serious in this section. There are high levels of stick-slip connected with oscillating torque on the topd rive. High ROP is emphasized rather than keeping drilling vibrations under control.

It is worth noting the approach of handling the drilling vibrations in this instance. Rather than going down on weight and up on RPM, they are doing the exact opposite; going up on weight and down on RPM. From this instance and onwards, drilling vibrations and stick-slip is frequent.

Figure 4.20: Case study from end of well 1.2

The drilling vibrations are shown in Figure 4.21. The amount of oscillations are clearly related to the degree of stick-slip shown in previous figure. It is worth noting the amount of standard deviation does not increase in average when oscillations occur. The maximum value of the vibrations remains the same as prior to stick-slip, but the oscillations lead to much lower values and a larger spread, causing lower average standard deviation values.

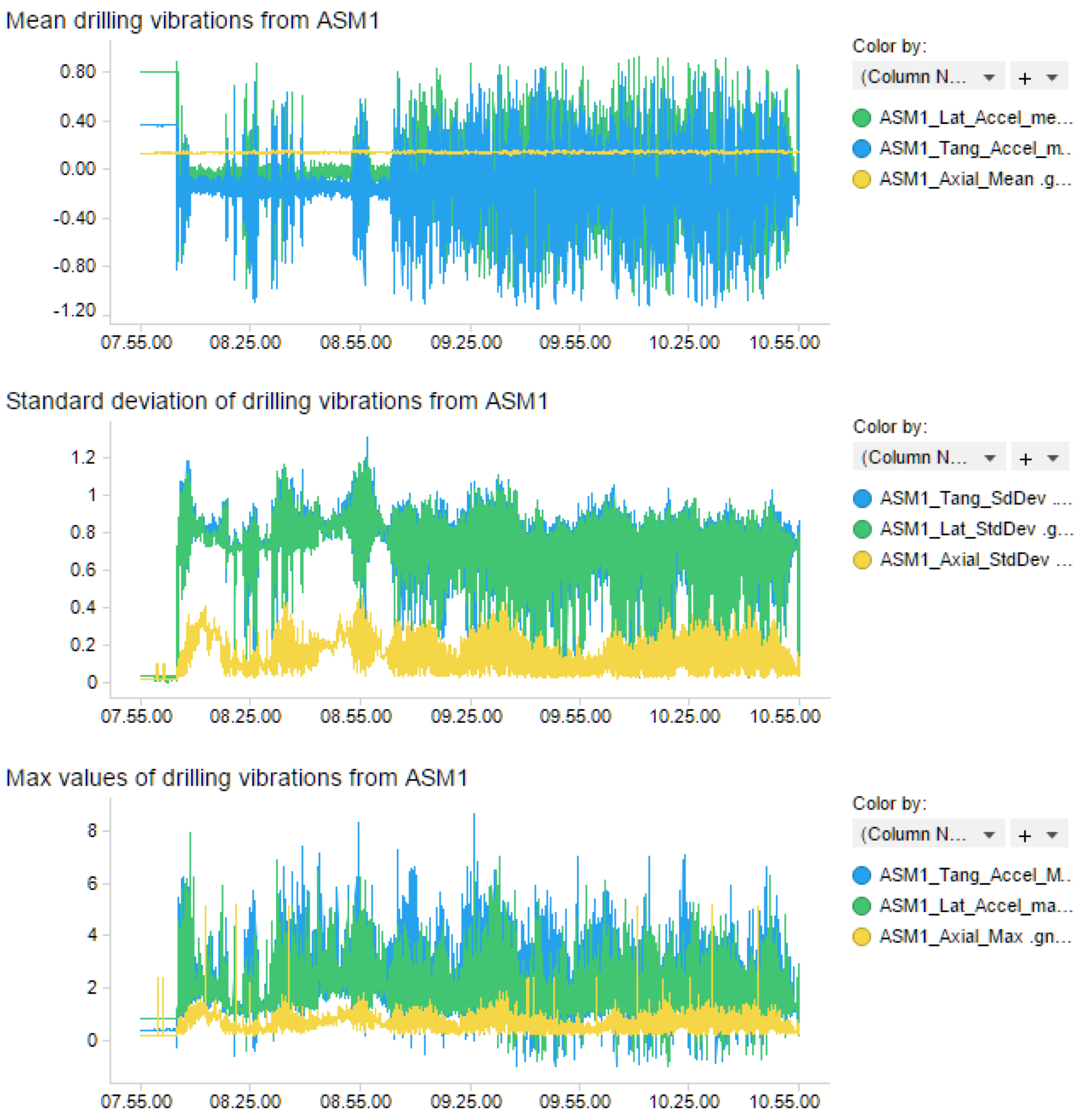

Figure 4.21: Drilling vibrations of case study from end of well 1.2

4.4 Well 1.2T2

Well 1.2T2 is continuing on the previous wellpath in a horizontal tangent with geosteering.

The section starts out in conglomerates, but after 50 meters enters a large claystone interval which lasts for 80% of the section. A smaller interval of sandstone is then drilled before entering an interval of calcite rich mudstone in which TD was set. There was approximately 15% sandstones and conglomerates in total throughout the section.

Table 4.4: Basic info surrounding well 1.2T2

Section length	700m
Section TD	4550m MD/1950m TVD
Bit hours	39.6 hrs
ASM1 offset	240m
ASM2 offset	1218m
Bit grading	1-1-BT-G-X-0-NO-TD
Average ROP	17.3 m/hr
Average MSE	504.3 ksi
Average $ASM1_{SSS}$	25.1 %
Average $ASM2_{SSS}$	26.0 %

The parameters in Table 4.4 shows a low stick-slip severity in this interval, but high MSE. The bit grading is reflecting the low stick-slip by being in very good shape when returning to surface. This is probably accounted to the large amount of claystone in this interval.

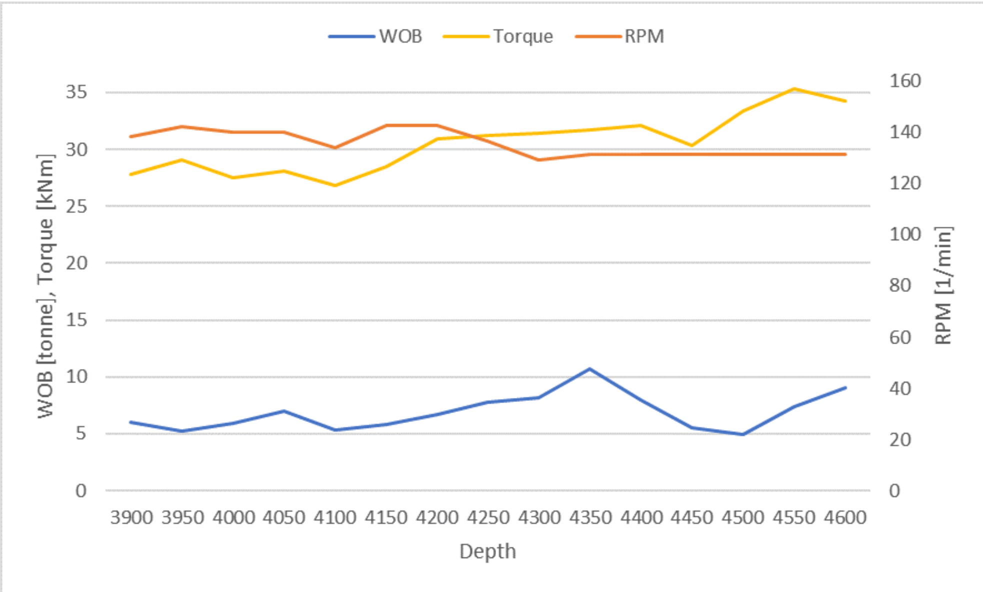

Figure 4.22: Development of surface parameters throughout well 1.2T2

Figure 4.22 shows a slightly increasing torque and relatively stable RPM. The WOB peaks corresponds very well with the increased MSE in Figure 4.23.

SSS shows high values at the beginning of the section. At this point the bit was still going through conglomerates prior to entering the claystone, which explains the high values. ROP decreases at two intervals, resulting in a massive increase in MSE. Stick-slip is also increasing slightly in these areas.

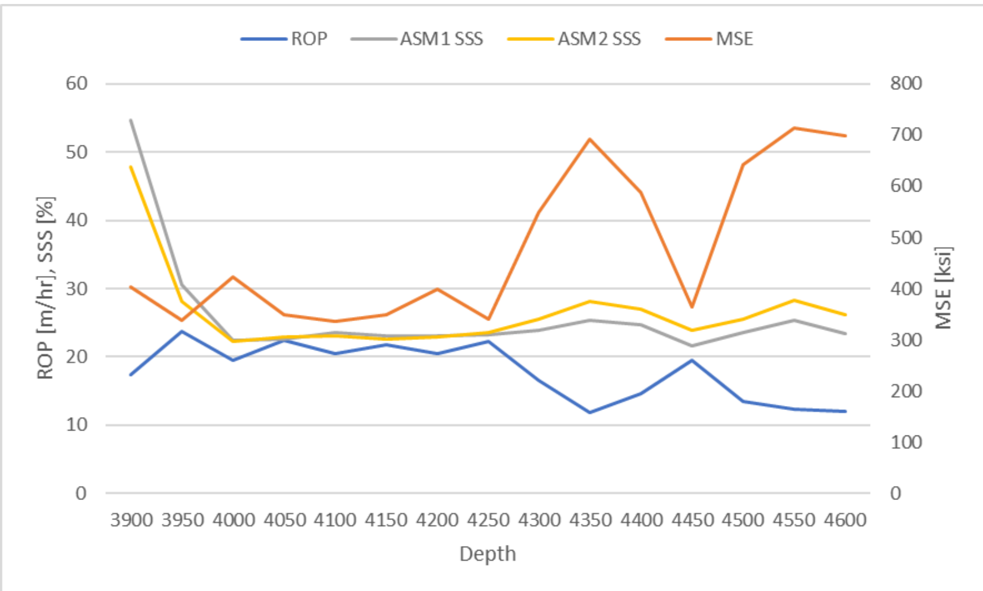

Figure 4.23: Development of performance parameters throughout well 1.2T2

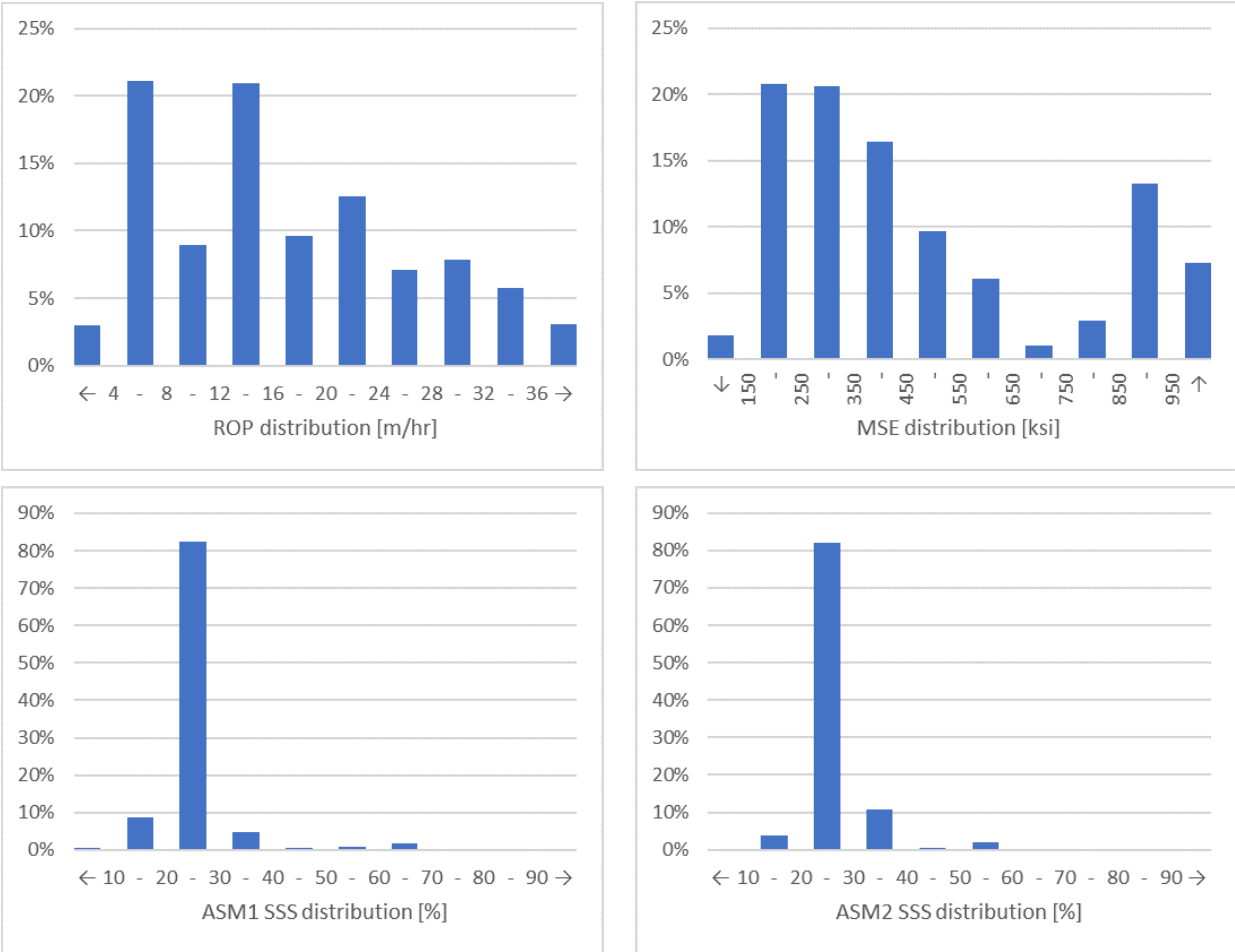

Figure 4.24: Distribution of performance parameters in well 1.2T2

The distribution in Figure 4.24 shows two abnormal peaks in an otherwise normally distributed ROP curve. These may be related to the two different low ROP intervals towards the end of the well. This may also be the reason for the second peak of high MSE. SSS is very low in this section with over 90% below 30% stick-slip for ASM1. ASM2 also shows a low spectrum of SSS values.

Due to the concentration of the low SSS values, the histogram has been adjusted for the comparison of parameters plot in Figure 4.25. It is therefore not too surprising to see low values of torque, WOB and MSE, and high values of ROP at the high end of the spectrum, as this only accounts to the interval above 30% stick-slip in other plots.

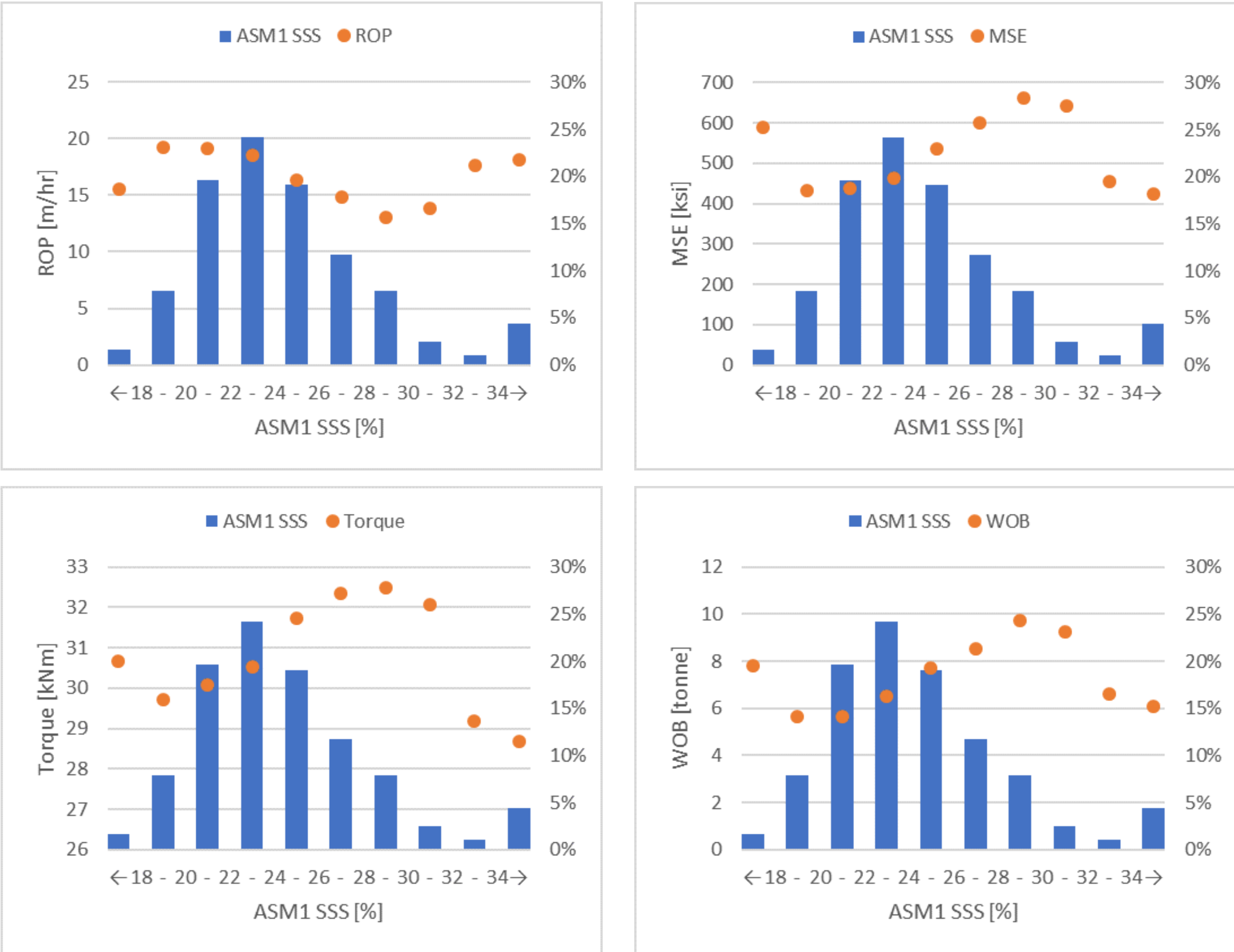

Figure 4.25: Comparison of ASM1 SSS spectrum against ROP, MSE, Torque and WOB in well 1.2T2

The distribution in Figure 4.25 is very close to a normal distribution, but with a second peak at the high end of the register. The behavior of the compared data is remarkable similar in a wave-like spread where ROP is inversely proportional.

The axial vibrations in Figure 4.26 are continuing the trend from Figure 4.19, both in magnitude and trajectory. The tangential and lateral vibrations are very linear for ASM1 and increasing towards the end of the well for ASM2.

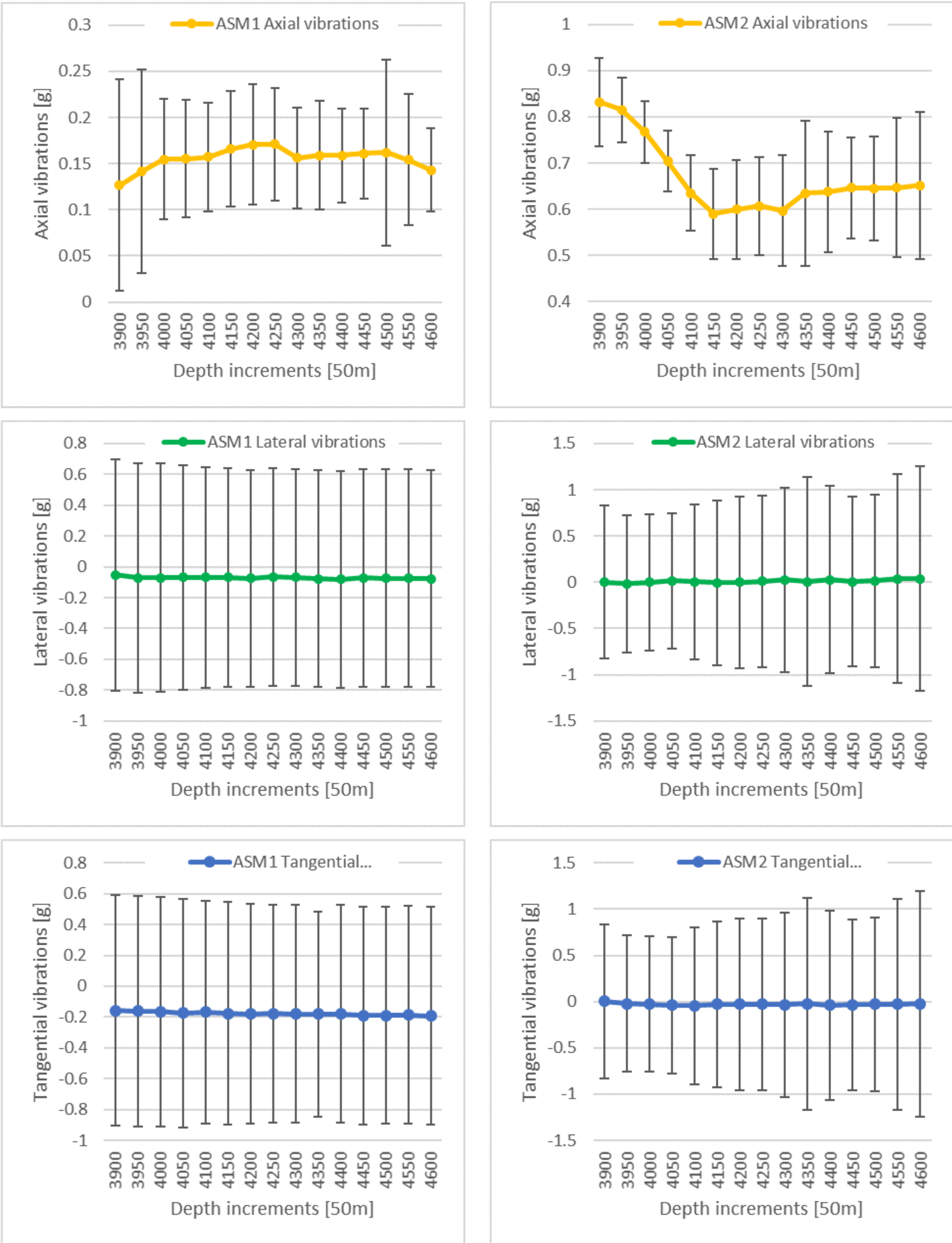

Figure 4.26: Drilling vibrations with standard deviation in well 1.2T2

Figure 4.27 shows an interval of high MSE in Figure 4.23. There are low stick-slip values due to little oscillations in rotation sensor. The average ROP for the stand is 10 meters per hour with a WOB around 11 tonnes.

Figure 4.27: Case study from well 1.2T2

The drilling vibrations are shown in Figure 4.28 and they contain very little oscillations. The standard deviation of both lateral and tangential vibrations are linear between 0.7 and 0.8g's. The standard deviation of the axial vibrations are very low, around 0. The maximum values are relatively linear and show little oscillations, with the lateral and tangential values lying steadily around 1g and the axial around 0.4g.

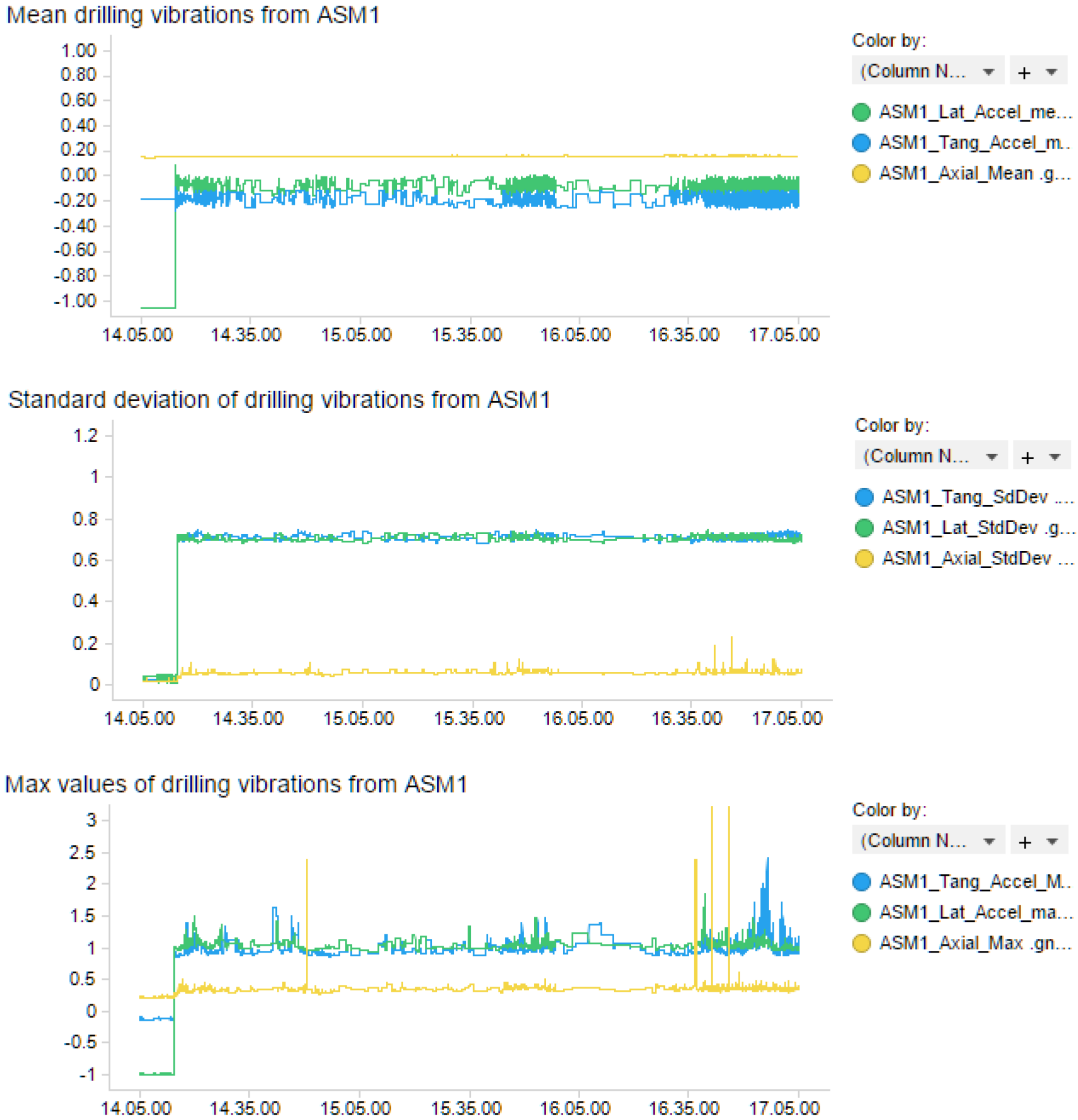

Figure 4.28: Drilling vibrations from case study of well 1.2T2

4.5 Well 1.3

The wellpath for the 8.5" reservoir section in well 1.3 kicks off from approximately 80° with a target inclination of 90° while turning 30° east.

The lithology in this section is reported to be purely conglomeratic after penetration of the caprock. The cuttings are siliceous and felsic with sizes up towards pebbles and cobbles. Boulders up towards 50 meters have been reported on the log based on resistivity readings. Total distribution of conglomerates in this section is approximately 90%.

Table 4.5: Basic info surrounding well 1.3

Section length	1450m
Section TD	4850m MD/1950m TVD
Bit hours	67.1 hrs
ASM1 offset	62m
ASM2 offset	1050m
Bit grading	1-1-BT-S-X-I-WT-HP
Average ROP	21.9 m/hr
Average MSE	350.2 ksi
Average SSS	8.17 %
Average $ASM1_{SSS}$	20.6 %
Average $ASM2_{SSS}$	22.2 %

Well 1.3 has the longest section yet, combined with an acceptable ROP and relatively low MSE. SoftSpeed has been used in this section, probably causing the low levels of ASM SSS and even lower levels of SoftSpeed SSS. The bit grading after the well shows a really good bit with only 1/8 wear on both inside and outside rim cutters. The wear consists of broken and chipped teeth, but the bit is otherwise in gauge. The last parameter indicates hole problems, but that was on the way out of hole and not while drilling.

Figure 4.29 shows high torque and WOB while drilling through the caprock, and otherwise a slightly increasing trend in torque and a relatively flat curve for WOB.

The small differences in surface parameters are reflected in the MSE and ROP curve in Figure 4.30 as they are close to inversely proportional. There is a decline in ROP, corresponding with an increase in both SSS and MSE around 4500 meters, otherwise the ROP inside the reservoir lies around 25 meters per hour.

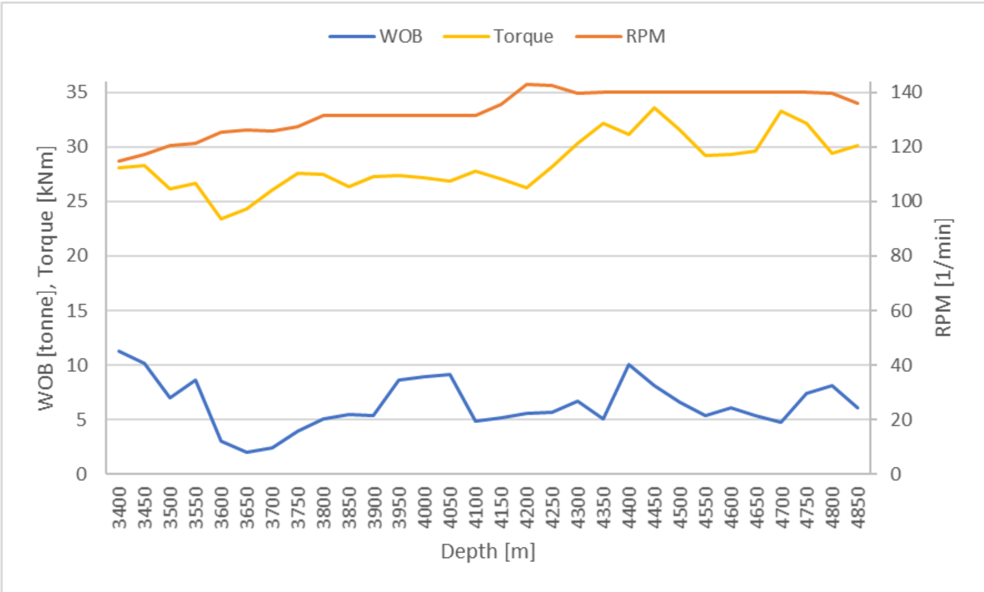

Figure 4.29: Development of surface parameters throughout well 1.3

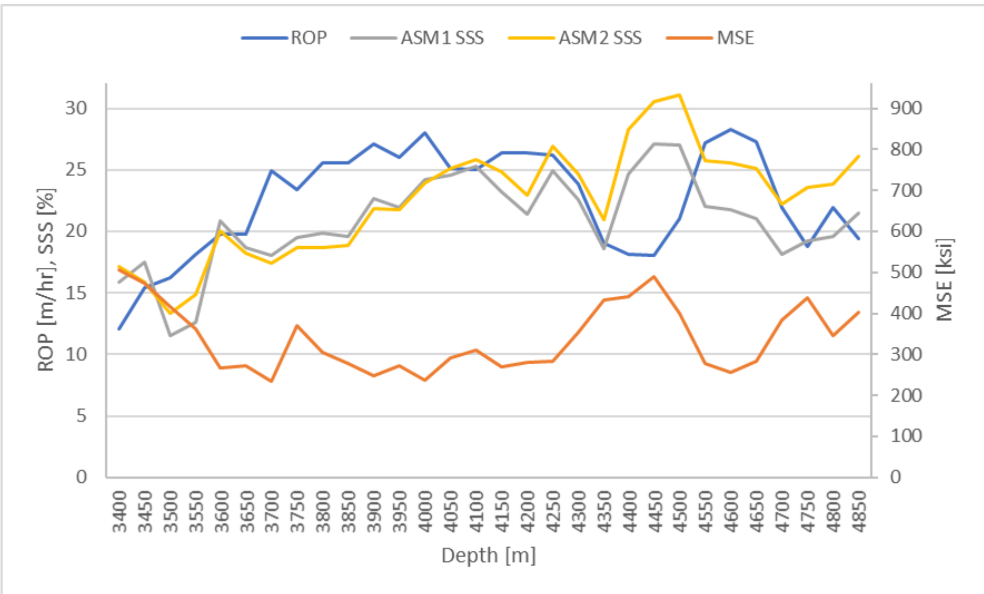

Figure 4.30: Development of performance parameters throughout well 1.3

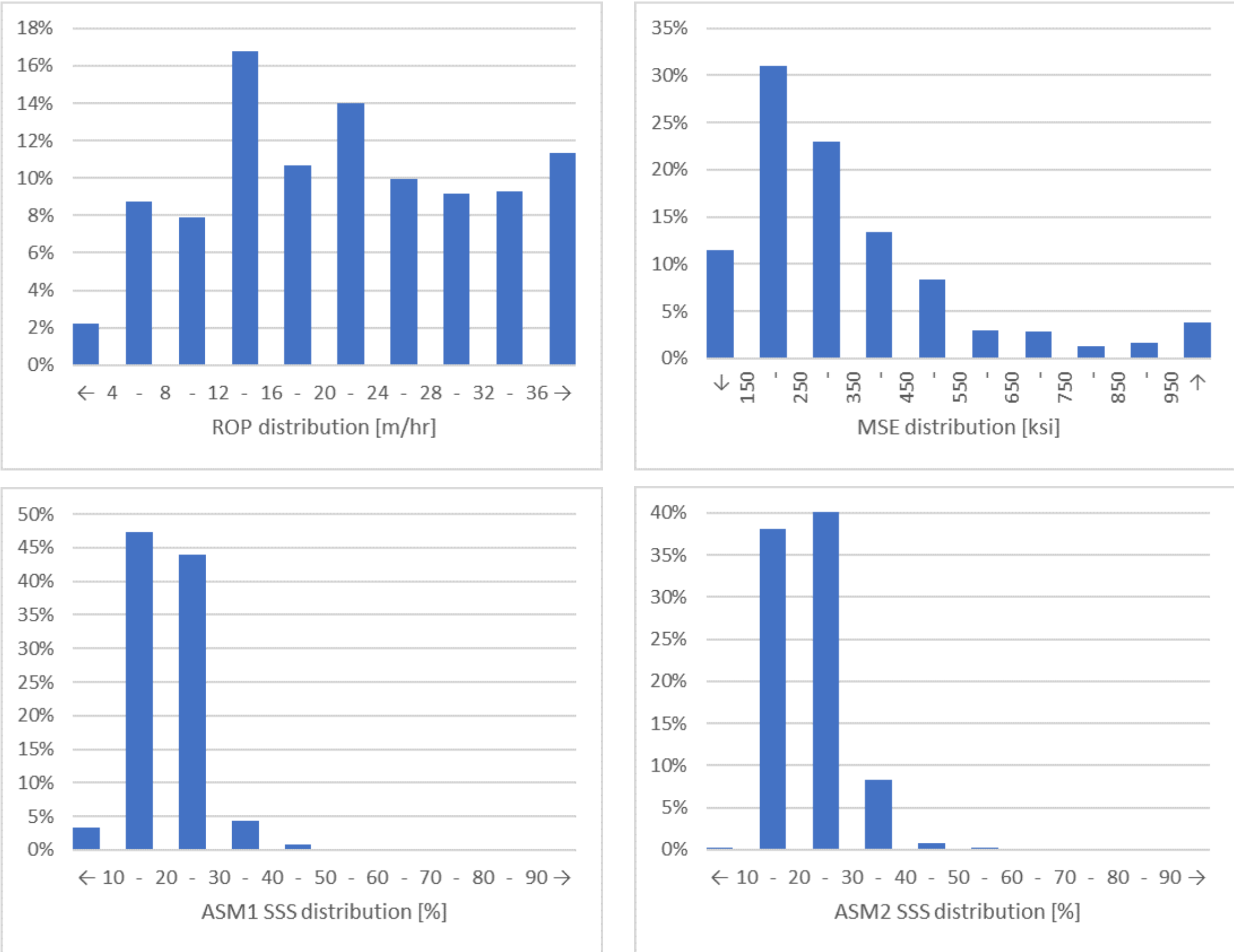

Figure 4.31: Distribution of performance parameters in well 1.3

The distribution of ROP in Figure 4.31 shows a very low density of low ROPs. Only 19% of the values lies below 12 meters per hour. The MSE distribution also shows a very low density of high values. Only 13% is above 550 ksi. Combining the very low levels of SSS, this is looking like a promising start for the SoftSpeed application.

The comparison plots in Figure 4.32 shows remarkably linear trends for all parameters. There is no dip in either ROP, WOB or torque. The lowest SSS values correspond with low ROP and inversely high MSE. The SSS spectrum is adjusted to a maximum of 34 ksi and above as highest bin.

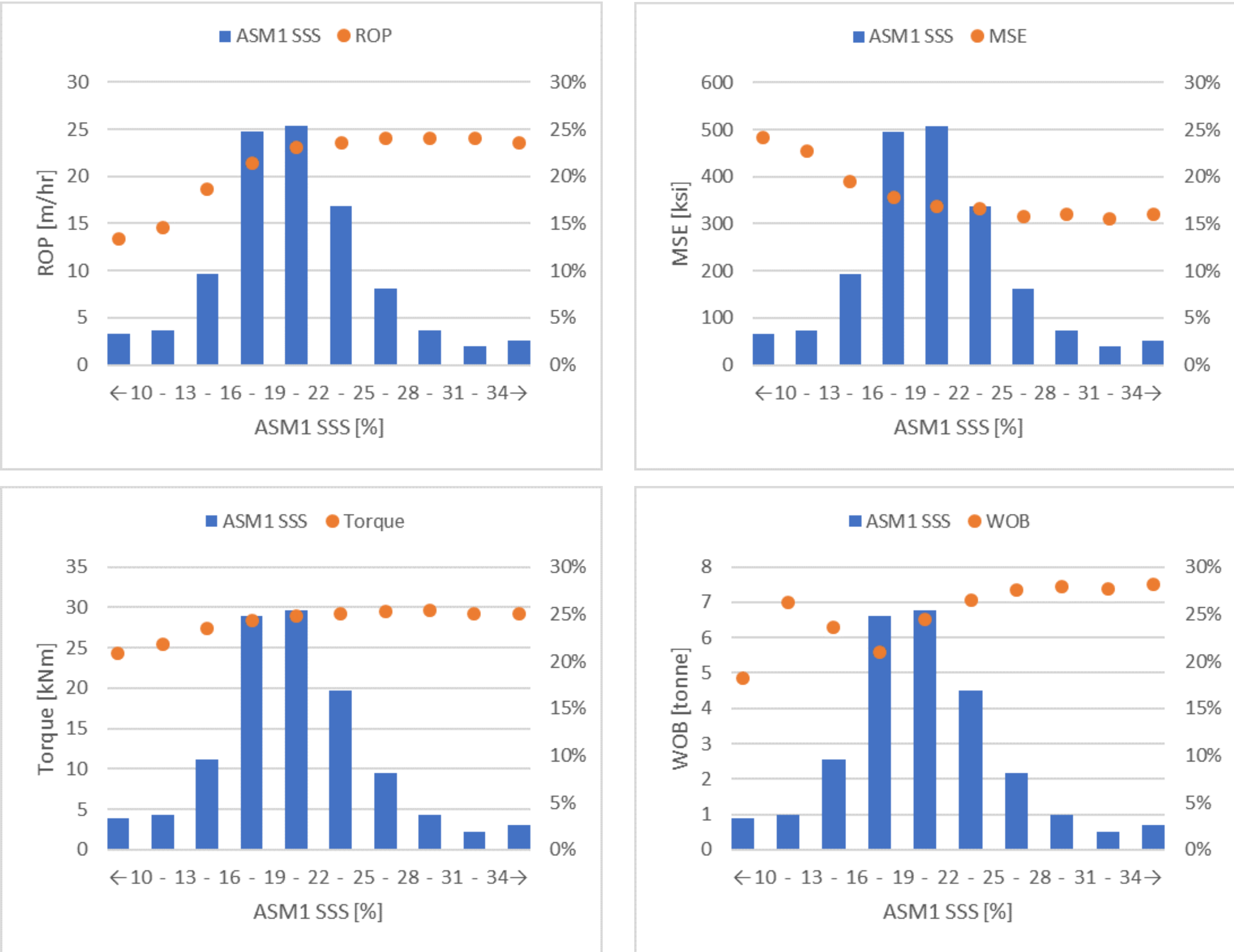

Figure 4.32: Comparison of ASM1 SSS spectrum against ROP, MSE, Torque and WOB in well 1.3

Drilling vibrations in this section are quite high, as shown in Figure 4.33. Axial vibrations in ASM1 have the largest magnitude standard deviations of all wells. Standard deviation in both lateral and tangential vibration from ASM1 are also very high. Note that the drilling vibrations from all wells will be compared in Section 4.7.3 and will be further discussed in Section 5.3.2.

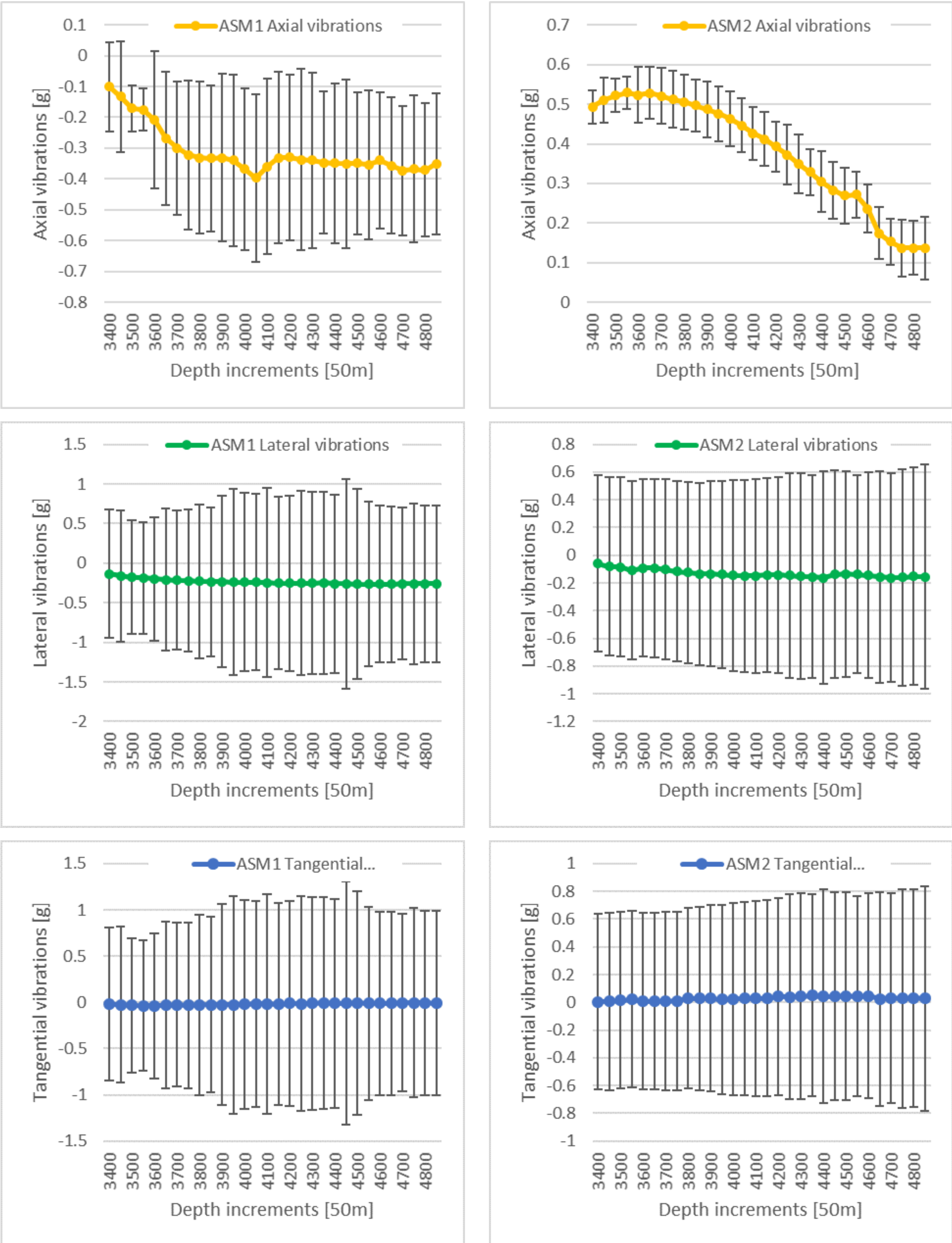

Figure 4.33: Drilling vibrations with standard deviation in well 1.3

4.5.1 SoftSpeed in well 1.3

The impacts of SoftSpeed will be studied in this section. As shown in Table 4.6, the application was used 63% of the total drilling time which should make this well ideal to identify areas where SoftSpeed has made a difference. The aim is to find an area where SoftSpeed has been turned on and effectively ceased drilling vibrations.

The approach to achieving this will be to study each stand where SoftSpeed is both off and on and compare parameters to look for any discrepancies. The drilling vibrations analysis will also be done in this way in order to look for differences with and without the application.

Table 4.6: Average values with SoftSpeed on and off in well 1.3

	SoftSpeed ON	SoftSpeed OFF
Drilling time	42.3 hrs	24.8 hrs
Distribution	63.0 %	37.0 %
Average ROP	22.17 m/hr	21.37 m/hr
Average MSE	361.4 ksi	355.6 ksi
Average SSS	7.89 %	8.64 %
Average $ASM1_{SSS}$	20.7 %	20.3 %
Average $ASM2_{SSS}$	23.2 %	20.5 %

Table 4.6 shows that SoftSpeed was turned off in low energy environments as both MSE and SSS from both ASMs are lower than when SS is turned on. The ROP is higher when the application is turned on, and the calculates SSS from the system is lower.

Figure 4.34 shows the distribution divided into stands of when SoftSpeed was turned on or off throughout the well. Only the stands in which the application is both on and off will be used in the upcoming analyzes. Each stand is approximately 30 meters long.

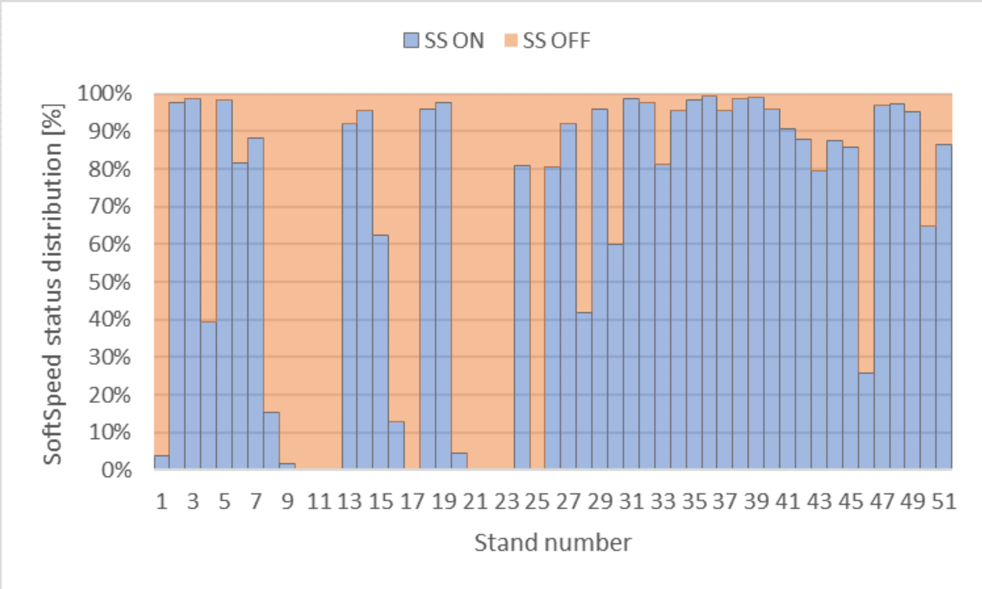

Figure 4.34: Depth based distribution of SoftSpeed status in well 1.3

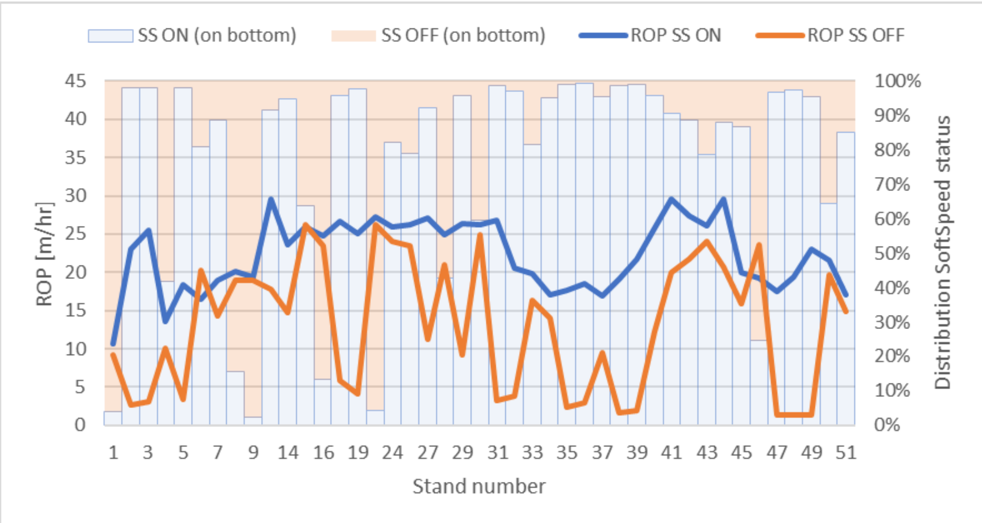

Figure 4.35: Effects of SoftSpeed on ROP in well 1.3

Figure 4.35 shows the ROP trend throughout the well. There are many spikes of low ROP when SS is inactive, but nearly all of them are related to a very short time period. Stand 31, which is an example of this, will be studied closer in Figure 4.46.

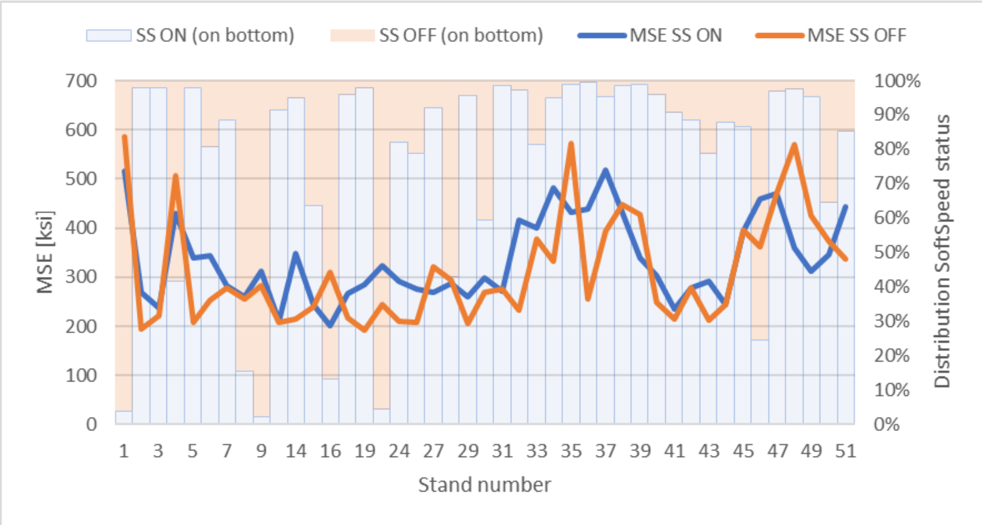

Figure 4.36: Effects of SoftSpeed on MSE in well 1.3

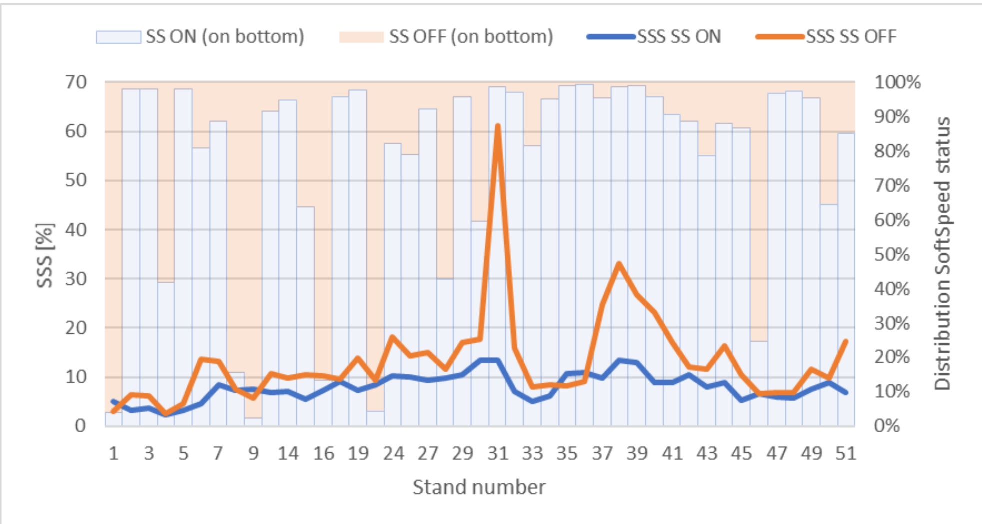

Figure 4.37: Effects of SoftSpeed on SSS in well 1.3

The MSE analysis in Figure 4.36 shows little variation between SoftSpeed on or off. There are some spikes to either side, but usually it is corresponding a very short time period.

Figure 4.37 shows a massive stick-slip spike in stand 31 which will be studied closer later on. Number 37-40 also shows an deviation from the trend, and stand 38 will be looked at more closely in Figure 4.47.

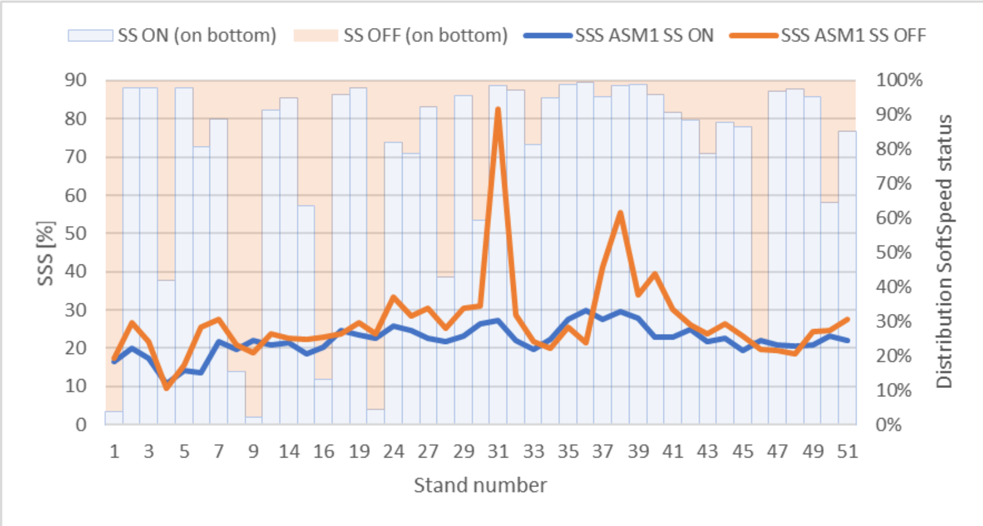

Figure 4.38: Effects of SoftSpeed on ASM1 SSS in well 1.3

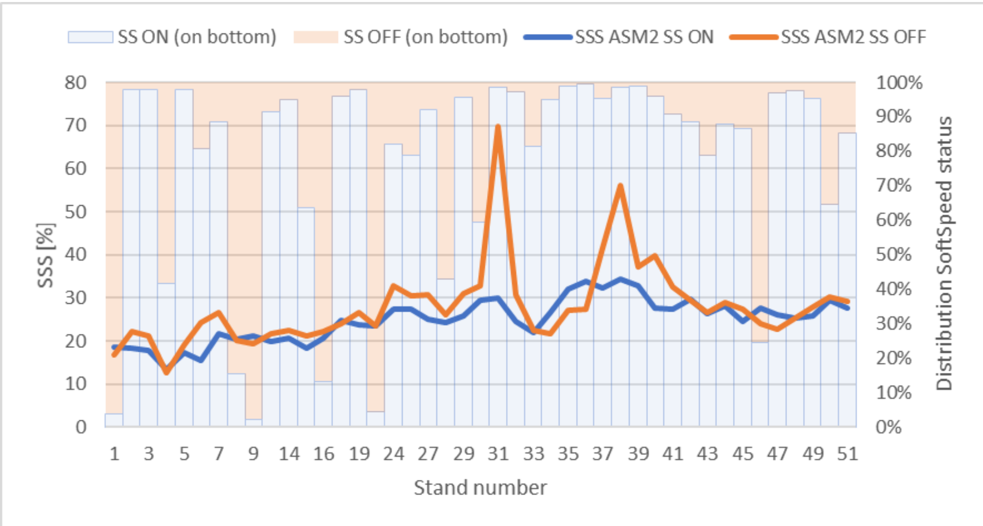

Figure 4.39: Effects of SoftSpeed on ASM2 SSS in well 1.3

Figure 4.38 and Figure 4.38 shows a very close correlation between ASM calculated SSS and the SoftSpeed SSS. The main difference between these two distributions is stand 39, which shall be analyzed in Figure 4.48.

The following figures compares the distribution of different performance parameters with SoftSpeed on and off. Generally, it is possible to say that the distributions are remarkably similar, indicating that the well conditions experienced were approximately the same when SS was on and off. These distributions confirms the average values of the performance parameters presented earlier in the section.

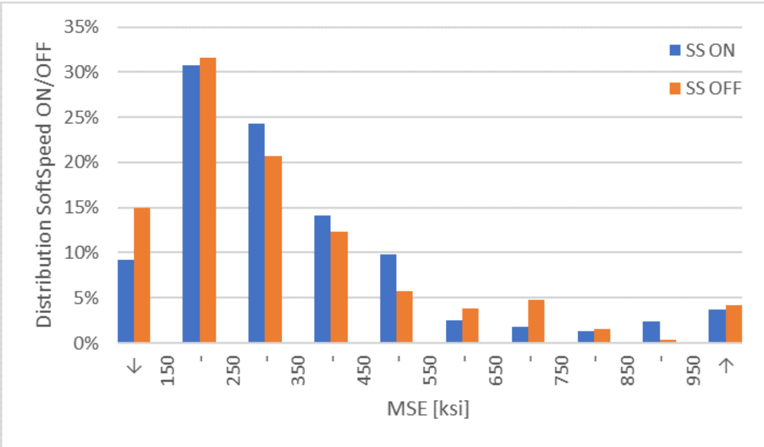

Figure 4.40: The MSE distribution with SoftSpeed on and off in well 1.3

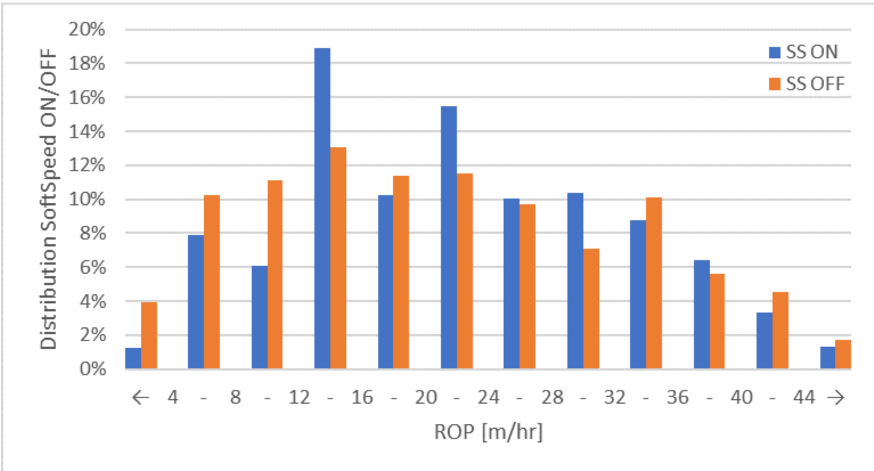

Figure 4.41: The ROP distribution with SoftSpeed on and off in well 1.3

MSE in Figure 4.40 shows a slightly higher density in values above 550 ksi when SS is off, but also more of lower values, resulting in a slightly lower average. The ROP values in Figure 4.41 shows a higher density of low values below 12 meters per hour with SS off, but also a slightly higher density of higher ROP, overall resulting in a slightly lower average.

SSS in Figure 4.42 shows a slightly higher density of higher stick-slip above 12% when SS is off, which is partly reflected in ASM1 in Figure 4.43 where the density above 31% is higher. ASM2 on the other side shows a slightly skewed distribution of when SS is on towards the high end of the spectrum.

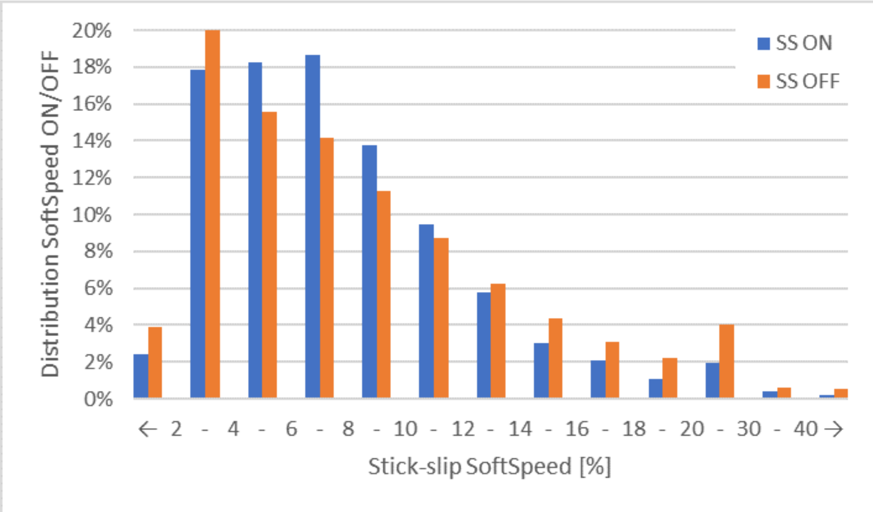

Figure 4.42: The stick-slip severity distribution with SoftSpeed on and off

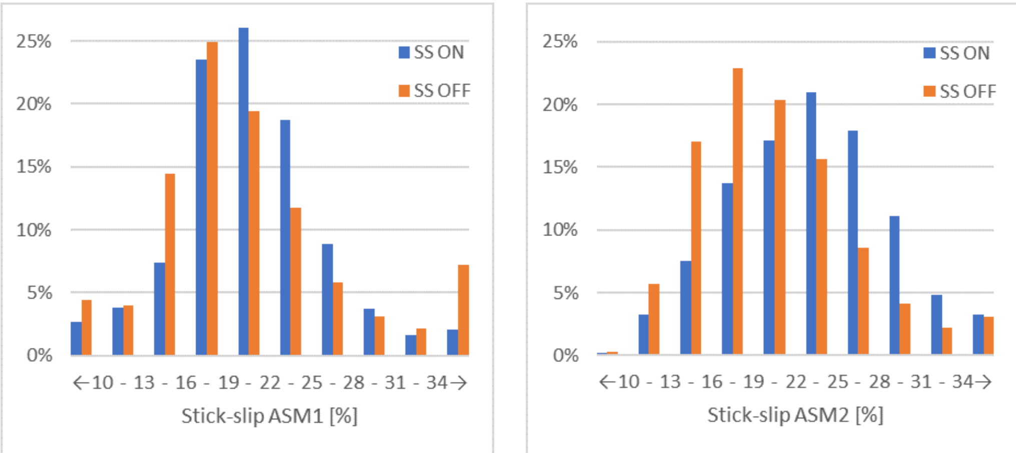

Figure 4.43: ASM1 & 2 SSS distribution with SoftSpeed on and off in well 1.3

The following figures shows the drilling vibrations for both SS on and off in same plot. Note that only the stands with SoftSpeed both on and off are taken into consideration. The downward peak in the axial vibrations on stand 24 in Figure 4.44 is actually preceded by three other stands with SS off which is part of that trend.

The drilling vibrations in Figure 4.44 are very similar both in mean values and in magnitude (standard deviation) for all directions. They are a bit less powerful when going through the caprock, compared to the reservoir. The one stand which is different yet again is stand 31 which will be studied in Figure 4.46.

Figure 4.44: Effects of SoftSpeed on drilling vibrations ASM1 from well 1.3

The drilling vibrations from ASM2 in Figure 4.45 are also remarkably similar. Stand 31 shows a bigger standard deviation in axial and tangential vibrations, but otherwise all standard deviations are similar.

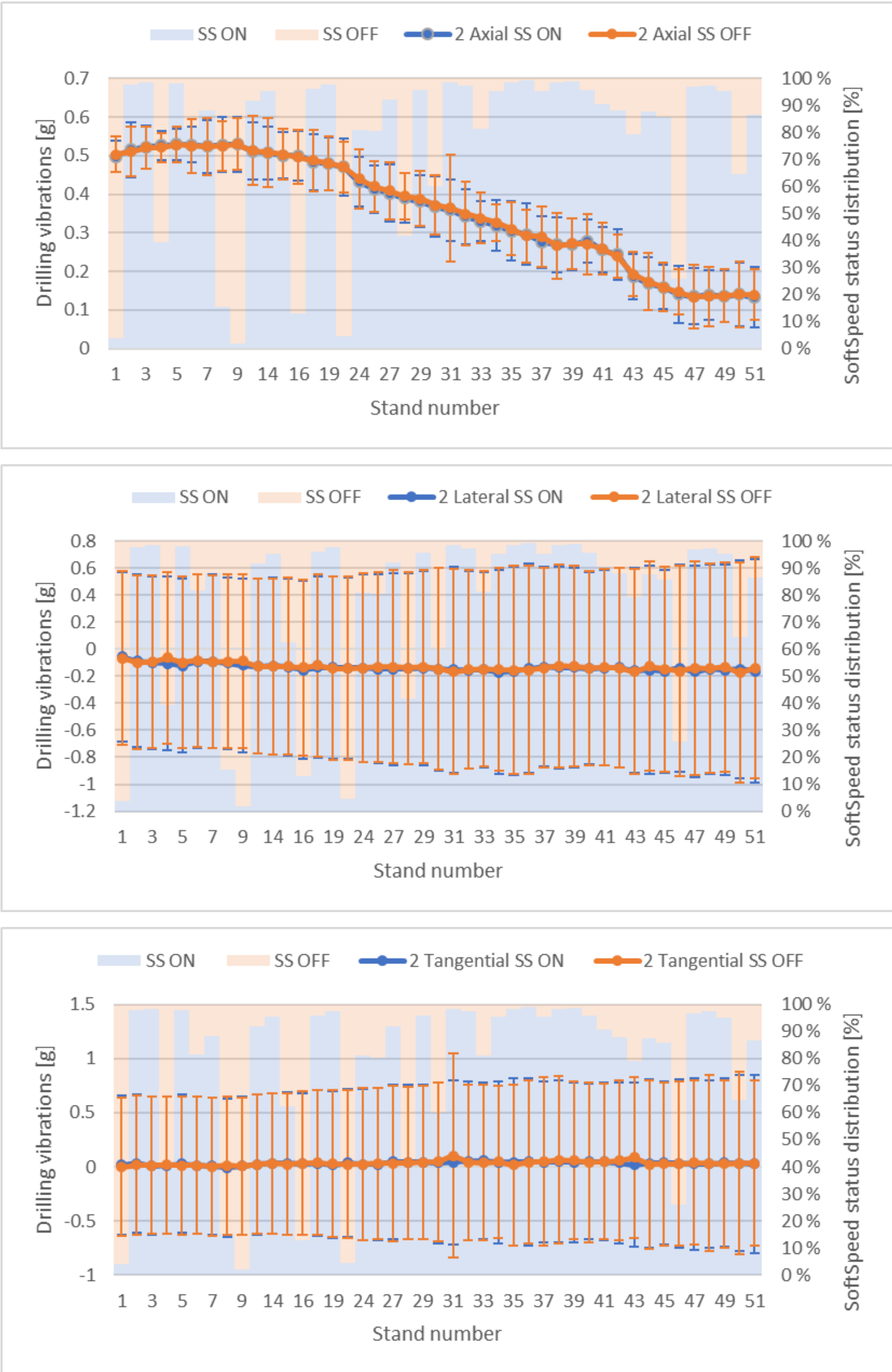

Figure 4.45: Effects of SoftSpeed on drilling vibrations ASM2 from well 1.3

Stand 43 in Figure 4.45 shows a deviation in tangential vibrations. Upon studies of the stand in the timebased dataset, nothing remarkable was observed other than a slight movement of the mean during the course of the stand. It will therefore not be presented separately in the following figures.

4.5.2 Case studies from well 1.3

Time based data from stand 31, 38 and 39 are presented here through the Spotfire software with surface parameters and downhole data from the ASMs. Note that the activation of SoftSpeed is depicted by the red line in all plots where 0 means inactive and 1 is active.

Stand 31 stood out clearly in the depth based stick-slip distribution, as well as in the drilling vibrations analysis, and Figure 4.46 shows why. The situation is after a connection and the stick-slip vibrations start immediately after rotation has begun. There are large oscillations in the surface torque, and the stick-slip severity index is also high. When looking at the rpm sensor, there are clearly oscillations in the string, and even drilling vibrations in the lateral and tangential direction. Drilling does not commence immediately, but when it does, the vibrations continue. When SoftSpeed is turned on, the effects are immediate. The oscillation and vibrations cease abruptly thanks to the application. Surface parameters stays unchanged while activating the system.

Stand 38 in Figure 4.47 shows stick-slip in combination with drilling vibrations after the bit started drilling. The weight was kept constant and all drilling vibrations ceased immediately upon activation of SoftSpeed.

Stand 39 in Figure 4.48, on the other hand, tells a different story. Stick-slip is moderate upon activating SoftSpeed, and the RPM graph from ASM1 together with the stick-slip severity parameters says that the vibrations continue to oscillate post activation. The surface parameters for stand 39 are especially interesting as it is possible to see how the top drive tries to counteract the torque by having an opposite oscillating phase. The SSS stays at an acceptable level and is not yet damaging to equipment, but this is an example of drilling vibrations that is not fully manageable by SS.

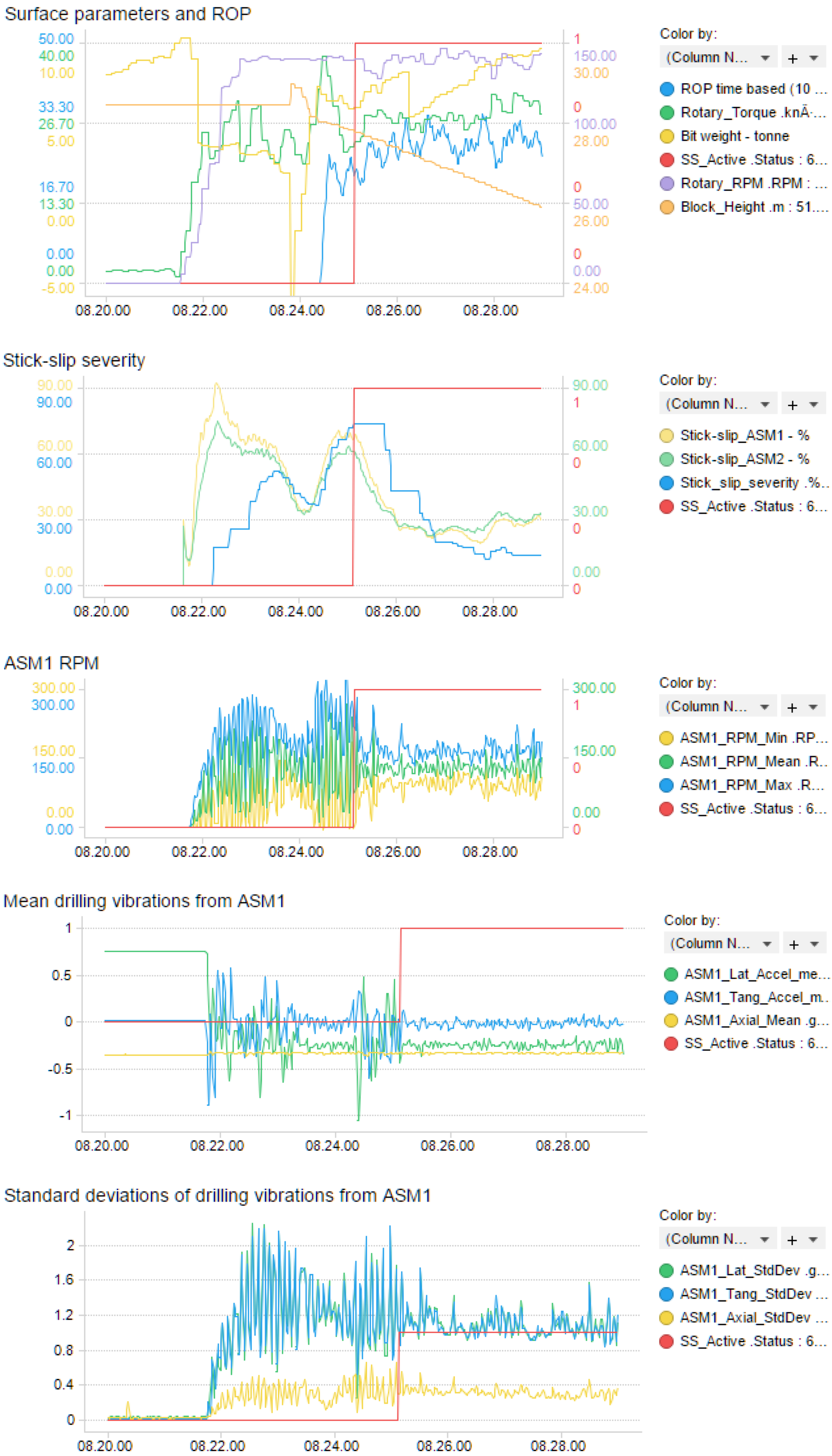

Figure 4.46: Case study from stand 31 in well 1.3

Figure 4.47: Case study from stand 38 in well 1.3

Figure 4.48: Case study from stand 39 in well 1.3

4.6 Well 1.4

Well 1.4 is the longest well and the longest section drilled so far on the field. The reservoir section kicks off from a 85° angle with a target inclination of 90° while slightly turning 8° east.

The lithology of the section consists of 70% sandstone and 20% weathered granite basement rocks past past penetrating the caprock. Two different sandstone bodies were penetrated, differentiated by a major fault with granite basement. The top sandstone cuttings were fine to very coarse in size and moderately to poorly sorted with trace to abundant calcite matrix. The sandstone met past the fault and onwards had very fine to fine grain sizes and was well sorted. The cuttings showed abundant traces of friable to plastic calcite matrix, grading the sandstone to sandy limestone. Faults of weathered basement rocks were met at different depths throughout the well.

Table 4.7: Basic info surrounding well 1.4

Section length	1750m
Section TD	5700m MD/1950m TVD
Bit hours	123.7 hrs
ASM1 offset	64m
ASM2 offset	1043m
Bit grading	1-1-BT-A-X-I-CT-TD
Average ROP	14.3 m/hr
Average MSE	456.6 ksi
Average SSS	8.17 %
Average ASM1$_{SSS}$	15.5 %
Average ASM2$_{SSS}$	19.0 %

Table 4.7 shows the lowest levels of stick-slip yet, but also the lowest ROP. MSE is moderately high, probably related to the lower ROP. The bit from this section shows very little wear with only level 1 of 8 grade broken and chipped teeth divided on the whole bit. The bit was used throughout the whole section and was in gauge.

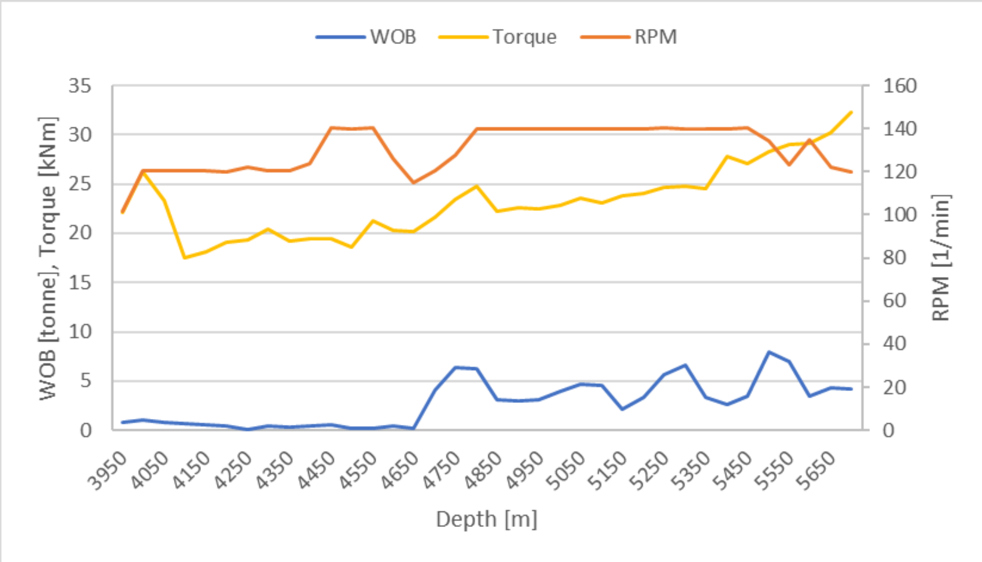

Figure 4.49: Development of surface parameters throughout well 1.4

Reports from the section reveal a limited ROP to 20 meters per hour throughout the well, which explains the low average ROP. The low spike in ROP around 4650 in Figure 4.49 is explained by the bit going through a major fault to weathered basement which led to static losses. While drilling through a loss zone, the ROP is generally limited in order to monitor loss rates and enabling the lost circulation material to settle.

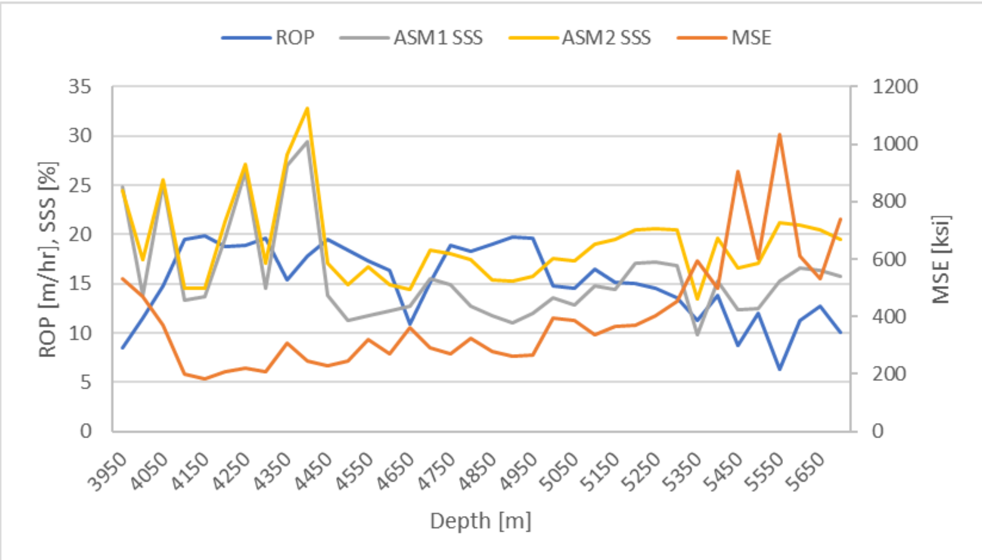

Figure 4.50: Development of performance parameters throughout well 1.4

The WOB is unnaturally low before 4700 meters. Upon investigation of the dataset it was discovered that the hook load sensor reading was incorrect until

4723 meters when it was reset. That means nearly half the well contains wrong WOB data, and that the MSE calculation is compromised. Surprisingly, the MSE curve in Figure 4.50 does not react to the sudden increase in WOB, which means that the first part of the MSE equation (4) does not carry much weight for the result.

SSS shows spikes in the first type of sandstone but stays relatively low otherwise. ROP is low in the beginning and end of the section and MSE is subsequently high in the same areas.

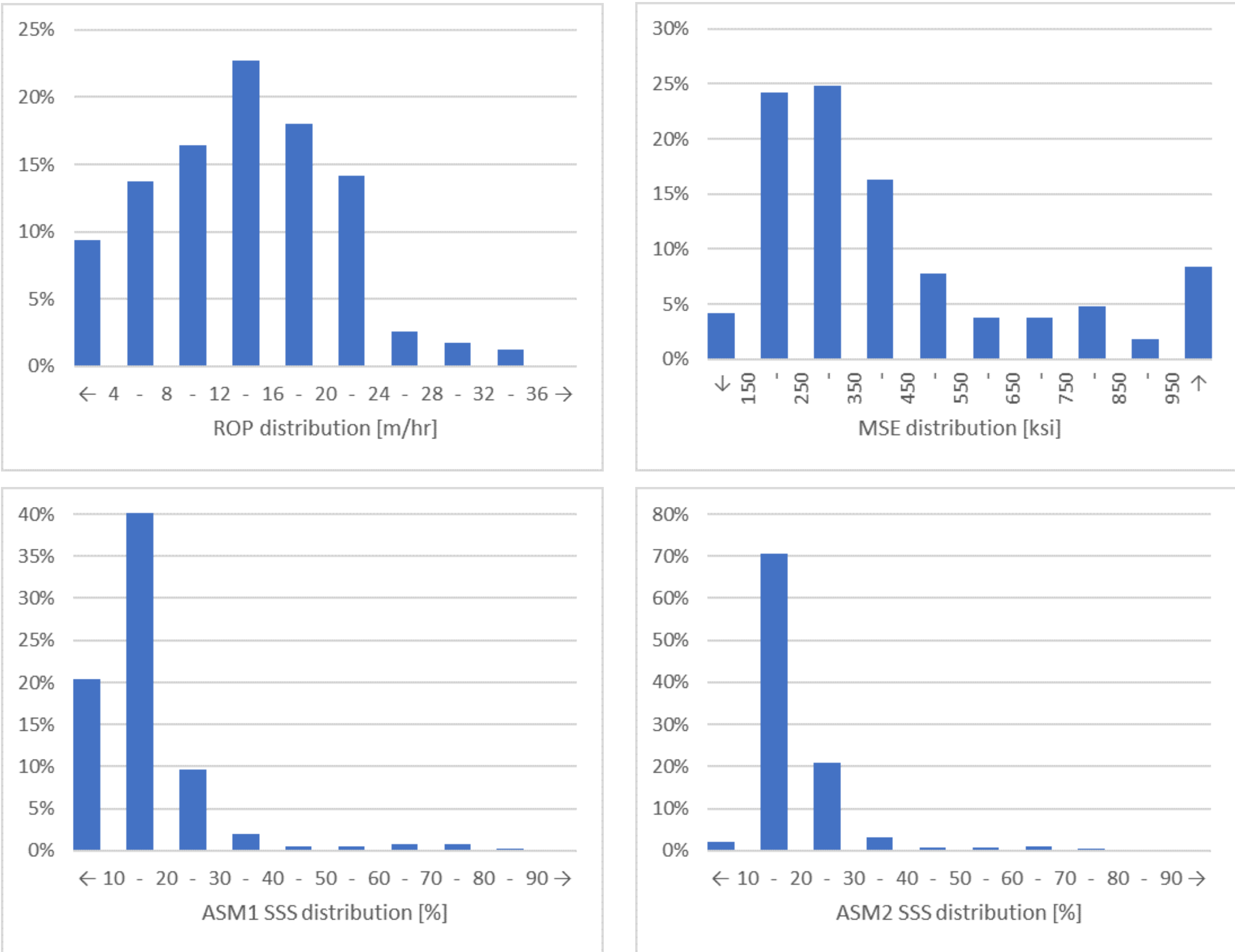

Figure 4.51: Distribution of performance parameters in well 1.4

The distribution of parameters shows a ROP spectrum with an abrupt drop in values above 20 meters per hour. Higher ROP than the limit are not uncommon, but is normally adjusted quite quickly. Around 5% of the values lies above 20 meters per hour. MSE distribution is as normal skewed towards the low end, with a main peak between 150 to 350 ksi. SSS generally stays below 30% stick-slip, but have values up towards 90%.

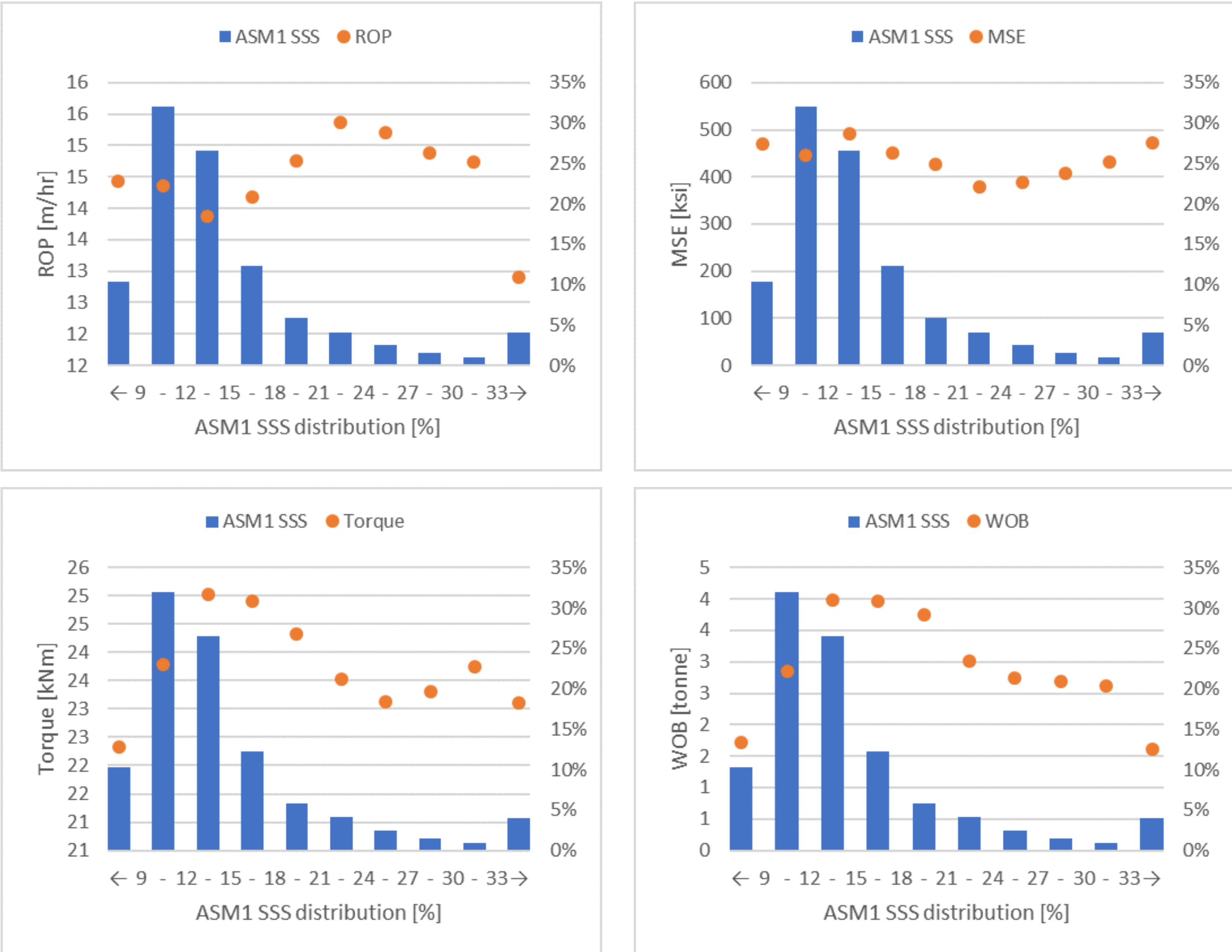

Figure 4.52: Comparison of ASM1 SSS spectrum against ROP, MSE, Torque and WOB in well 1.4

The comparison of parameters with the ASM1 SSS spectrum shows that the highest values of stick-slip are related to low values of torque, WOB and ROP. The trend of the MSE curve seems unaffected by the high levels of stick-slip. WOB is as mentioned compromised in this well and may not be trusted entirely in this comparison. Since MSE stays unaffected, it may indicate that the WOB data point for the highest levels of stick-slip is erroneous as MSE was more or less unaffected by the lower WOB in the depth analysis of the surface parameters.

Axial vibrations from ASM1 in Figure 4.53 varies quite a bit. When studying the lithology log from the section, the largest peaks of standard deviation coincides well with drilling phases through basement rocks. These intervals fits nicely with higher levels of lateral and tangential vibrations from ASM1 as well.

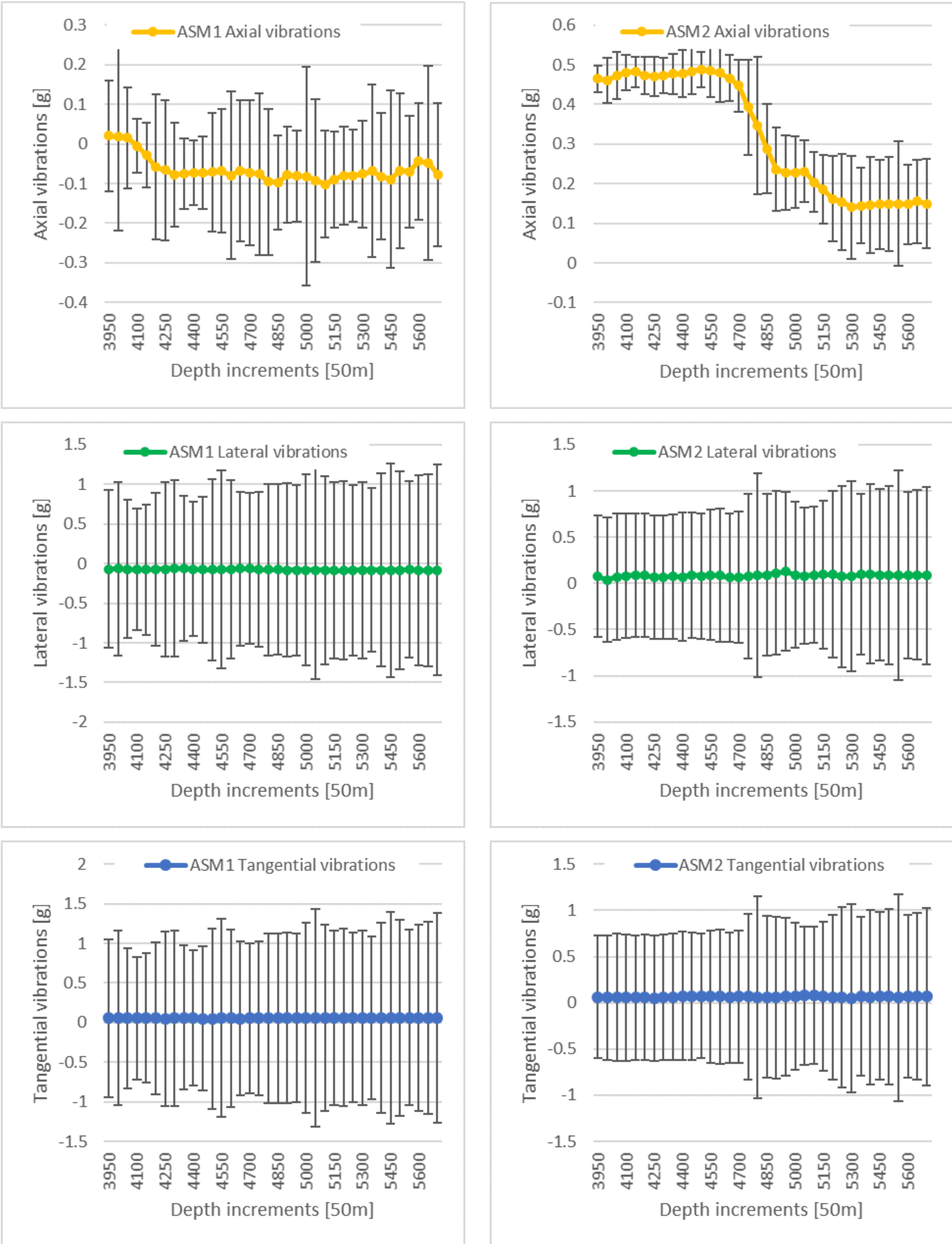

Figure 4.53: Drilling vibrations with standard deviation in well 1.4

4.6.1 SoftSpeed in well 1.4

SoftSpeed was used nearly constantly in this section, in total 98.4% of the drilling time. Unlike well 1.3, there is a real difference of when the application was inactive. As seen in Table 4.8, the levels of stick-slip are much higher when SS is off, in addition to higher MSE and lower ROP. The time period SS was inactive amounts to 2 hours. This may seem like a low number in the bigger picture, but even 2 hours of stick-slip may induce a lot of damage.

Table 4.8: Average values with SoftSpeed on and off in well 1.4

	SoftSpeed ON	SoftSpeed OFF
Drilling time	121.7 hrs	2.0 hrs
Distribution	98.4 %	1.6 %
Average ROP	14.3 m/hr	11.4 m/hr
Average MSE	455.7 ksi	510.7 ksi
Average SSS	9.1 %	40.0 %
Average $ASM1_{SSS}$	15.1 %	39.8 %
Average $ASM2_{SSS}$	18.6 %	39.9 %

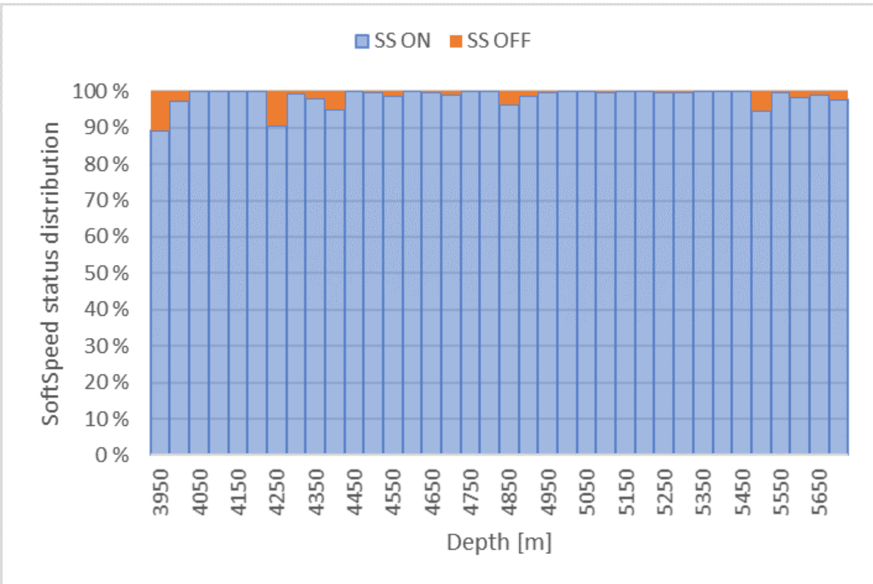

Figure 4.54: The SoftSpeed status distribution in well 1.4

Figure 4.54 shows the depth based distribution of SoftSpeed status, given in 50 meters intervals where the highest value in each interval is denoted as the axis value. Only intervals containing more than 0.5% is included in the following depth based parameter and drilling vibrations analyses.

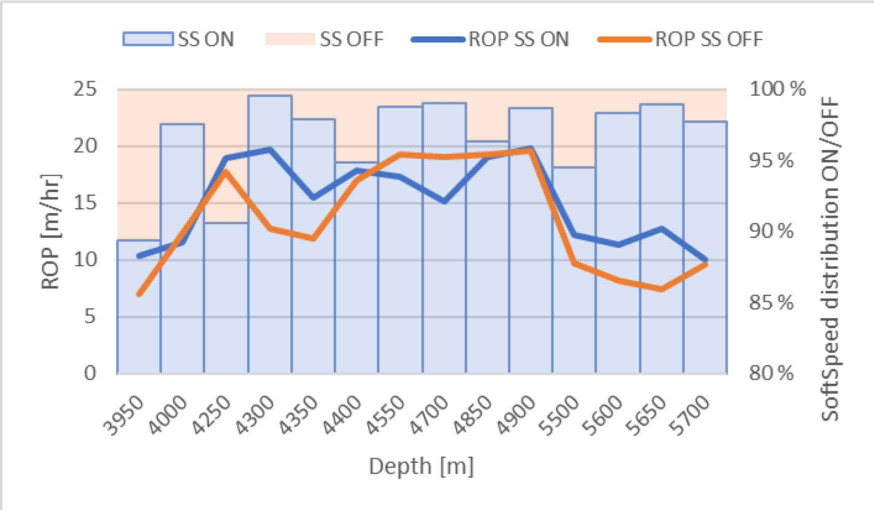

Figure 4.55: Effects of SoftSpeed on ROP in well 1.4

The scale of SoftSpeed distribution is given from 80-100% in all comparisons as there is no need to show the entire scale. The effects on ROP is given in Figure 4.55. Two areas show lower ROP when SS is inactive. The interval towards the end is due to a slow activation of SoftSpeed, but the early interval is related to small areas with stick-slip and low RPM where the system is reset for a very short period of time. This phenomenon will be shown in Section 4.6.2.

The effects on MSE in Figure 4.56 are inversely proportional to the ROP.

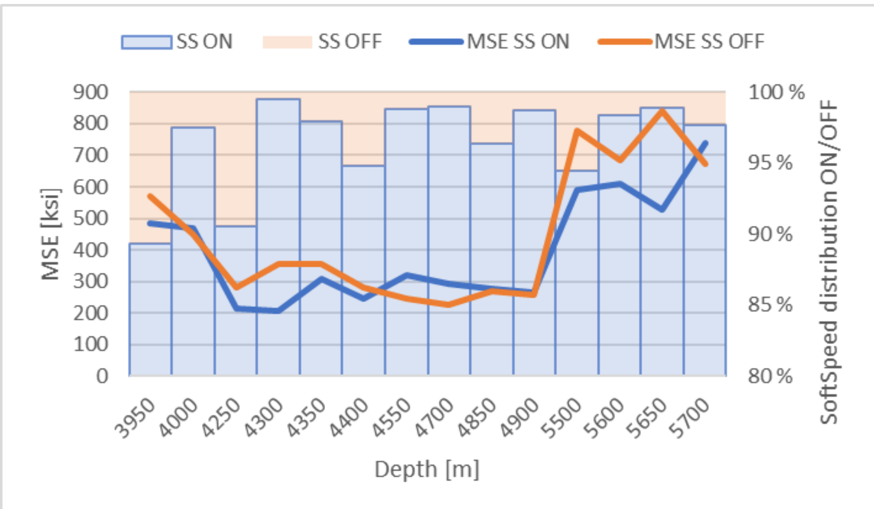

Figure 4.56: Effects of SoftSpeed on MSE in well 1.4

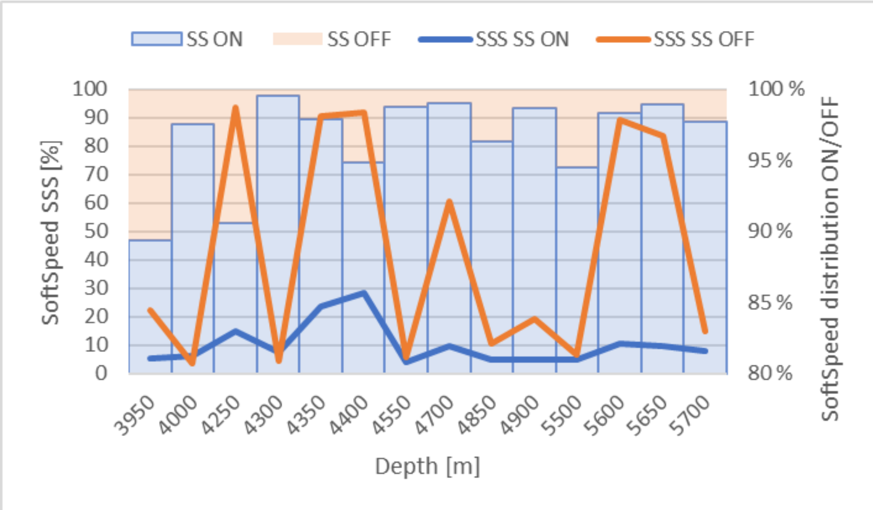

Figure 4.57: Effects of SoftSpeed on system SSS in well 1.4

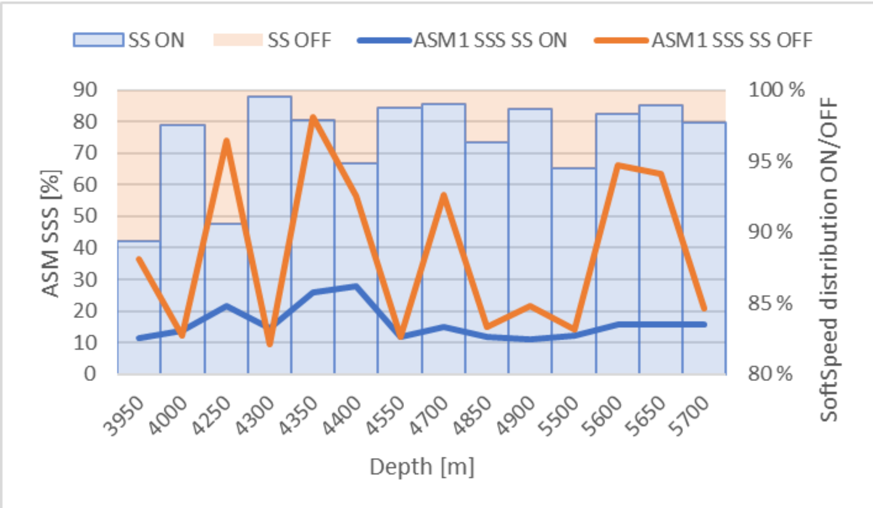

Figure 4.58: Effects of SoftSpeed on ASM1 SSS in well 1.4

The effects of SoftSpeed on SSS is quite substantial in this well, as shown in Figure 4.57, Figure 4.58 and Figure 4.59. Even though the time period off is very low, the increase of stick-slip is massive, showing that the system is doing a good job of keeping the vibrations at bay. It is also remarkable that the calculation from the system coincide very closely with the ASM derived values. Two example will be studied closer, namely the depth interval up to 4250 meters and the depth interval up to 4400 meters.

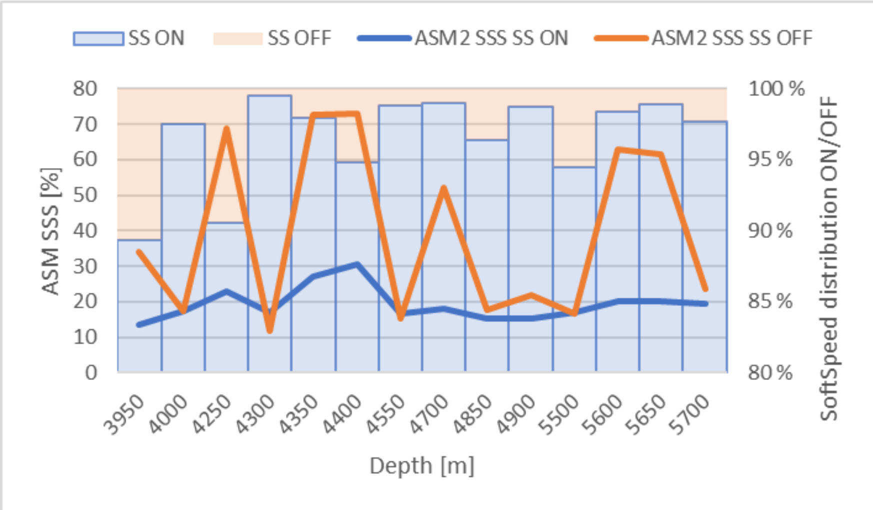

Figure 4.59: Effects of SoftSpeed on ASM2 SSS in well 1.4

The following figures will show the distribution of performance parameters in the well with SoftSpeed on and off. Keep in mind that the distribution with SS off only represent 2 hours of total drilling time, or 1.6%.

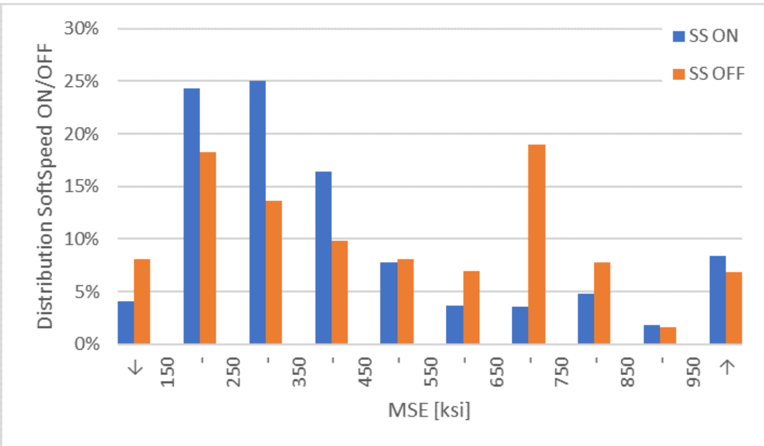

Figure 4.60: The MSE distribution with SoftSpeed on and off in well 1.4

The distribution of MSE in Figure 4.60 shows higher MSE values with SS off, peaking in the 650-750 ksi interval. However, 65% of the values are below 650 ksi and shows a distribution skewed to the right, which may indicate that not all of the time period with SS off led to high-energy environments.

ROP in Figure 4.61 shows a much larger distribution of low values when Soft-Speed is inactive. Over 30% is below 4 meters per hour, which seems to be taken straight out of the 12-20 interval, as the distribution otherwise is very similar. This may indicate that SS off leads to lower ROP.

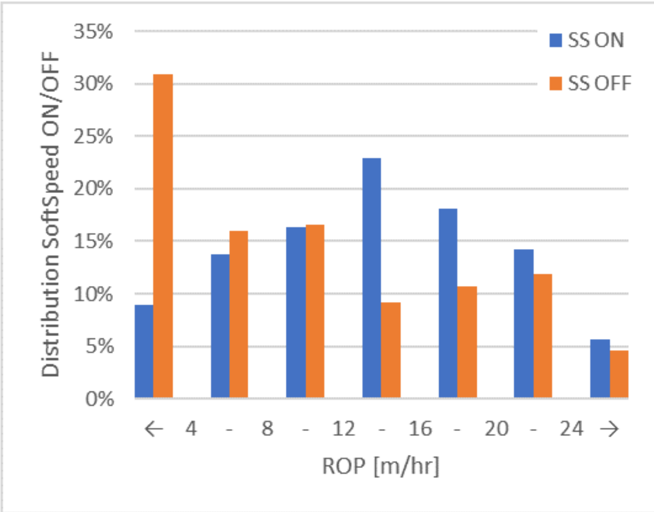

Figure 4.61: The ROP distribution with SoftSpeed on and off in well 1.4

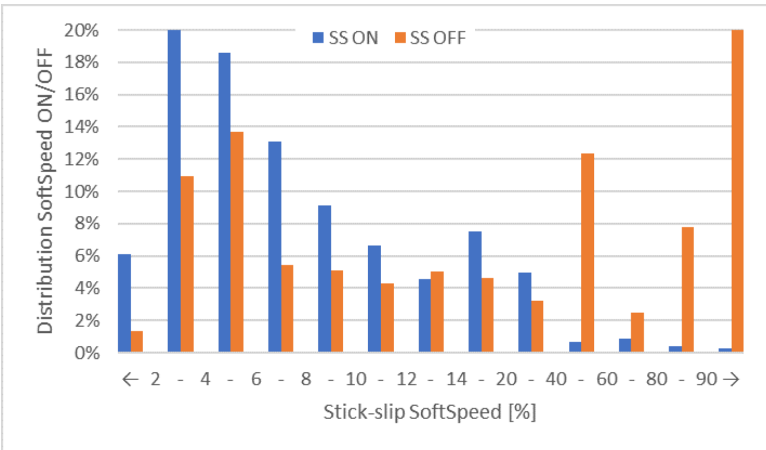

Figure 4.62: The stick-slip severity distribution with SoftSpeed on and off in well 1.4

The stick-slip severity distribution from both SoftSpeed in Figure 4.62 and for ASM in Figure 4.63 are very interesting as they show much higher values of stick-slip when the system is inactive. Note that the distributions are not linear in either figures.

45% of the values in the SoftSpeed distribution are above 20% stick-slip when the system is off, while 67% are above 30% stick-slip for ASM1. ASM2 shows a distribution with a lower stick-slip density than for ASM1. It has been said earlier that ASM1 SSS is expected to reflect SoftSpeed SSS the best as the sensor is closest to the bit. The indications from these comparisons are that ASM1 reflects more stick-slip than SoftSpeed calculations, and that ASM2 which is located further back in the string does not experience stick-slip to the same degree. More discussion of this will follow in Section 5.4.

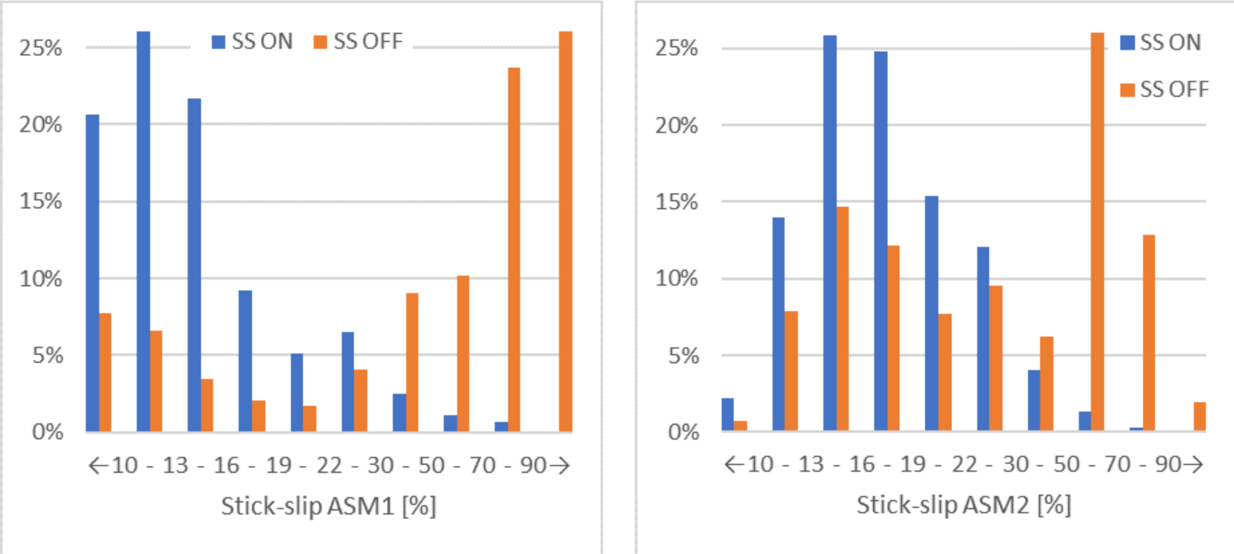

Figure 4.63: The calculated stick-slip distribution for ASM1 & 2 with SoftSpeed on and off in well 1.4

The following figures compares the drilling vibrations with SoftSpeed on and off for both ASM1 and 2. There is a trend of higher magnitude vibrations (standard deviation) when SS is off, especially for ASM1. Main exceptions are in the beginning and the end of the well. ASM2 does not seem to be equally effected by the vibrations experienced at ASM1, which indicates a dampening effect of the string.

Most occurrences of deviation between SS on and off are due to a small time period in the beginning of each stand before the system is activated. But in some cases, SoftSpeed is turned off and on mid stand where stick-slip is building.

The cases presented in Section 4.6.2 are of the latter. They are from the 50 meter interval up to 4250 and up to 4400. It may be interesting to note that these areas does not represent major differences in neither lateral nor tangential vibrations.

Figure 4.64: Effects of SoftSpeed on drilling vibrations in well 1.4

4.6.2 Case studies from well 1.4

The three case studies here represent the most interesting parts of drilling that explains the most, even though there are more indications of interesting sections from the depth based parameter and drilling vibrations analysis. The last case is used to describe a phenomenon appearing in the first two.

Figure 4.65 shows a stand drilled from 4200-4230m MD. The interesting part is where SoftSpeed was turned off for a longer period, which shows that the drilling environment definitely is within the stick-slip regime and drilling vibrations are much higher. SoftSpeed was deactivated manually by the driller due to pack off tendencies. A closer look on this will be presented in Figure 4.67.

Figure 4.66 shows the same occurrences of shutting down SoftSpeed adjacent building stick-slip. This figure shows a stand between 4370 and 4400 meters in the well. Here is a good example of how SoftSpeed may struggle against stick-slip, as there were many small peaks, but eventually keeps it under control. There are many occurrences of building and declining stick-slip, and in the worst cases of stick-slip the driller deactivates the system to go down on weight and subsequently ROP.

Figure 4.67 shows a close up of an occurrence where the driller turns off SoftSpeed, or more accurately turns off the auto driller, in order to drill manually. When the auto driller is shut off, the SoftSpeed system deactivates automatically.

Through reports from the wellsite, the driller responded in these cases to indications of pack-off. These are normally detected through monitoring of standpipe pressure which in this figure is plotted in the surface parameters graph. In these wells, also stick-slip and drilling vibrations accompanies the pressure variation in the standpipe.

The values for stick-slip are high in these cases, which may explain the difference in distribution of stick-slip with SoftSpeed on or off.

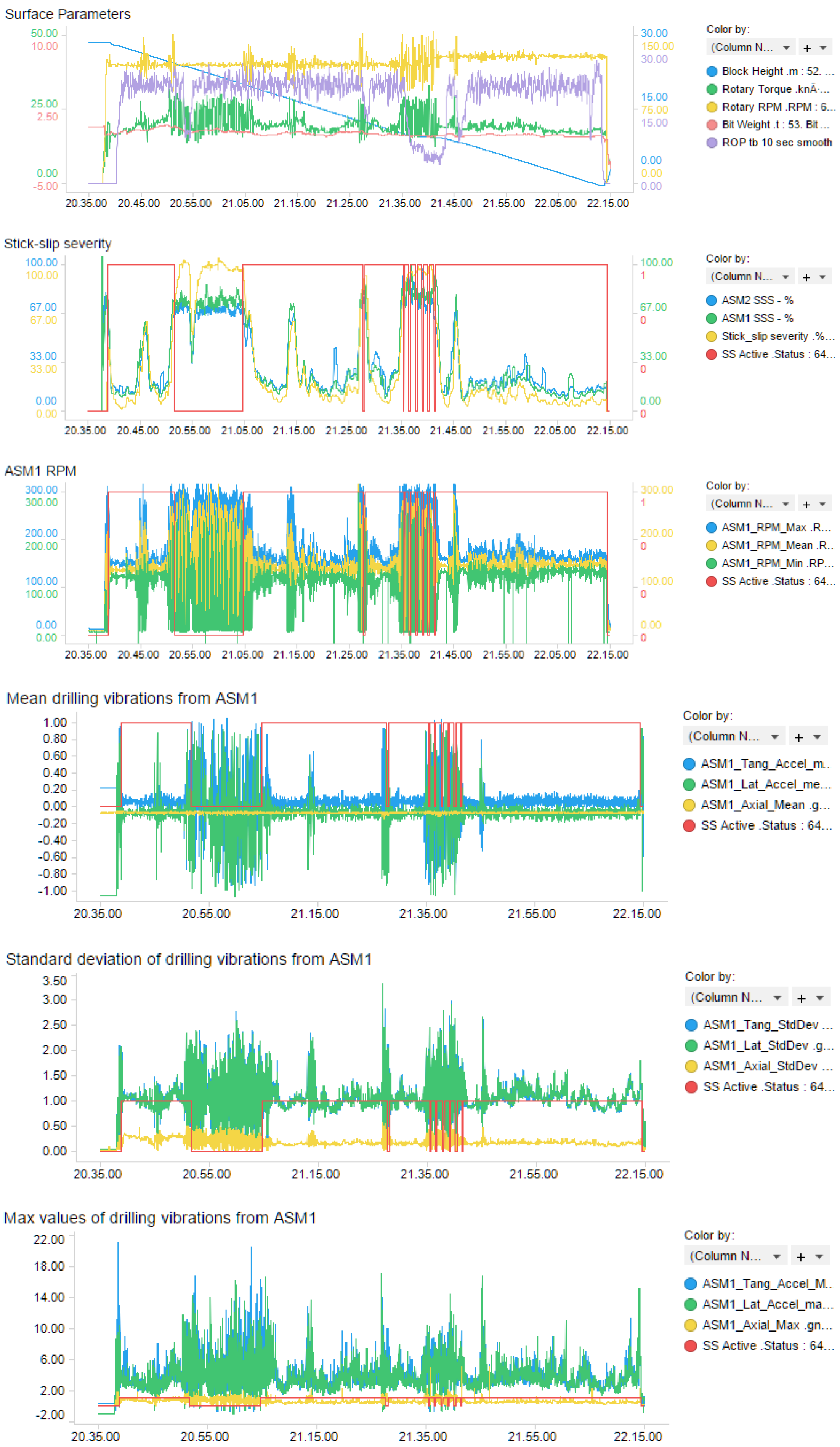

Figure 4.65: Case study from 4200-4230m MD in well 1.4

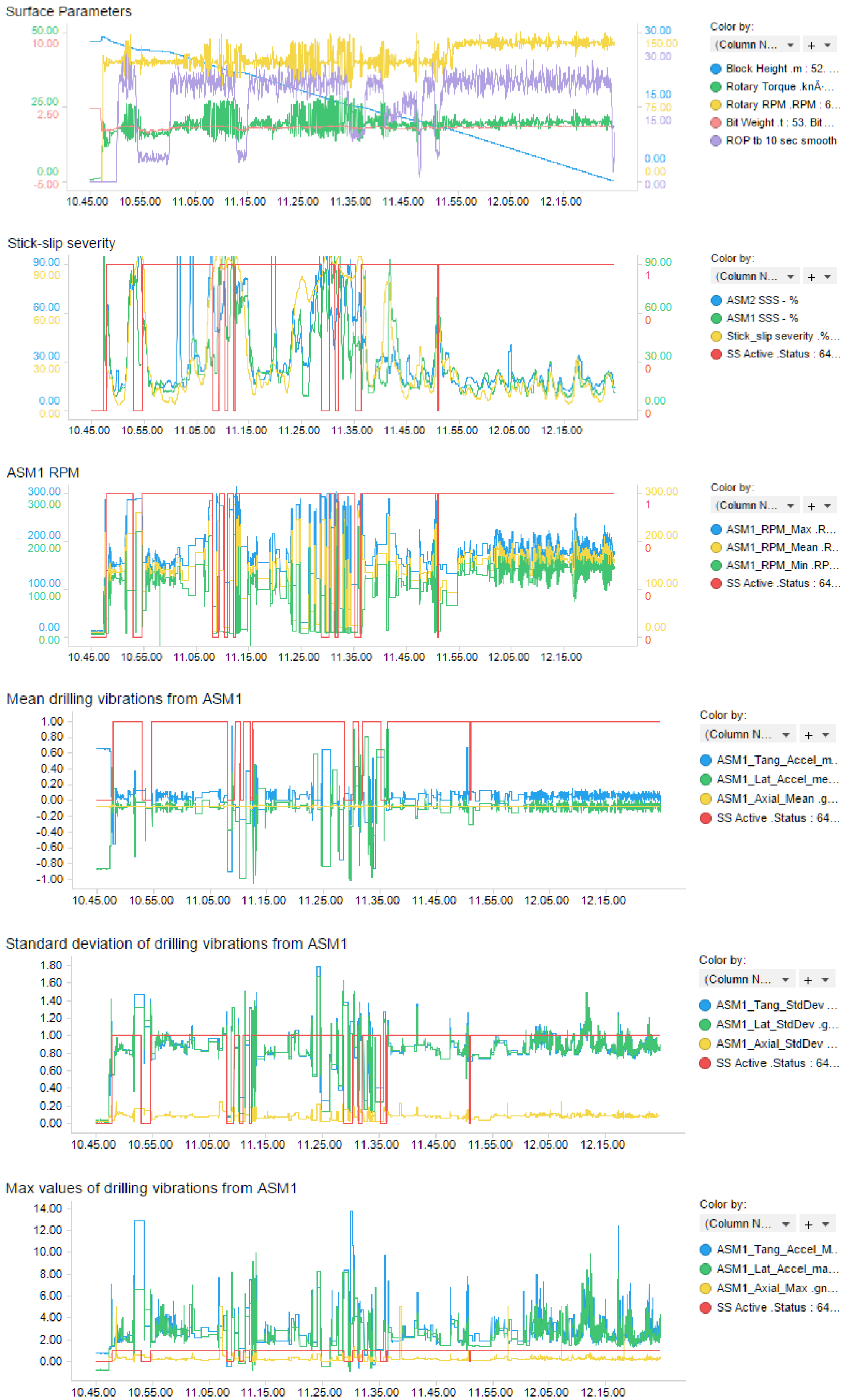

Figure 4.66: Case study from 4370-4400m MD in well 1.4

Figure 4.67: Case study from 5236-5240m MD in well 1.4

4.7 Comparison of all wells

In this section, the differences between each well will be established by comparing lithology, performance parameters, drilling vibrations and bit gradings. Some results are convincing, others doubtful, but all results will also be discussed in Section 5.

4.7.1 Lithology and stick-slip

Lithology is maybe the most important factor causing drilling vibrations in a borehole, therefore it is important to take it into consideration when comparing different wells. For a completely scientific approach all wells should be equal in lithology, wellpath and input parameters, but that is of course not the case in real life. Therefore an estimation must be made on account of all different parameters available.

Table 4.9: Approximate lithology distribution from all wells

Well #	1.1	1.1T2	1.2	1.2T2	1.3	1.4
Caprock	10 %	-	10 %	-	10%	10%
Sandstone	67.5%	40%	40%	7.5%	-	70%
Conglomerates	2.5%	20%	50%	7.5%	90%	-
Silt/claystone	20%	40%	-	80%	-	-
Basement	-	-	-	-	-	20%

In well 1.1, stick-slip is recurrent when drilling through the caprock. However, there was also an interval between 2350 and 2500 with recurrent stick-slip. The lithology of this interval was sandstones and small layers of conglomerates.

Well 1.1T2 shows an increasing trend of stick-slip towards the end of the section. These areas are dominated by interbedded clay- and siltstones with conglomerates. The bit from this well is very worn, which is of course a contributing factor, but upon research of the time based data set, the drilling vibrations are closely related to intervals containing conglomerates.

Well 1.2 shows a trend of increased stick-slip from the 3450-3500m interval to 3750m. Lithology up till then has been layers of sandstones and conglomerates, and lithology is not changing drastically at the time of incurring stick-slip. Upon investigation of the time based dataset it was discovered that there were small periods of stick-slip and drilling vibrations prior to the area in question, but the vibrations abated without interference. The case for 3450m onwards is an attempt of ceasing the drilling vibrations by reduced RPM and increased WOB, exactly the opposite of recommended drilling practice.

Well 1.2T2 shows very little drilling vibrations overall, except for in the beginning of the section which starts out in conglomerate. The rest of the section consists mainly of silt- and claystone, which indicates that this lithology is not very abrasive against the bit.

Well 1.3 is drilled through conglomerates for the whole section past the caprock. Stick-slip is absent in most of the section, even those parts drilled without Soft-Speed active. However, the system was active for most parts of the deeper section, showing trends of recurring stick-slip in the areas prior to activation as shown in the case studies.

Well 1.4 is perhaps the most technical well of them all. A very long well and section, drilling through multiple faults and weathered basement rocks (granite). Despite all this, stick-slip and drilling vibrations are mainly absent.

4.7.2 Performance parameters

Table 4.10 shows the average values of all performance parameters for all wells. Two values are added to this list which is SSS above 30% that shows how much higher levels of stick-slip there is in the well.

The best and the worst ROP values are awarded to the two wells utilizing Soft-Speed; well 1.3 and 1.4 respectively. The low ROP in well 1.4 is due to a upper limit set to 20 m/hr during drilling operations in addition to drilling through hard and challenging basement rocks.

The lowest MSE value goes to well 1.3, which is quite impressive as that section is very long and the well has a very long reach. A longer well requires generally more energy to drill, especially when drilling through hard conglomerates. Well 1.4 also has a relative low MSE, especially considering the length of the well and section. The worst MSE value is from well 1.1T2, due to a very worn bit (Figure 4.71).

SSS values are reduced gradually from well to well. Well 1.2T2, 1.3 and 1.4 stands out with the lowest values where a measly 8% of all values are above 30% stick-slip for well 1.2T2, while only 5.5% and 5% of all values are above 30% stick-slip for well 1.3 and 1.4. As established in the lithology section, the low values of stick-slip for well 1.2T2 are mainly due to an easily drillable formation, while for well 1.3 and 1.4 it is purely thanks to SoftSpeed.

Table 4.10: Average performance parameters for all wells

Well #	1.1	1.1T2	1.2	1.2T2	1.3	1.4
AVG ROP [m/hr]	19.4	16.9	15.7	17.3	21.9	14.3
AVG MSE [ksi]	447.7	641.8	383.8	504.0	350.2	456.6
AVG $ASM1_{SSS}$ [%]	49.7	52.9	36.9	25.1	20.6	15.5
AVG $ASM2_{SSS}$ [%]	42.3	49.3	31.9	26.0	22.2	19.0
$ASM1_{SSS}$>30% [%]	56.2	72.1	41.4	8.0	5.5	5.0
$ASM2_{SSS}$>30% [%]	51.9	69.8	35.5	13.9	9.3	6.4
SoftSpeed SSS [%]	-	-	-	-	8.2	8.2

For a more extensive comparison of the performance parameters, all distributions have been compiled in Figure 4.68 and set in a bar chart system, where all different intervals amounts to 100%. The color scale is set from blue (best) to black (worst), and is shown in the opposite direction for ROP, since the worst ROPs are the low ones.

The figures reflects the average values, but the distribution is not evenly in most cases. A few interesting distributions are the MSE for well 1.1, the ROP for well 1.4 and the SSS for well 1.2T2.

Well 1.1 shows the highest concentration of low MSE values of them all. This well is also the shortest well drilled, and the large amount of low MSE confirms the principle of lower energy input for shorter wells.

The ROP for well 1.4 is interesting as it shows a relatively uniform distribution of all velocities except above 24 meters per hour where there are almost no values. This was also noticed in the original distribution of the well.

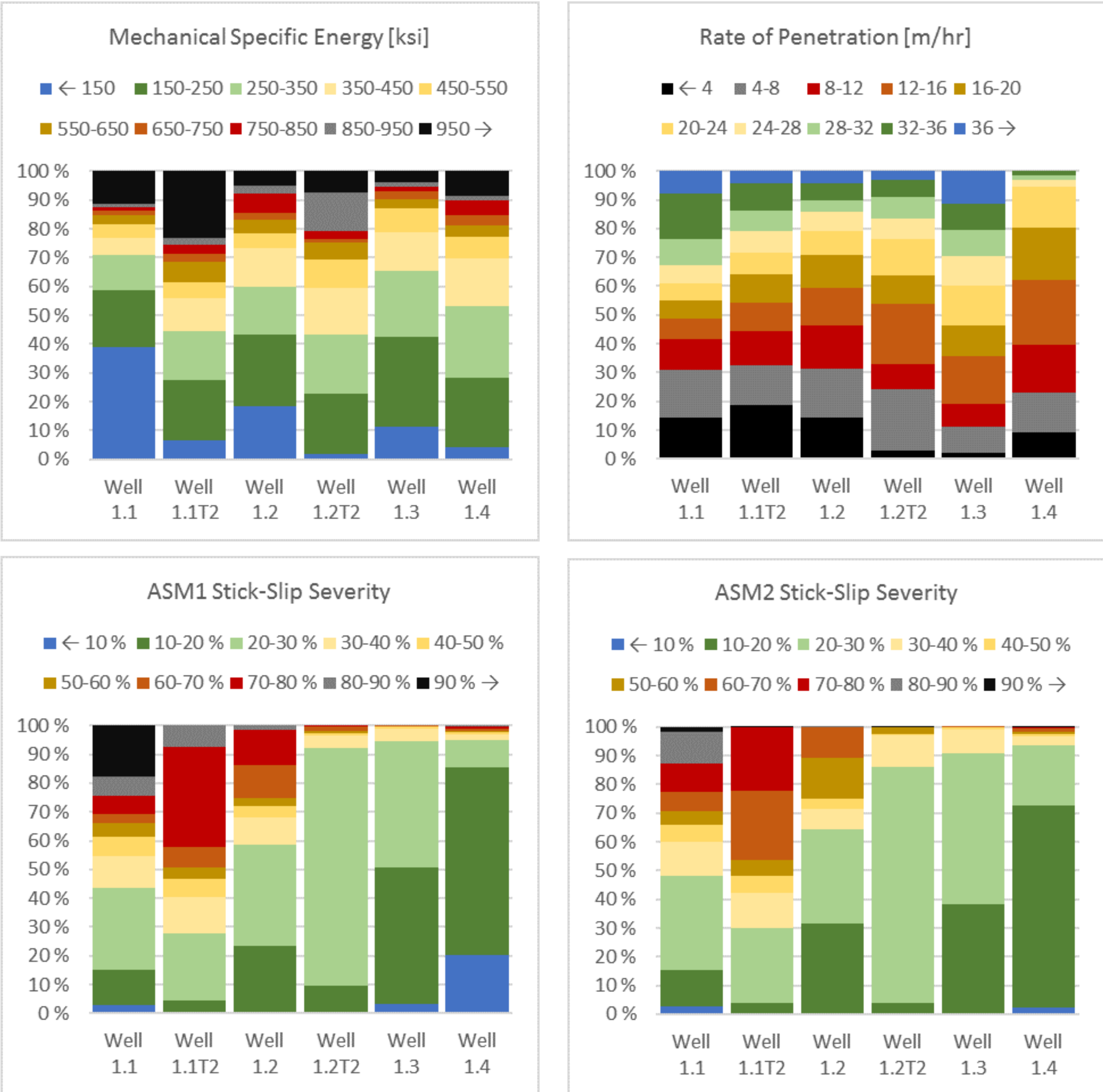

Figure 4.68: Comparison of distributions for all wells: ROP, MSE and SSS from ASM1&2

SSS in well 1.2T2 lies mainly between 20-30% stick-slip. It is interesting to see this distribution next to the others. No other well has such a large distribution of any values. Around 80% of the values lies within that interval. Also, around 80% of the lithology consists of silt- and claystone. The relation of percentages are remarkable.

4.7.3 Drilling vibrations

This section compares the standard deviation and maximum deviation of the drilling vibrations recorded by ASM1 and 2 for all wells. These charts are interesting as the actual magnitude of the vibrations are compared, which is difficult to achieve when plotting drilling vibrations depth based where the scale of the graphs needs to be adjusted according to the magnitude in order to see differences in trend.

Maximum deviation is defined as the maximum value minus the mean, which means that movement in axial vibrations does not affect the value. The graphs plot the average values for each section on top of each other to achieve "total vibrations" in all directions from both sensors.

Figure 4.69 shows the average standard deviation stacked on top of each other for all wells. Axial vibrations contribute very little in the overall picture. The results of this analysis is very disturbing when looking for positive effects of the SoftSpeed system. This analysis actually shows that well 1.3 and well 1.4 has the second highest amount of drilling vibrations in total after well 1.1T2, and it shows that they have the highest values of drilling vibrations from ASM1 of them all.

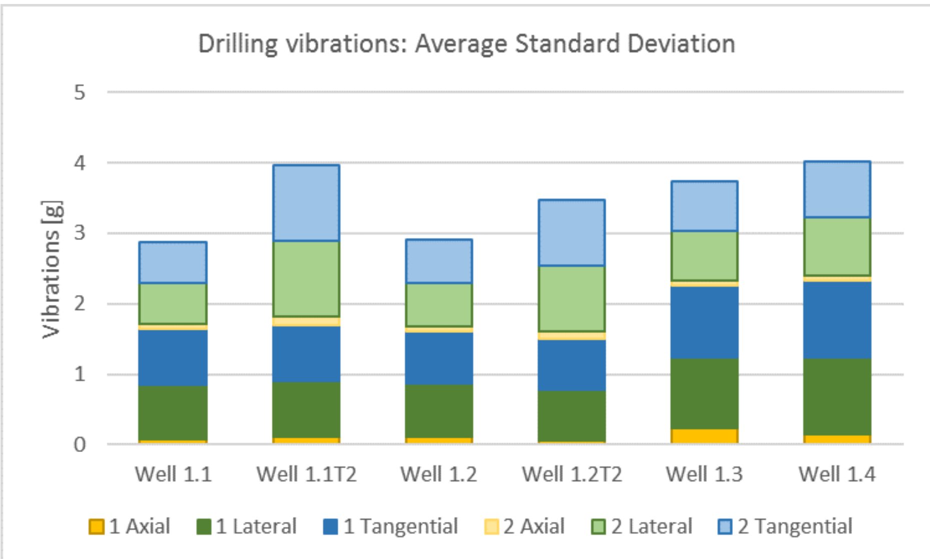

Figure 4.69: Comparison of average drilling vibration standard deviations for all wells

Maximum distribution was introduced in hopes of showing a different trend when including the highest oscillations.Figure 4.70 shows the results of this analysis, and again have well 1.3 and 1.4 the highest combined values for ASM1. Well 1.1T2 shows the highest total amount again, and it is interesting to note the magnitude of lateral and tangential vibrations from ASM2. These actually shows that there are more vibrations higher up in the string than it is close to the bit. The standard deviations in Figure 4.69 shows the same trend.

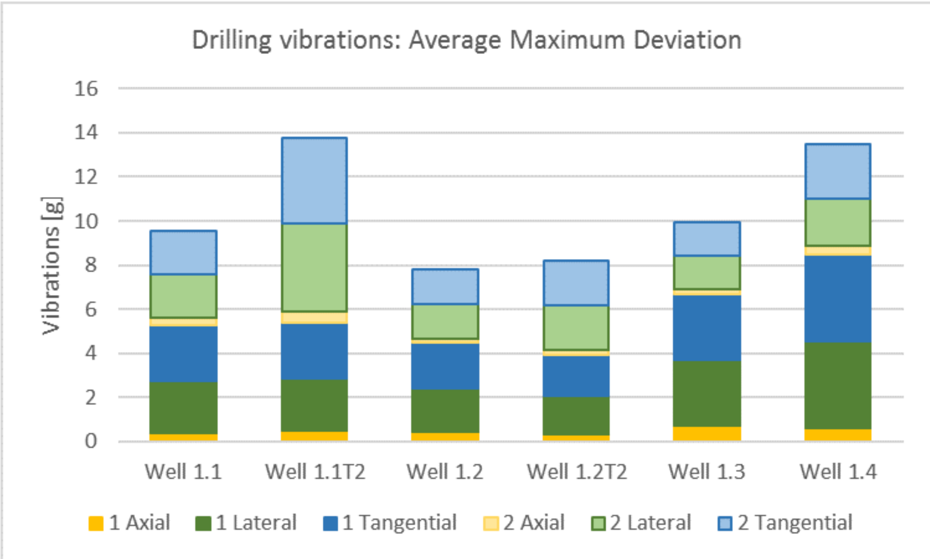

Figure 4.70: Comparison of average drilling vibration maximum deviations for all wells

The results of these analyses will be discussed, and explained, in Section 5.3.2 and Section 5.3.3.

4.7.4 Bit gradings

Bit wear is perhaps the most convincing performance parameter of them all. It is possible to discuss the approach of different data analyses, but it is difficult to argue against a broken bit.

Stick-slip vibrations are caused by bit-to-formation interactions, which means the condition of the bit therefore is a prime indicator of stick-slip induced while drilling.

Both well 1.1 and 1.2 needed two runs to complete the reservoir section, and both were due to a change of bit. All bits, except for well 1.2T2 which mostly drilled through silt- and claystone, are in a really bad shape when they are pulled out of hole.

Bit gradings for all wells are shown in Table 4.11 together with the total bit revolutions, which is the number of revolutions made by the bit while on-bottom drilling. An explanation for all codes found in the IADC bit grading system can be found in Section 2.4.

Table 4.11: Bit grading and total revolutions for all wells

	Bit gradings	Bit revolutions
Well 1.1	1-3-CT-N-X-I-LT-BHA	639048
Well 1.1T2	5-3-RO-N-X-0-WT-PR	320808
Well 1.2	3-5-BT-A-X-1-CT-BHA	600180
Well 1.2T2	1-1-BT-G-X-0-NO-TD	350700
Well 1.3	1-1-BT-S-X-I-WT-HP	559710
Well 1.4	1-1-BT-A-X-I-CT-TD	1026540

The bit from well 1.4 is in remarkable good shape after having drilled such a technical section and with over 1 million bit revolutions. It was graded with only 1 out of 8 wear on the cutters and was deemed okay to use in the next run.

The bit from well 1.3 is also in a very good shape with very low wear on the cutters, validating the low stick-slip occurrences from previous analyses.

The two worst bits are definitely the ones from well 1.1T2 and 1.2. MSE values increased drastically towards the end of well 1.1T2 as ROP declined.

Figure 4.71 shows a picture of the bit from well 1.1T2. The cutters are in some places completely worn down and the body of the bit itself have started to erode. This phenomenon is called ring out and is commonly known to occur in very hard formations. Stick-slip probably played a big part in this instance, as the cutters chipped away sufficiently the body of the bit was subjected to the formation and subsequently eroded.

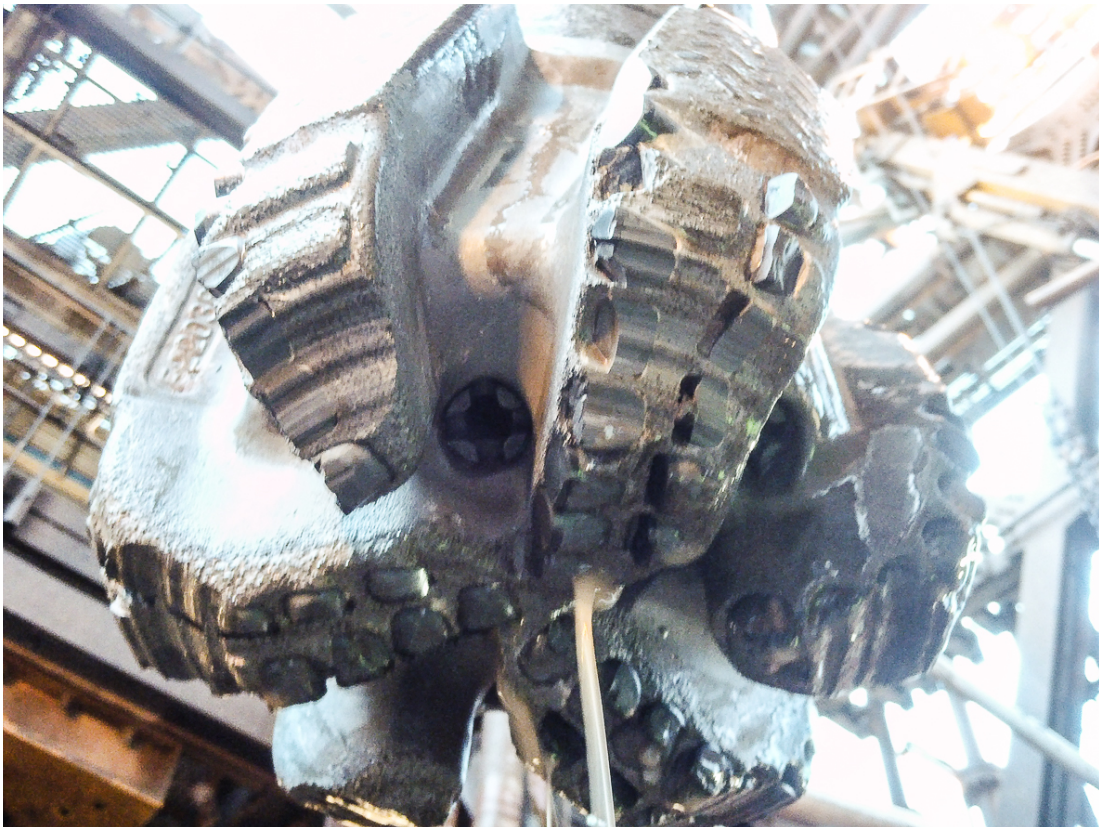

Figure 4.71: Picture of bit from well 1.1T2

5 Discussion

The results from the previous section will be discussed, debated and explained here. Topics that will be discussed are: The relations between lithology and stick-slip. The effects of SoftSpeed on stick slip, drilling vibrations, ROP, and other. Drilling vibrations will be discussed in general and also the movement of axial vibrations, the relation of average torsional vibrations with stick-slip and the relation of lateral vibrations to stick-slip. The validity of the calculated parameters and the method used in this thesis will be discussed. And finally an example of a similar analysis of SoftSpeed from another field will be presented.

5.1 Stick-slip occurrences

Stick-slip is frequent in the first three well sections and in the beginning of the fourth. There is no doubt that the phenomenon have decreased after the implementation of SoftSpeed. But is it possible to accredit the results to the application alone or are there other factors that plays an equally important role?

Stick-slip occurs at the bit when the friction between the bit and formation is too large for the rotational forces to overcome. The critical part of the phenomenon is that the vibrations are self sustaining as the torsional wave is reflected back to the bit by a stiff top drive.

It is this self-sustained vibration mode that must take credit for the very worn bits for the three first sections. When the bit and BHA are subjected of forces up towards 10 g's and quickly decelerated, something must break. Prime examples are the bit gradings and the image of the bit in Figure 4.71.

It is easy to ask if the formations drilled by the two wells with SoftSpeed were easier to drill, but these formations are all part of the same reservoir. Besides, it seems like it is not necessarily all due to one formation interface rather than a gradual wear of the bit over time. Well 1.2 is a good example of this as stick-slip generally stayed low 700 meters into the section where vibrations suddenly started to be recurrent.

Well 1.3 has drilled long sections without the aid of SoftSpeed not showing any issues. But it seems apparent that drilling vibrations occur further into the well and that the system effectively dampens the vibrations. It may be a gradual wear of the bit, or it may be an increased hardness of the rock further into the reservoir.

Well 1.4 used SoftSpeed almost consistently. In the few areas where it was inactive, either due to pack offs or early in the drilling stand, it showed high levels of stick-slip. However, stick-slip vibrations were observed when the application was turned on but they were quickly reduced back to an acceptable level. It is not about hindering stick-slip all together, it is rather all about not allowing the vibrations to be self-sustained.

5.2 SoftSpeed effects

The alleged effects of SoftSpeed are reduced stick-slip, reduced drilling vibrations, increased ROP, improved borehole quality, reduced bit wear, reduced drillstring fatigue and decreased drilling costs (Appendix A). That is a tall order to achieve, but four or perhaps five of those allegations may be answered in this thesis.

5.2.1 Stick-slip and drilling vibrations

Stick-slip is quantified by the calculated factor Stick-Slip Severity index (SSS) which only takes into account drillstring rotation. SSS was originally created for the SoftSpeed system, but an approximation based off the ASM sensor has been made for use and comparison in this thesis. The SoftSpeed estimation and the ASM estimation varies widely on low values but are very similar in higher values and are otherwise linearly related.

Based upon the SSS parameter, there are no doubts that stick-slip have been reduced when comparing the different wells of this field. Average values from the ASM1 have been reduced from 52.9% stick-slip in well 1.1T2 to only 15.5% stick-slip in well 1.4.

The question related to if drilling vibrations are reduced are a bit more complicated as the comparison of average drilling vibrations from all wells showed dismaying results. This will be discussed and explained in Section 5.3.2 and Section 5.3.3. What can be said already now based on the case-studies is that the oscillations of the drilling vibrations are reduced immediately upon activation of the system.

5.2.2 ROP and drilling time

ROP was not increased significantly due to the use of SoftSpeed when looking at the statistics. ROP was not improved very much, especially not for well 1.4 where it was lower than all other wells. Well 1.3 has the highest ROP of them all, but with a 40/60% distribution of system activation, it shows almost equal values of ROP with the system on or off.

However, if stick-slip would actually be taken seriously and avoided, the ROP for the wells without SoftSpeed would not be equally high. The only way to reduce stick-slip in most cases is to go down on bit weight. When that is not an option, drilling may commence with sufficient ROP but at the cost of stick-slip and drilling vibrations. An additional cost in these two cases were a trip out of hole to change bit. When taking into account the time it takes to trip out, change bit and continue drilling, the progress of the well is significantly lower.

Table 5.1: Total drilling time from start to finish of drilling for all wells

	Total time	Meters drilled	NPT bit trip	Other NPT
Well 1.1	226 hrs	1900 m	52 hrs	9.5 hrs
Well 1.2	261 hrs	1800 m	65 hrs	10 hrs
Well 1.3	93 hrs	1450 m	-	6.5 hrs
Well 1.4	207 hrs	1750 m	-	23.5 hrs

Table 5.1 shows the total drilling time from start to finish. The calculation used in this table is a bit unconventional as the "Total time" only takes into account the time used from drilling the first new formation to the final true depth is set. NPT for the bit trip is the time used from stop of progress to start of progress after bit trip. Other NPT is taken from the daily drilling reports. Both NPT are included in the "total time" estimate.

When excluding the other NPT but including the NPT of the bit trip, the overall progress for the wells changes. Well 1.1 drills 8.8 meters per hour in average, well 1.2 has a progress of 7.2 meters per hour, well 1.3 has a stunning progress of 16.8 meters per hour, while 1.4 shows a progress of 9.5 meters per hour. This approach is very unconventional, but it shows that progress of the well increases when SoftSpeed is utilized.

5.2.3 Other effects

Besides effects on stick-slip, drilling vibrations and ROP, SoftSpeed is said to improve borehole quality, reduce bit wear and drillstring fatigue, in addition to decreased drilling costs.

Reduced bit wear is a side effect of reduced stick-slip, and there is no doubt when studying the bit gradings from these 6 sections that the bit wear is reduced by using SoftSpeed. The bits from well 1.3 and 1.4 was equally as nice as the bit from well 1.2T2, which mostly went through silt- and claystone, even though they drilled much further and through much harder formations. When comparing the bits from well 1.3 and 1.4 with bits that have drilled through similar formations, the difference is striking.

Regarding borehole quality, it is not possible to procure any hard evidences in this thesis as the access to MWD data and logs are limited. However, the lithology logs for well 1.2, 1.3 and 1.4 contains caliper data from the MWD caliper log, and some observations will be included here. First, the transition from caprock to reservoir is affiliated with an increased borehole diameter in all wells, which is not uncommon in such transitions. The transitions between sandstone and basement rock in well 1.4 are also associated with cave-ins of the borehole. However, when comparing well 1.2 and 1.3 there are big differences. Well 1.2 shows large cave-ins in several sandstone and conglomerate intervals that normally increases the borehole by an inch, and in the worst case by 2.5 inches. Well 1.3 does not show the same characteristic at all, being in gauge for most of the well.

Borehole quality is associated with lithology and drill string movement. In a consolidated sandstone there are usually no reasons for the rock to cave in due to the rock composition. However, drillstring movement can hit and scrape the sides of the borehole and such create a cave-in. Stick-slip is associated with tangential vibrations and tangential vibrations are closely related to lateral vibrations (Section 5.3.3). Lateral vibrations move the string from side to side in the borehole, and with enough force, that can create increased borehole diameters.

String fatigue is closely related to both bending, twisting and erosion against formation, and thus closely related to both bit wear and borehole quality. Stick-slip induces torsional waves that travels through the drillstring, and with enough force, it can damage pipe and connections over time. Lateral movement of the string will also cause a slow erosion of the surface which over time will cause the string to deteriorate. It is therefore viable to say that the statement of reducing drillstring fatigue is credible.

Decreased drilling cost comes, amongst others, with reduced drilling time and reduced wear on components. Both conditions are present in this analysis, as the drilling time have effectively been reduced and the bit wear have been massively reduced. When taking into account the reduced wear on the drillstring and other BHA components on top of it all, there is no doubt that SoftSpeed reduces drilling costs.

5.3 Drilling vibrations

There is no doubt that SoftSpeed cures stick-slip, and that oscillations of both lateral and tangential vibrations are reduced as a side-effect of the application. An example of this is shown in Figure 4.46 where both stick-slip and oscillations in lateral and tangential vibrations cease at the activation of the software in well 1.3. Comparing similar sections from different wells also shows that both stick-slip and drillstring vibrations in lateral and tangential directions are recurrent throughout the well.

However, when comparing average drilling vibrations, both in depth based increments and as average values for whole sections, it does not seem as SoftSpeed has made an impact. Both SSS and the bit gradings show that the application makes a big difference, but not when comparing average vibrations.

This section will try to explain why statistical parameters may not work well for stick-slip oscillations. Movement in mean values for axial vibrations will also be explained here.

5.3.1 Axial vibrations

The axial vibrations often changed its mean value in all of the figures presented in the last section. This is thought to be related to the trajectory and curvature of the well.

In Figure 5.1 and Figure 5.2 the axial vibrations from well 1.1 are plotted together with the local inclination and azimuth of the wellpath surrounding each sensor. The azimuth is divided by 3.6 in order to better visualize the direction of the wellpath together with the inclination.

The axial vibrations from ASM2 are especially interesting as they increase in the beginning of the section and later decreases. When studying the wellpath, it is evident that the movement of the axial vibrations are inversely proportional to the inclination and azimuth of the well, as the well actually turns downwards for ASM2 in the beginning of the section, before leveling off later on.

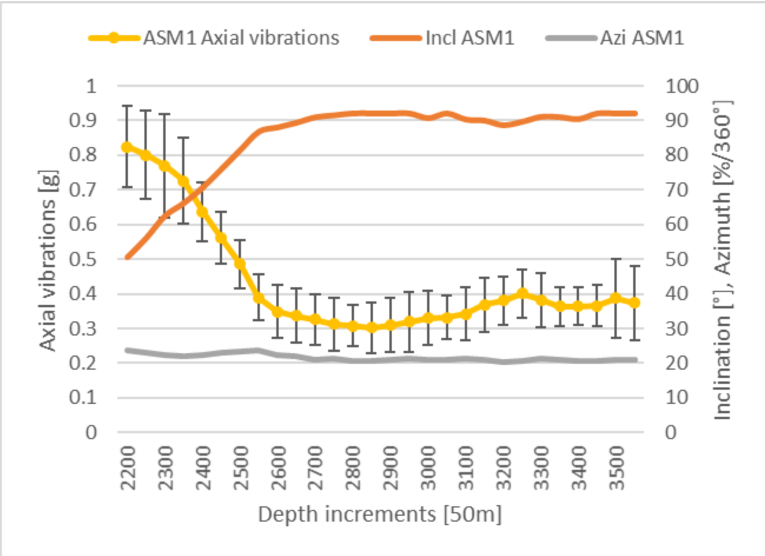

Figure 5.1: Axial vibrations from ASM1 in well 1.1 plotted together with inclination and azimuth

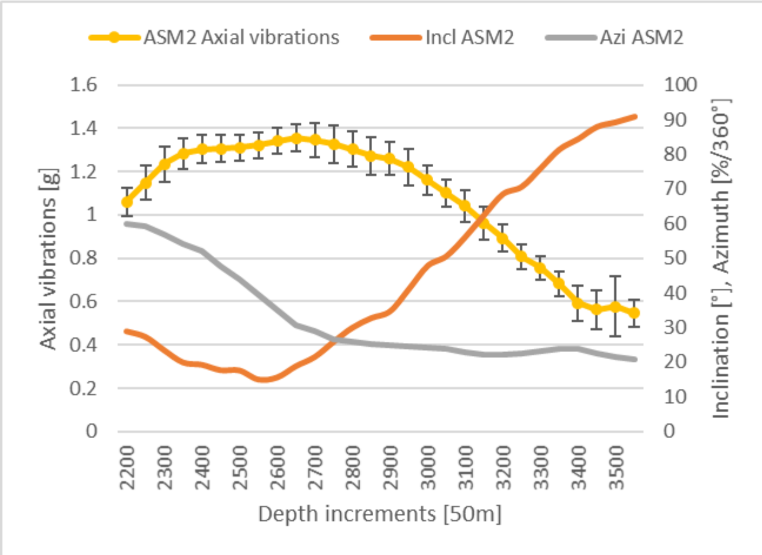

Figure 5.2: Axial vibrations from ASM2 in well 1.1 plotted together with inclination and azimuth

The magnitude of the axial vibrations reflects the compressional forces in the drillstring. The compressional forces are closely related to the neutral point in the string which is always designed to be below or within the BHA at any point in the planned wellpath, in order to prevent buckling. That means they are higher further up in the well. Also, steeper slopes induce higher axial forces because of the force distribution of an angled wellpath. The inclination in Figure 5.2 represents a drop in the wellpath after a tangent section and prior to entering the reservoir. The drop in the wellpath gives higher axial forces as gravitational forces in addition to the compressional force in the well is directed in the axial direction of the drillstring.

The axial vibrations from ASM1 in well 1.3 and 1.4 were both negative when entering the reservoir (Figure 4.44 and Figure 4.53). This indicates that the ASM was located below the neutral point in the string as the axial vibrations indicate tension rather than compression. Since ASM1 in these two wells is located very close to the bit, inside the BHA itself, there should be no reason to conclude that there are any danger of inducing buckling as there is still 130 meters of heavy weight drillpipe, jar and accelerator above. ASM1 was located above the BHA in the other sections and there were no negative vibrations from any of those wells.

5.3.2 Tangential vibrations and stick-slip

The comparison in Section 4.7.3 showed no improvement in magnitude (standard deviation) of tangential or lateral vibrations in either well using SoftSpeed. However, there are clear differences between the wells in terms of stick-slip. And if stick-slip is the definition of extreme tangential vibrations, then why does it not reflect in the comparison of average vibration magnitude?

The difference between stick-slip and tangential vibrations can not be described by average values. When looking at the different case studies of stick slip in Figure 4.6, Figure 4.13 and Figure 4.20, the mean value of tangential vibration is oscillating in the occurrences of stick-slip. However, the mean value will always oscillate around the same point, and that is why the drilling vibrations depth based plots shows a similar mean for all sections, as it only portrays the average over 50 meters.

The ASM sensors sample vibration points in 256 Hz and distribute the mean, standard deviation and maximum value in 0.5 Hz. Figure 5.3 and Figure 5.4 is an attempt to simulate a simple oscillating system with and without stick-slip that is sampled in 256 Hz and distributed by statistical parameters every two seconds. This is only meant to be an example and does not feature actual stick-slip oscillations.

Figure 5.3 shows a simple oscillating sine wave with a period of $\pi/32$ in a 256 Hz system. The vibrations oscillate between $\pm$ 1 g with a mean of around zero and a root mean square of 0.71. This is an example of a system free of stick-slip, but with steady oscillations.

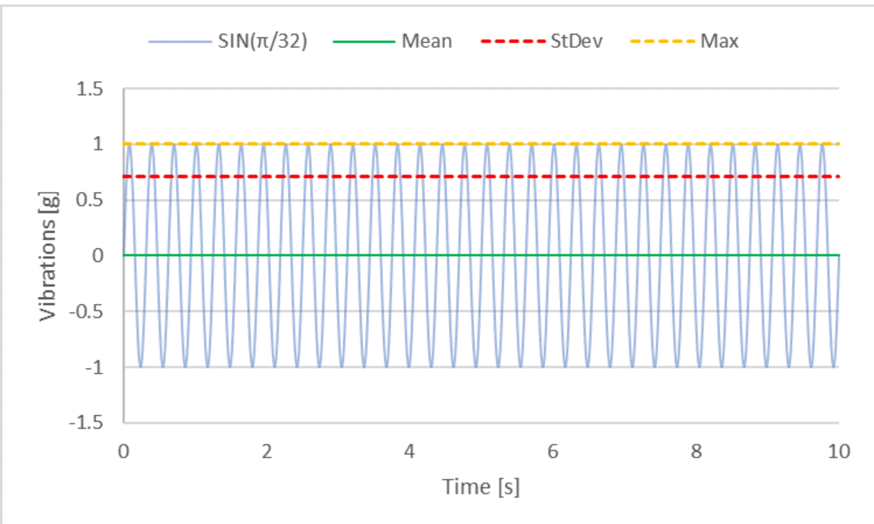

Figure 5.3: Oscillations of steady state vibrations system (256 Hz)

Figure 5.4 represents a system with stick-slip involved which is represented by a sine curve with a longer period. By adding the stick-slip oscillations, the system is now effectively oscillating between ± 2 g. The recorded mean value will also oscillate and will be recorded at different levels, which in turn will look like oscillations when only plotting the mean. The standard deviation on the other hand does not reflect the fact that the system is oscillating more violently and averages on 0.79 during these 10 seconds, only 0.08 higher than for the steady state system. Maximum value is recorded at 2 g, but in average over 8 seconds only 1.5 g is recorded.

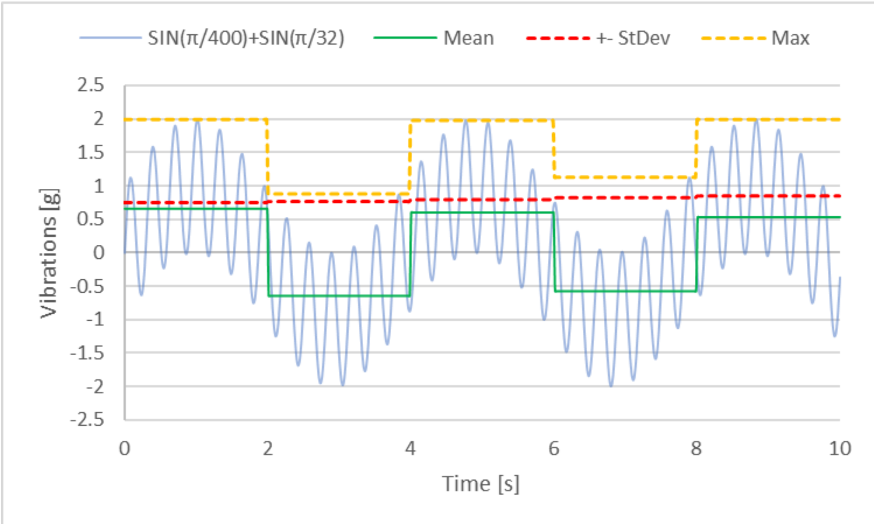

Figure 5.4: Vibration system with higher order oscillations (256 Hz)

These examples are only meant to illustrate the fact that statistical parameters for multiple oscillating systems may not be trusted entirely. Average stick-slip severity index seems to be a better indication for violent tangential and lateral vibrations than average vibration measurements. But when plotting time based data, either in real time or in hindsight, lateral and tangential vibrations are good to illustrate local hole conditions.

For an overall description of the torsional vibrations experienced in a well, SSS is a much better parameter to use, rather than average torsional vibrations. SSS use only average string rotation speed and is therefore not affected by the oscillating nature of drilling vibrations.

5.3.3 Stick-slip and lateral vibrations

One of the initial goals for this thesis is to determine if SoftSpeed reduces lateral vibrations along with stick slip. Through all case studies in this thesis, lateral vibrations have been present alongside tangential vibrations. And both are present under high stick-slip severity values.

One examples is chosen from the case studies of well 1.3, where vibrations were present prior to activation of SoftSpeed. Figure 5.5, Figure 5.6 and Figure 5.6 shows a zoomed in view of the mean, standard deviation and maximum lateral and tangential vibrations from stand 38 in well 1.3. The mean values have been offset from each other in order to see the difference more clearly, while the standard deviation curve and the maximum values are overlapping.

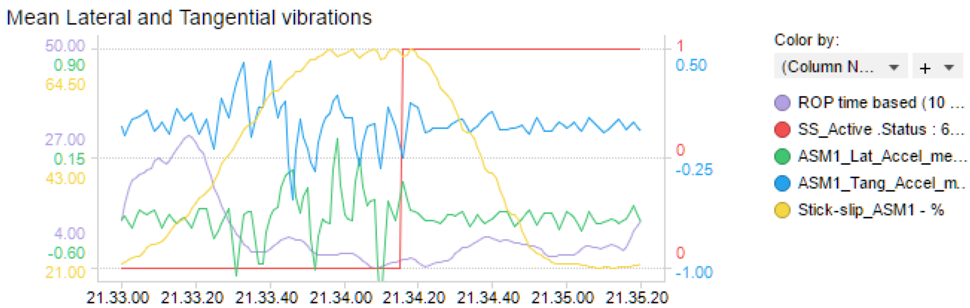

Figure 5.5: Mean lateral and tangential vibrations from stand 38 in well 1.3

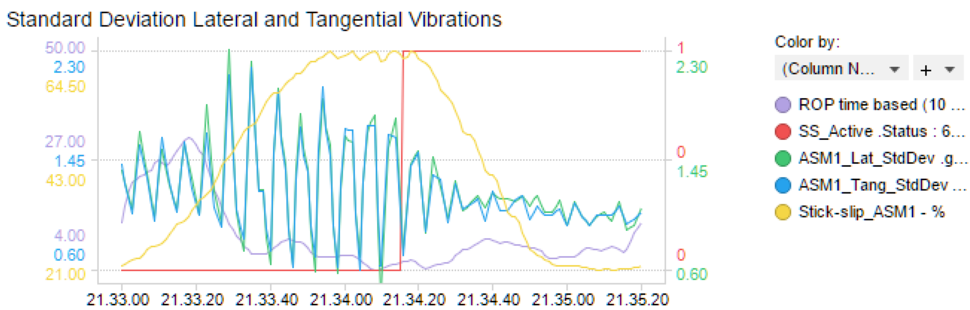

Figure 5.6: Standard deviation of lateral and tangential vibrations from stand 38 in well 1.3

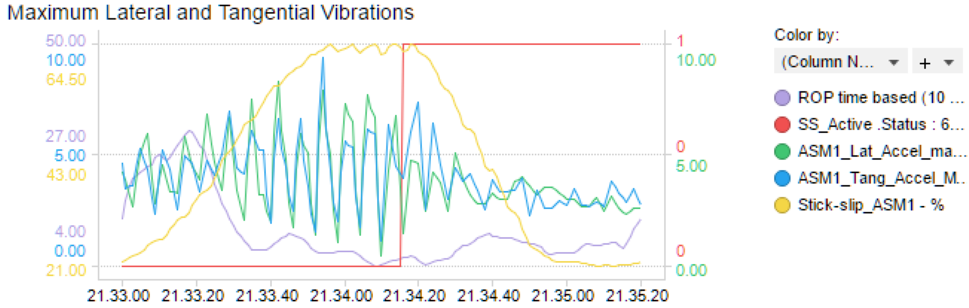

Figure 5.7: Maximum lateral and tangential vibrations from stand 38 in well 1.3

The mean values does not harmonize very well, perhaps slightly inversely proportional. The standard deviations and the maximum values from the lateral and tangential vibrations, on the other hand, are harmonizing almost perfectly. Not only are lateral and tangential vibrations related, they are practically twins.

The lateral vibrations may be backwards whirl induced by stick-slip oscillations, which can be extremely damaging to equipment, but it is not clear from these analyses what type of lateral vibration it is. It is clear however, that SoftSpeed has a positive impact on lateral vibrations as they are effectively dampened in all aspects upon activation of SoftSpeed.

These graphs also exemplifies perfectly why average values of either parameter can work in comparisons. All values are oscillating around approximately the same level as drilling vibrations without stick-slip. However, the vibrations are much more severe while stick-slip is present. In this case, the standard deviation peaks at over twice the mean value when stick-slip is present.

5.4 Validity of calculated parameters and analyses

This thesis has been built on field data, both sensor readings and calculated parameters based on sensor readings. The analyses have been mostly improvised in order to try to explain and divulge as much as possible. The goal was to make it comprehensible for the reader and at the same time not disguise the facts.

5.4.1 Calculated ROP

The calculated parameter with the most emphasis in this thesis is the ROP. That is due to its importance as a performance parameter by itself and because it is a very important input in the MSE calculation. The final chosen timespan for the ROP is 10 seconds, which is due to a couple of important factors; firstly, because it has the least deviation from actual ROP, and secondly, because it is used in many of the analyses to indicate on-bottom time. purely on-bottom data is used in these calculations and analyses, and it is therefore important to filter out as much false data as possible, and a shorter timespan for ROP is accomplishing that better.

The downside of choosing a short timespan for ROP are the visualization of the parameter in some cases, which is partly resolved by the smoothening of the curve, but it is also a disadvantage during really slow ROP's When drilling very slowly, the depth may not update itself every 10 seconds which is required for the parameter to register any value. Therefore the ROP will show zero in areas that is drilling very slow. The lowest value that is possible to register by the calculation is actually 3.6 meters per hour, which occur when the depth is updated by 0.01 meters over the last 10 seconds.

The limitation in low ROP actually limits the amount of high MSE. ROP is a very important factor in the calculation, and as it is the denominator, it decides how large values of MSE is possible. A longer range ROP calculation would enable higher values of MSE to register, but it occurs very rarely.

5.4.2 Calculated MSE

The MSE calculation is meant to indicate how much energy that goes into drilling at any given point. The average MSE may not reveal much, but when exploring the comparison of MSE distributions for all wells, it was discovered that the shortest well had the highest density of low MSE values. This confirms the assumption that shorter wells have less friction and drag forces acting on the drilling assembly and therefore requires less energy to drill.

When comparing well 1.4 to 1.1, it is clearly a difference in low MSE values, indicating a higher energy drilling environment for a longer reach wells. The average MSE value from well 1.4 is therefore impressively low considering the length of the section.

5.4.3 Calculated SSS

The calculated SSS from the ASM rotation sensor is the most useful calculated parameter in this thesis as it enables an estimation of stick-slip in all wells, not only those featuring SoftSpeed. This is crucial for comparison reasons and have proved to be a necessary parameter.

When ASM SSS is compared to SoftSpeed SSS, it fits really well with the high levels of stick-slip, but does not compare very well to the low values distributed by the SoftSpeed system. This may be because of the long sample period of the ASM rotation sensor. The value is based on the highest and the lowest reading every two seconds, and as discussed above, readings may fluctuate during a short period of time. It may also be due to the calculations of the SoftSpeed system does not calculate quick enough to catch the minuscule variations which will be picked up by a 256 Hz sample rate.

Information regarding the update rate of SoftSpeed, nor the "sample frequency, has not been found, and the assumption can not be confirmed. However, the ASM SSS and SoftSpeed SSS are linearly related which proves the estimations from the rotation sensor compare very well with the calculated values from the system. It also accredits the calculations made by the system to be very accurate. Perhaps, if the ASM SSS should be developed further, it should be based on 2x standard deviation which would cover 95% of the sampled values, rather than the absolute minimum and maximum. That is assuming the values of rotation are normally distributed.

6 Conclusion

This field has experienced multiple problems related to stick-slip and drilling vibrations prior to implementation of SoftSpeed. Massive amounts of stick-slip, two bit trips, changing BHA element and badly worn bits are common for both wells drilled before the system was implemented. These problems costs both time and money, neither of which are beneficial in a field development.

Two more wells have been drilled after the implementation of SoftSpeed, both longer and more complex than all wells previously drilled. They have all been drilled by the same drilling rig at the same location. Lithology is similar to previous wells as all have been drilled within the same reservoir. This should be a good baseline to make comparisons of the effects made by the new system.

Very little stick-slip was detected while drilling the two new wells as SoftSpeed was active majority of the time. Recurrent stick-slip occurred only at times when the system was inactive, but ceased almost immediately after activations of SoftSpeed. Smaller peaks of drilling vibrations were observed while the system was on, but these were quickly suppressed.

The average amount of drilling vibrations did not reduce overall when comparing old wells against new ones. But stick-slip cause an oscillating nature of the vibrations causing higher highs and lower lows, making the average values close to equal of stick-slip free environments. Rapid acceleration and deceleration of string speed causes the oscillations which are damaging to drilling equipment.

Average tangential vibrations are therefore not sufficient to explain the amount of high-energy torsional waves experienced by the drillstring. The calculated stick-slip severity index (SSS) made for the SoftSpeed system and modified for use with ASM data in this thesis is a much better measurement for extreme torsional vibrations as it is based on the difference in string speed instead of average vibrational forces.

Lateral and torsional vibrations are very closely related in a oscillating vibration system caused by stick-slip. Maximum and standard deviation values harmonize with each other for the two types of vibrations in an oscillating system. Both types of vibrations are equally affected by the activation of SoftSpeed and ceases very quickly.

The drill bits used in the different wells can attest to the positive effects of SoftSpeed. Badly worn bits to the limit of unusable were common for the earlier wells, and progress and steerability was compromised to the degree of bit trips for both wells. The drill bits from the sections running the SoftSpeed system came out in very good condition with only 1/8 wear on all cutters. This also led to both new wells being completed in just one run.

It is not possible to say that SoftSpeed increases ROP in a general term. However, if drilling is supposed to be stick-slip free, SoftSpeed will definitely grant higher ROPs than excluding it. The two wells drilled without the application ignored the drilling vibrations and carried on with the same ROP, which ultimately led to two broken bits and expensive bit trips. When all that time is accounted for, SoftSpeed will increase progress overall.

Total energy used for each well is definitely reduced after the system was implemented. MSE values for well 1.3 was the lowest of all wells in this comparison, even though it was the second longest well. MSE values for well 1.4, which was restricted on ROP, was also very low compared to the rest. Two wells showed slightly lower values, but well 1.4 is approximately 50% longer than either of them which means much higher friction forces compared to the rest.

Other positive effects of the application is improved borehole quality and reduced wear on drillstring. These two subjects have barely been touched upon in this thesis, but there is reason to believe the statement is valid. Since SoftSpeed effectively reduces stick-slip and related lateral vibrations, the drillstring and BHA elements are not subjected to whirl or rapid torsional vibrations and the wear of connections and body elements will be reduced. Upon reduction of lateral vibrations also follows less contact by the string to the borehole wall, and less cave-ins will occur.

In conclusion: SoftSpeed enables stick-slip free drilling in areas otherwise associated with such drillstring vibrations, the effects of which enables good progress and low drilling vibrations that prolongs the life of the bit and in turn enables drilling of long and hard sections more effectively.

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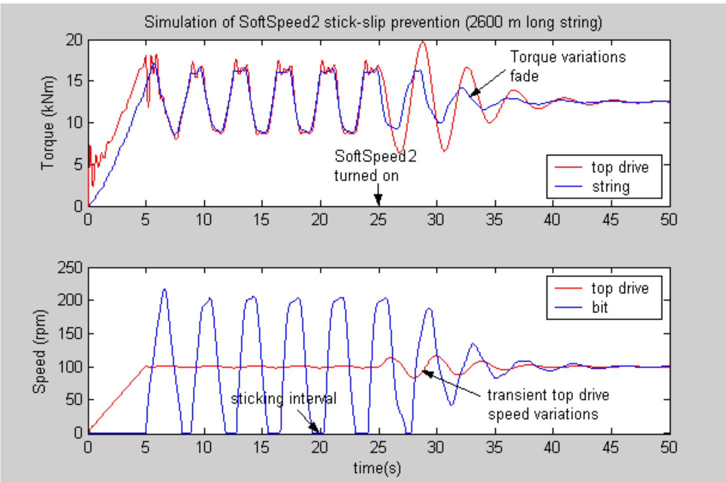
A SoftSpeed Specifications

SoftSpeed2™ – Stick-Slip Prevention System

SoftSpeed2™ from National Oilwell Varco® is a top drive enhancement that helps reduce stick-slip oscillations. It is the result of an extensive research program including field tests and Hardware-In-the-Loop simulation tests.

What is Stick-slip?

Stick-slip oscillations are severe, cyclic variations of the drill string twist and torque, driven by non-linear bit torque and well bore friction. As the name indicates, the lower string toggles between a sticking phase with zero speed, and a slip phase where the BHA rotation speed can reach very high peak levels, typically 2-3 times the mean speed. Stick-slip is recognized as a major cause of drilling inefficiency and non-productive time due to such as excessive bit wear, premature tool failure, drill string fatigue and poor drilling rate.



SoftSpeed2™ allows smooth drilling in conditions that normally generates stick-slip. The illustration above shows how effective the SoftSpeed2™ eliminates stick-slip.

SoftSpeed2™ – Stick-Slip Prevention System

OPERATION:

The operator only needs to input a simplified drill string configuration.

SoftSpeed2™ analyzes the drilling process and detects when stick-slip occurs and calculate optimal control parameters.

The operator activates SoftSpeed2™ when stick slip is detected.

Mean speed is unaffected and smooth drilling is quickly accomplished.

The auto-tuning feature causes the speed controller to provide optimal damping of both 1st and 2nd modes stick-slip.

OPERATOR INPUTS:

- SoftSpeed2™: ON/OFF
- Nominal drill pipe size or simplified drill string configuration.

OPERATION MODES:

Analyzer

The Analyzer is always operating.

Prevention Module

Based on demand, the Prevention Module is activated on command.

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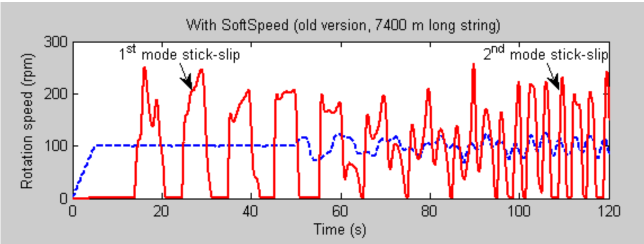
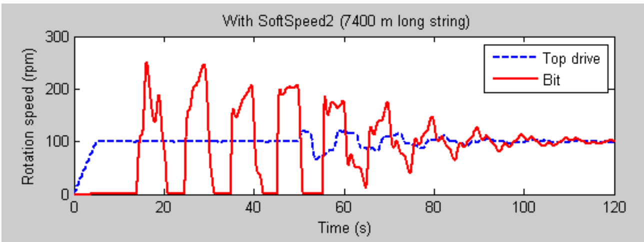
NATIONAL OILWELL VARCO

SoftSpeed2™ – Stick-Slip Prevention System

The National Oilwell Varco® SoftSpeed2™ uses the latest and **patent pending** technology to cure and prevent torsional stick-slip oscillations of the drill string. This second revision has **improved performance** and can migrate stick-slip over a wide range of conditions, including **extremely long wells** where competitive systems normally fail. Although the system is more advanced, the inputs are simplified through the use of **auto-tuning features** to ease operation. It also provides a good **bit speed estimation** based on drive torque and string geometry.



To illustrate the advantage with the new higher mode stick-slip prevention feature, the figure above shows a simulation from a 7400 m long well without this feature. SoftSpeed is turned on at 50 seconds and it only cures the main stick-slip frequency and the second mode starts to dominate.



To resolve this issue we developed a new and improved version. In the figure above you can see how the new SoftSpeed2™ cures both 1st and 2nd modes of stick-slip.

FEATURES

- Severity of stick-slip indication.
- Dampens and prevents stick-slip oscillations.
- Inhibits both 1st and 2nd modes stick-slip.
- Estimates bit rotation speed
- An automatic analyzer finds optimal parameters.

BENEFITS

- Easy to operate.
- Improves the bore hole quality
- Improves ROP
- Reduces axial and transversal drill string vibrations
- Reduces bit wear
- Reduces drill string fatigue
- Save the number of bit trips
- Good estimation of bit rotation speed
- Decreased drilling cost

INSTALLATION

- Works with both AC and DC top drives.
- Interfacing to existing SCR or VFD drive system.
- Uses a tuned and optimized soft PLC-based speed controller.
- No additional sensors needed
- Can be controlled from a separate screen or integrated into an existing one.

SoftSpeed2™ – Stick-Slip Prevention System

SYSTEM DEPENDENCIES:

- Accurate and fast speed feedback from the drive
- Accurate and fast torque feedback from the drive
- Speed control signal to the drive
- Torque control (limit) signal to the drive

VERSIONS:

- Standalone. Integrated as a new PLC with its own interface panel.
- Integrated into the NOV Top Drive PLC. With its own operator interface panel.
- Integrated into the NOV Top Drive and control system such as Cyberbase and Amphion.

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B ASM Specifications

5-in. Series BlackStream ASM Dynamics Tool

The BlackStream™ along-string measurement (ASM) tool is a collar-based, downhole drilling dynamics measurement tool with a compact design that lends itself to flexible placement along the drillstring. The tool is designed to connect to the IntelliServ™ networked drillstring, providing real-time data for 25 channels every 2 seconds.

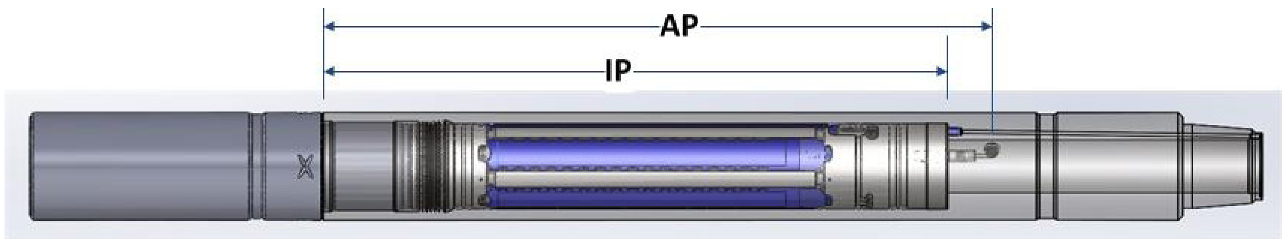
Specifications 5-in. Drillpipe

Tool	Specifications	Sensors	Specifications
OD	6.625 in.	Radial (lateral) acceleration (x2)	±50 g (0.002 g resolution)
ID	3.25 in.	Tangential acceleration (x2)	±50 g (0.002 g resolution)
Length	71 in. shoulder to shoulder	Axial acceleration (x1)	±35 g (0.0013 g resolution)
Pressure rating	25,000 psi	RPM (x1) (gyro)	+/-1200 RPM (0.05 RPM resolution)
Material	High-strength steel alloy	Pressure (internal/external)	0 to 25,000 psi (0.4% FS accuracy)
Connection type	GPDS50 pin and box	Temperature	-40 to 302°F (-40 to 150°C)
Rated temperature	302°F (150°C)		
Battery life	Up to 1,000 hr		
Reporting period	Every 2 seconds		

Specifications 5½-in. and 5⅞-in. Drillpipe

Tools	Specifications	Data Acquisition	Specifications
OD	7 in.	Background sampling rate	256 Hz
ID	3.50 in.	Data acquisition / power enable	Cycled through the network
Length	71 in. shoulder to shoulder	Storage (buffer size)	256 bytes
Pressure rating	25,000 psi	Number of channels	25
Material	High-strength steel alloy	Reporting time	Every 2 seconds
Connection type	5½-in. Tool: TT550 pin and box 5⅞-in. Tool: XT57 pin and box	Statistics reported	Minimum/average/maximum values for radial acceleration, tangential acceleration, internal pressure, external pressure, rotation, mean and standard deviation on azimuthal radial acceleration, and tangential acceleration.
Rated temperature	302°F		
Battery life	Up to 1,000 hr		

Pressure sensors are located as follows	5-in. BlackStream ASM Tool	5½-in. and 5⅞-in. BlackStream ASM Tool
From the internal mid-sub box internal pressure-IP	38.54 in.	38.675 in.
From the internal mid-sub box annular pressure-AP	41.25 in.	41.375 in.



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C Scripts to remove null-values and false readings in Microsoft Excel

```
Sub Slett_999()
Dim v
v = -999.25

Dim Arr() As Variant
Arr = Range("A2:CH900000")

Dim R, C As Long
For R = 1 To UBound(Arr, 1)
    For C = 1 To UBound(Arr, 2)
        If Arr(R, C) = v Then
            Arr(R, C) = ""
        End If
    Next C
Next R

Range("A2:CH900000") = Arr
End Sub
```

```
Sub Slett_over_30000()
Dim v
v = 30000

Dim Arr() As Variant
Arr = Range("E2:CH900000")

Dim R, C As Long
For R = 1 To UBound(Arr, 1)
    For C = 1 To UBound(Arr, 2)
        If Arr(R, C) > v Then
            Arr(R, C) = ""
        End If
    Next C
Next R

Range("E2:CH900000") = Arr
End Sub
```

Input parameters:

Range: Insert range of dataset (Input twice per script)

v: Input value to search for and delete/delete over

D Excel formulas

Table D.1: Excel equivalents of formulas created in thesis

Eq #	Equation	Excel equivalent
(6)	$\text{ROP}(t) = \frac{z(t)-z(t-\Delta t)}{\Delta t} \cdot 3600$	B34=(A34-OFFSET(A34;-B2))/B2*3600
(7)	$\text{ROP}(z) = \frac{\Delta z}{t(z)-t(z-\Delta z)} \cdot 3600$	C34=IF(A34-A33>0;(A33- VLOOKUP(A33-C2; A$2:A33;1))/(COUNTIF(A$2:A33;">" &VLOOKUP(A33-C2;A$2:A33;1))/3600);C33)
(9)	$SSS_{ASM} = \frac{RPM_{Max}-RPM_{Min}}{2 \cdot RPM_{surface}} \cdot 100\%$	D34=(AVERAGE(E5:E34)-AVERAGE(G5:G34))/(2*AVERAGE(H5:H34))*100

Column A Depth column

Column B Target column for time based ROP

B2 Fixed location for Δt

Column C Target column for depth based ROP

C2 Fixed location for Δz

A$s:A33 Lookup column with anchor at top

Column D Target column for ASM SSS

Column E ASM RPM Maximum value

Column G ASM RPM Minimum value

Column H Surface RPM