AN INNOVATIVE TOOL FOR MEASURING EFFICIENCY AND ENERGY CONSUMED WHILE DRILLING

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ABSTRACT

The up-to-date, open-source technologies in data streaming, enable us to build versatile systems to capture drilling data, allowing the computation of Mechanical Specific Energy (MSE) and Confined Compressive Strength (CCS) in real-time. When combined, they are a powerful tool to measure drilling efficiency.

When we plot Rate of Penetration versus MSE, we can visualize the instantaneous power applied to the system. As the drilling performance is a function of effective power at the bit and drilling efficiency, the value of such plots at three levels: total power, effective power on the bit, and the difference between them, the lost power, is evident. Applying analytics to these plots would enable drilling engineers to understand the best well trajectories, tools, bottom hole assemblies, drilling practices, and drilling bits that minimize the lost power and maximize the power at the bit.

We address the computation of power and MSE at the three mentioned levels. The mathematical integration of instantaneous power as a function of time allows the calculation of energy consumed in a run or section, and some metrics such as kilowatt.hour per meter. Accurate estimations of MSE at bit and CCS, allow computing drilling efficiency at bit level. We have a physical technical limit, the minimum energy needed to destroy a rock with specific properties.

In the era of the United Nations Sustainable Development Goals, and the Environmental, Social and Corporate Governance score, having a tool to measure the energy consumed during drilling, will help identify initiatives to improve efficiencies and reduce gas emissions.

INTRODUCTION

Based on Teale's original MSE equation (Teale, 1965), Pessier rewrote it as follows (R. C. Pessier & Fear, 1992):

$$MSE = \frac{WOB}{A_{bit}} + \frac{120\,\pi\,N\,TQ}{A_{bit}\,ROP}$$

The work here presented, proposes to apply this equation with the data of drilling parameters taken through surface measurement instruments, in typical drilling rigs used in the oil and gas industry. To carry out the analysis, we must first assume some simplifications: rigid string with no torsional deformations and RPM oscillations on itself, steady-state with no transients.

In oil and gas operations the drilling parameters WOB, RPM, TQ, and ROP are usually measured through sensors located at the surface. Therefore, WOB measures the effective weight on the bit plus the drag weight between the string and borehole, and TQ measures the effective torque on the bit plus the friction torque between the string and the borehole. In those cases where a motor is used, the total MSE applied to the system is (Chen *et al.*, 2018):

$$MSE_{total\ system} = \frac{WOB_{surf}}{A_{bit}} + \frac{120\ \pi\ N_{surf}\ TQ_{surf}}{A_{bit}\ ROP} + \frac{120\ \pi\ N_{motor}\ TQ_{motor}}{A_{bit}\ ROP}$$

This equation can be generalized to cases where a rotary BHA is used, if the last term of the equation is not considered, meaning that all the energy is supplied by the top drive. When a motor is used the equation has three terms. The first one is the total axial energy supplied by the own weight of the string. The second term is the rotational energy supplied by the top drive on the surface. The measured surface torque is composed of the cutting torque effectively supplied to the drilling bit, plus the lost torque that does not reach the bit. This lost torque, as we found in our research, is not only made up of friction between the string and the borehole but also has a component that can be attributed to the dynamic effects of the BHA, for example, vibrations. The third term represents the rotational energy supplied by the motor. The hydraulic energy of the mud flowing inside the string is transformed into rotational energy in the power section of the motor.

If we have the ability of measuring WOB, RPM, and TQ effective on bit, we can have the MSE at bit level:

$$MSE_{bit} = \frac{WOB_{bit}}{A_{bit}} + \frac{120\ \pi\ N_{bit}\ TQ_{bit}}{A_{bit}\ ROP}$$

The ideal situation is to have a device that could measure weight, rotary speed, and torque at bit, and transmit the information to surface in real-time. As typically this is not available, we must ideate a way to get this important information. Bit rotary speed is simply:

$$N_{bit} = N_{surf} + N_{motor}$$

Under the above assumptions, next model is considered:

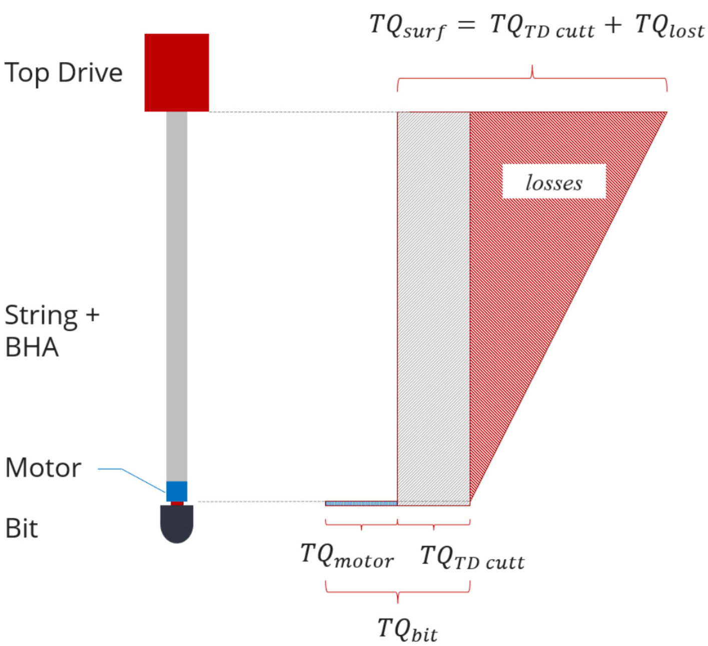

Figure 1. Model to estimate TQbit and WOBbit from surface instrument measurements.

Focusing on the bottom hole, the torque caused by the cutting action of the bit over the rock is driven by two mechanisms of torque, the component of cutting torque supplied from the surface and the motor torque. At surface level, the torque measured in the top drive is the same component of cutting torque supplied by the top drive itself plus the lost torque due to friction, vibrations and other possible irreversibilities. Considering this model, we can obtain an equation for the bit torque:

$$TQ_{TD\ cutt} = TQ_{bit} - TQ_{motor}$$

$$TQ_{TD\ cutt} = TQ_{surf} - TQ_{lost}$$

$$TQ_{bit} = TQ_{surf} + TQ_{motor} - TQ_{lost}$$

Using the next relation between torque and weight on bit (R. C. Pessier & Fear, 1992):

$$TQ = \frac{\mu\, D_{bit}\, WOB}{36}$$

We find a way to estimate the effective weight that reaches the drilling bit:

$$WOB_{bit} = \frac{36\, TQ_{bit}}{\mu\, D_{bit}}$$

The bit-specific coefficient of sliding friction μ depends on the type of drilling bit. For roller-cones type usually takes values 0.2-0.25, and for PDC 0.6-2.

To know the variables motor rotary speed, Nmotor, and motor torque, TQmotor, there exists detailed equations that take into consideration the decrease of rotary speed due to slip flow through the seal line (Chen *et al.*, 2018), and the decrease of torque due to mechanical friction, elastomeric friction and viscous shearing of drilling fluid (Samuel *et al.*, 1997). For simplicity reasons, we take advantage of the motor chart, where these variables are plotted as a function of the differential pressure and the flow rate. The differential pressure is the difference between the instantaneous values of the standpipe pressure, SPP, with the bit on-bottom, and the reference value of the SPP. The reference SPP is registered by the driller before starting every three-joint stand, with the bit off the bottom and the flow rate in use. We simply fit equations over these curves. We must consider that these plots are taken with water as fluid in lab tests. In the case of a fluid of higher density or viscosity, the torque and pressure drop will be higher. We are not considering this difference in our work.

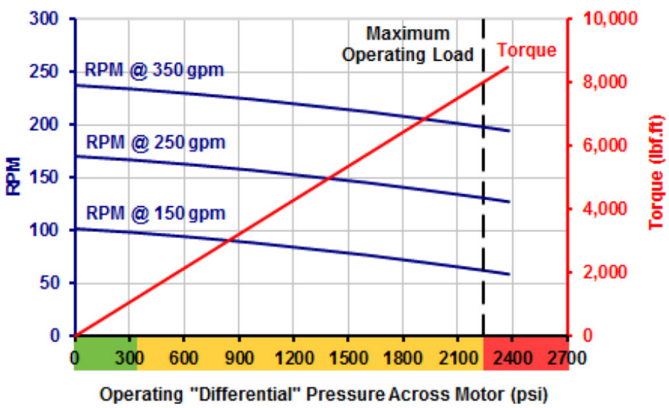

Figure 2. Typical motor chart where motor RPM and motor Torque are plotted as a function of motor Differential Pressure and Flow Rate.

Here we make a new assumption, and that is that differential pressure information is transmitted instantaneously from downhole to surface. However, as the pressure waves move at the speed of sound in the medium, depending on the depth measured, the information registered at a specific time actually belongs to a time a few seconds earlier. We expect this to cause some errors at moments of high differential pressure variation.

Finally, we can estimate the MSE lost in the process:

$$MSE_{lost} = MSE_{total\ system} - MSE_{bit}$$

Now it is possible to propose a Global Efficiency factor, considering the energy that effectively reaches the drilling bit in comparison with the total energy supplied to the system:

$$Global\ Efficiency = \frac{MSE_{bit}}{MSE_{total\ system}}$$

The energy balance of the drilling system when a motor is used, can be seen in Figure 3.

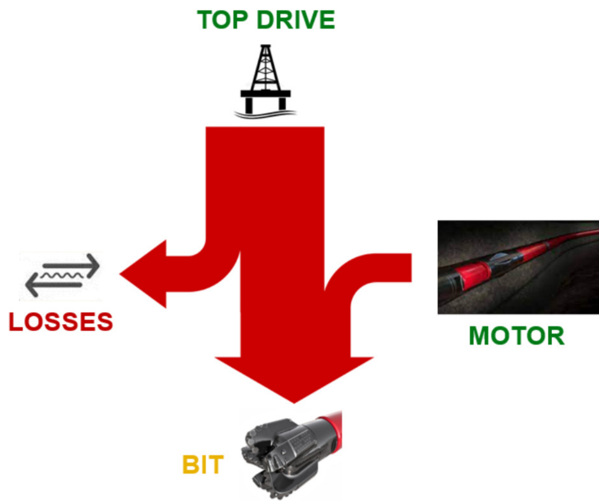

Figure 3. Energy balance of the drilling system when a motor is used.

As stated by Pessier *et al.* (R. Pessier *et al.*, 2012), the drilling performance is a function of the power that reaches the bit and the drilling efficiency. When working in a determined area, applying analytics to data collected from different wells, would enable to understand which are the best well trajectories, tools, bottom hole assemblies, drilling practices, and drilling bits that minimize the lost MSE and maximize the bit MSE.

APPLICATION AND RESULTS

To check the value of the proposed model and equations, we have applied them to a couple of actual datasets. The results are plotted in ROP versus MSE graphs (R. Pessier *et al.*, 2012). In these plots, it is possible to visualize lines of constant power and represent the instantaneous power applied at every point. The plots are presented for the three levels mentioned above: total energy applied to the system, effective energy that reaches the drilling bit, and the energy lost in the process. Due to the nature of the variables involved in every equation, the most accurate equation is the total system MSE as it involves variables measured at the surface and the estimated motor rotary speed and torque through the motor chart. The MSE at bit considers the model and assumptions presented in this work to estimate bit torque, but of course the process is subjected to complex dynamic processes that are not being considered here. The error made when estimating WOB effective on bit is negligible, as the term of axial energy is much smaller than the rotational energy.

Another important issue to consider is the estimation of the lost torque. We start considering that:

$$TQ_{lost} = TQ_{friction} + TQ_{vibrations}$$

In $TQ_{vibrations}$ we summarize all components of lost torque other than friction. A reference friction torque could be registered by the driller at the beginning of every three-joint stand, in a similar way as the reference SPP is taken, with the drilling bit off the bottom, the flow rate in use, and now the surface RPM in use. For historical cases, as presented here, we create a friction torque model through a machine learning regression (ML), fed by data taken from sliding sheets. These sheets are manually loaded by the directional driller and have useful information such as the off-bottom torque. The attributes used for the machine learning job are bit diameter, hole depth, inclination, azimuth, cumulative vertical section, cumulative dog leg severity and surface rotary speed. Vertical section and dog leg severity are cumulated to have the history of the trajectory, since punctual values of them do not contribute useful information. The target variable of the process is the off-bottom torque. The ML model gives us values for $TQ_{friction}$ to consider in our model looking for TQ_{bit} and WOB_{bit}.

We start a kind of iterative process, where first $TQ_{vibrations}$ is zero. When data is plotted, we found that MSE_{bit} is overestimated and MSE_{lost} is negative, Figure 4. We then increase $TQ_{vibrations}$ until the MSE_{lost} does not have negative values, Figure 5. At this point, some of the values of MSE_{bit} are now negative. The only way that this could happen is that TQ_{bit} is negative, and this is caused by high values of TQ_{lost} in the equation:

$$TQ_{bit} = TQ_{surf} + TQ_{motor} - TQ_{lost}$$

This situation is caused by fluctuations and dynamic effects of the drill string, different than the assumptions raised in the work. For example, stick and slip vibrations. We then need to limit the values of lost torque to always get positive values of bit torque:

$$TQ_{bit} = TQ_{surf} + TQ_{motor} - TQ_{lost} > 0$$

$$TQ_{lost} < TQ_{surf} + TQ_{motor} = TQ_{lost}^{max}$$

$$TQ_{lost}^{corr} = \alpha \,.TQ_{lost}^{max}$$

We have an equation to compute corrected lost torque, based on maximum lost torque and α, which is a random number between 0.5 and 0.8 to give a stochastic behavior to the system. Also, we expect a relative high value of lost torque in those moments where we originally had higher than actual values of it.

In the couple of datasets analyzed, we found that $TQ_{vibrations}$ is around 1.3-1.4 times the $TQ_{friction}$, in average Of course, this is only a global number and in fact this factor changes at every point, but at least we have a global reference to consider in our analysis.

We finally have the sought ROP versus MSE and isopower lines plots, Figure 6, for the total system MSE, effective on bit MSE and lost MSE. In this figure the color scale represents the influence of the depth on the plots. The MSE scale on the x axis is a measure of the drilling efficiency (R. Pessier *et al.*, 2012). The lower the MSE, the higher the efficiency, and hence the increase in ROP. The isopower lines give us very useful information, the instantaneous power applied to every point in horsepower. In the plots we have represented, from left to right and from bottom to top, the lines of 10 hp, 50 hp, 100 hp, 150 hp, 200 hp, 250 hp, 300 hp and 350 hp, Figure 7.

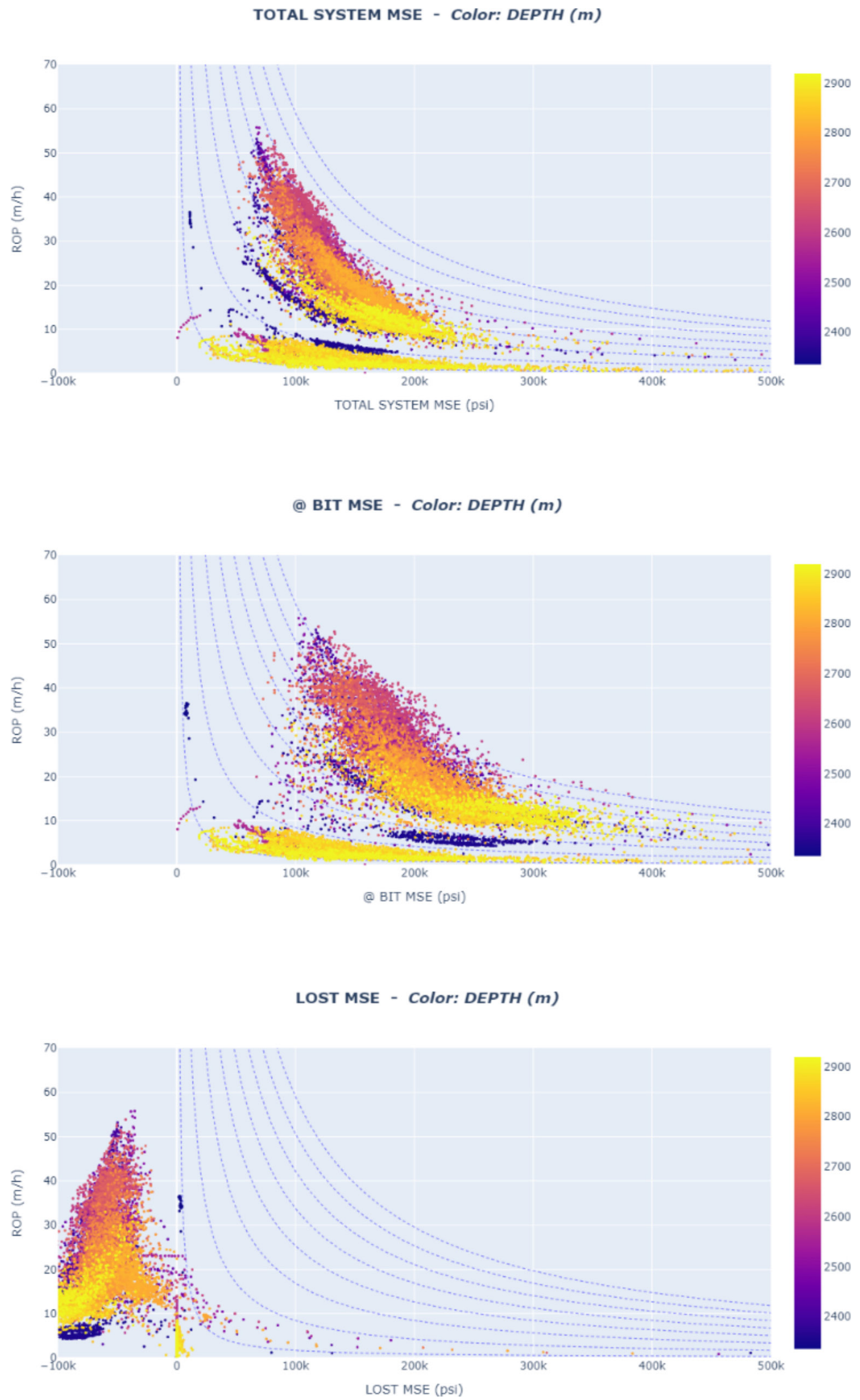

Figure 4. Total System MSE, at Bit MSE and Lost MSE in the first step of the iterative process.

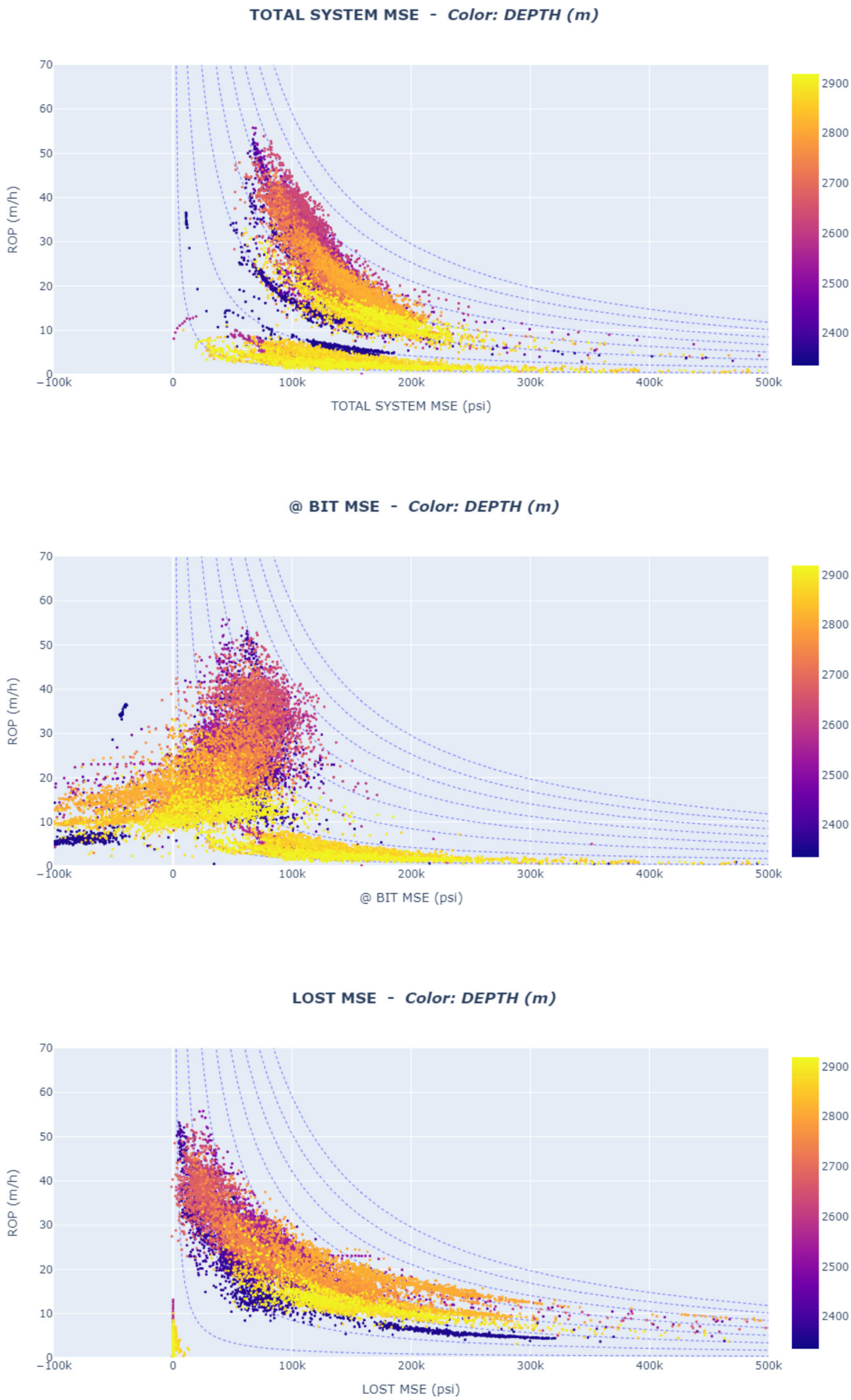

Figure 5. Total System MSE, at Bit MSE and Lost MSE in the second step of the iterative process. The Total System MSE remains unchanged during the process since its calculation does not depend on estimated variables.

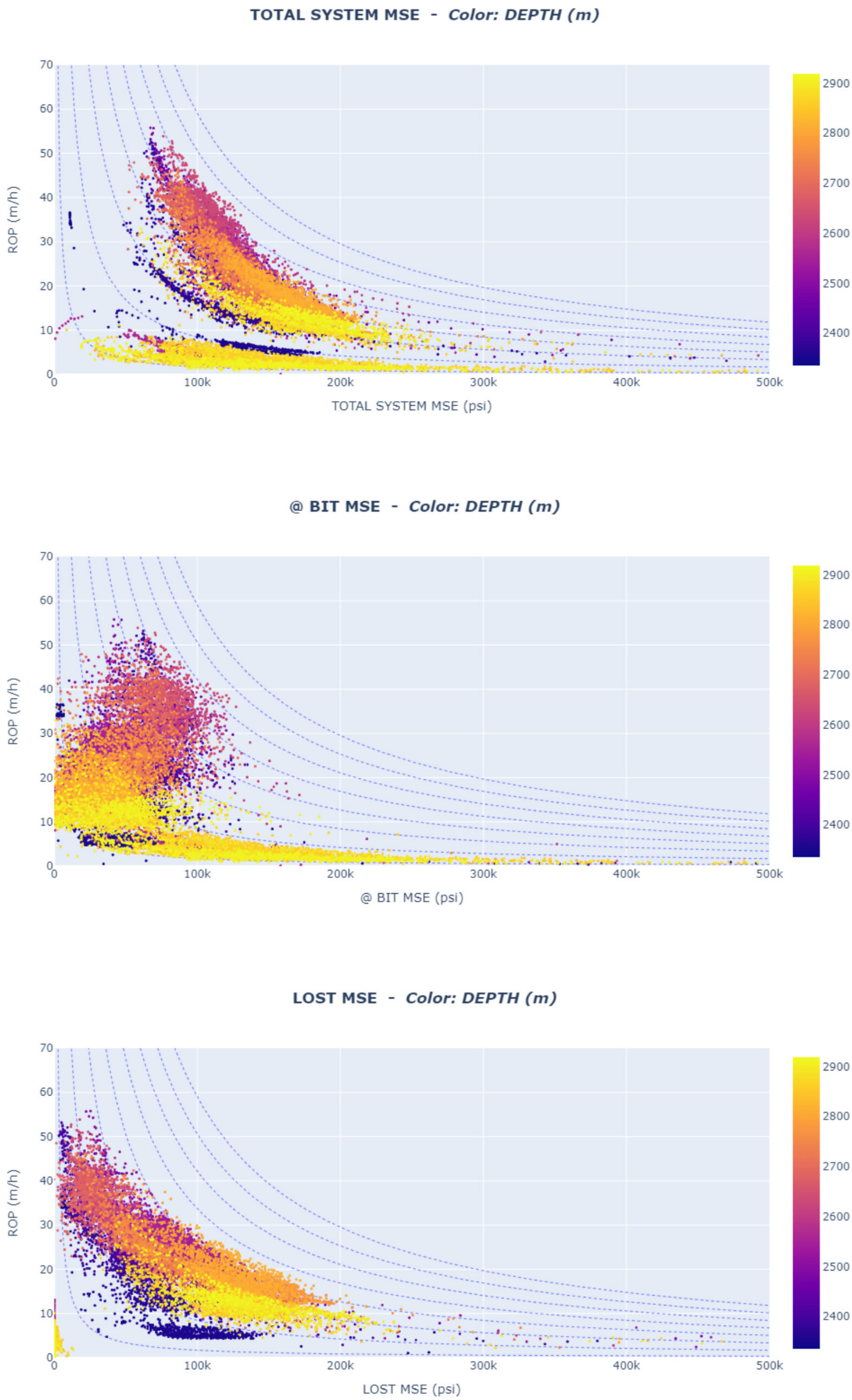

Figure 6. Total System MSE, at Bit MSE and Lost MSE in the last step of the iterative process.

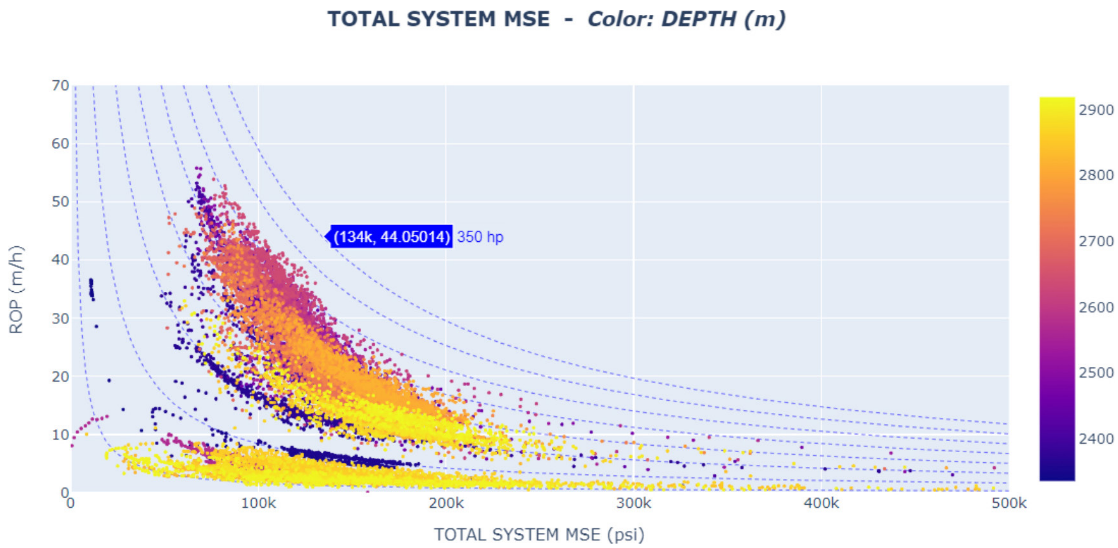

Figure 7. Isopower lines, from left to right and from bottom to top: 10 hp, 50 hp, 100 hp, 150 hp, 200 hp, 250 hp, 300 hp and 350 hp.

It is interesting to note two groups of points in Figure 7. The upper one corresponds to rotary drilling operations and the below one to sliding drilling operations. In the latter only 10 to 50 hp are applied as only power from the motor is supplied. In Figure 7 can be seen that the sliding drilling points have a similar representation in the Total System MSE and At Bit MSE plots. This is evident from the equations:

$$MSE_{total\ system} = \frac{WOB_{surf}}{A_{bit}} + \frac{120\,\pi\, N_{surf}\, TQ_{surf}}{A_{bit}\, ROP} + \frac{120\,\pi\, N_{motor}\, TQ_{motor}}{A_{bit}\, ROP}$$

$$MSE_{bit} = \frac{WOB_{bit}}{A_{bit}} + \frac{120\,\pi\, N_{bit}\, TQ_{bit}}{A_{bit}\, ROP}$$

During sliding operations, Nsurf and TQsurf are zero, Nbit=Nmotor and TQbit=TQmotor. The only variance remains in the axial energy term due to the difference between the surface WOB and the effective on bit WOB. The axial energy term is negligible when compared to the rotational energy term, it usually represents only 2 to 5 percent of the total energy.

In the At Bit MSE plot, Figure 6, for rotary drilling operations, it is possible to see that the effective power that reaches the bit decreases with depth. The yellow points do not exceed 50 hp, while in shallower depths it is possible to find points around 200 hp. It is also evident the highly inefficient process while sliding, the long tail of yellow points between 10 and 50 hp isopower lines.

Now that we have a plot of effective MSE at the bit, these are the points that we must compare with Confined Compressive Strength, CCS, to compute a Mechanical Efficiency at bit level (R. C. Pessier & Fear, 1992). There are several methods to calculate CCS in a highly accurate way (Caicedo *et al.*, 2005). This Mechanical Efficiency allows us to calculate a theoretical ROP at maximum drilling efficiency, a kind of technical limit.

$$Mechanical\ Efficiency = \frac{CCS}{MSE_{bit}}$$

The drilling process is inherently inefficient, and the Mechanical Efficiency is never higher than 30–40% (Dupriest & Koederitz, 2005).

Figure 8 shows a schematic of the iterative process needed to find the correct plots of MSE_{bit} and MSE_{lost}. Again, the $MSE_{total\ system}$ does not need to be corrected.

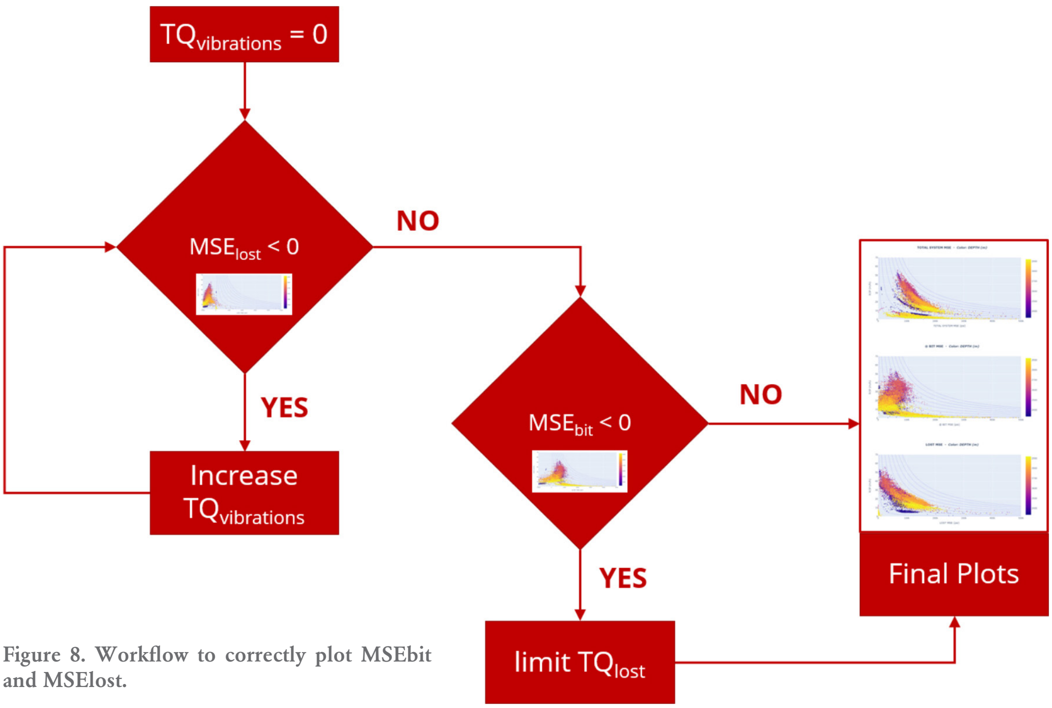

Figure 8. Workflow to correctly plot MSEbit and MSElost.

Other influences over ROP versus MSE plots

So far, we have seen how depth influences the ROP versus MSE plots. In the following figures we analyze the influences of other variables on the plots.

Figure 9 shows the influence of surface rotary drilling. The total system MSE clearly shows three groups of points. The blue points are the sliding operations with no rotary drilling, all the energy is supplied by the motor. The instantaneous power values are between 10 to 50 hp. At about 60 rpm, 100 to 200 hp of total system power is applied, some points are overlapped by yellow points. In the at bit MSE plot we see that the power that reaches the bit falls to values between 0 to 100 hp for a lot of points. Finally, the yellow points show values of rotary speed higher than 100. The total system power increases to 150 to 275 hp. An increase in ROP is evident, despite a slight increase in inefficiency shown by the increase in MSE.

The influence of surface weight on bit is shown in Figure 10. The WOB used during sliding maneuvers is lower than the used during rotary drilling, to control the tool face and correctly orient the BHA.

The differential pressure exerts a great influence over the values of MSE and instantaneous power as seen in Figure 11. As with the case of WOB, the values of differential pressure used in sliding are low, to control the tool face fluctuation. Values of differential pressure higher than 800 psi are only seen for rotary operations, provoking that instantaneous power reaches values higher than 250 psi. On the at-bit MSE plot, we see that the highest values of ROP correspond to the highest values of differential pressure, despite a clear increment in inefficiency.

Global Efficiency and Power on Bit plot

The Power on Bit values can be calculated through (R. Pessier *et al.*, 2012):

$$POWER_{bit} = \frac{ROP\ MSE_{bit}\ A_{bit}}{1.98\ 10^{6}}$$

The computed values of MSE_{bit} and $MSE_{total\ system}$, allow the calculation and plot of a Global Efficiency curve. Figure 12 shows the evolution of Global Efficiency and effective power on bit, and how they are affected by differential pressure and surface RPM. When sliding the global efficiency goes to 1 as MSE_{bit} is almost equal to $MSE_{total\ system}$. In general, power on bit and global efficiency follow the differential pressure. This behavior is not seen between 2470 to 2560 meters of Figure 12, where the values fall despite the application of high differential pressure. This portion corresponds to a hard formation called Mulichinco, that is composed by hard sandstones, pelites, and carbonates.

Consumed Energy Computation

If values of total system instantaneous power are multiplied by the delta time, it is possible to calculate and cumulate the energy consumed during drilling in horsepower.hour or kilowatt.hour. In this way, we could gain valuable information about how much energy we are consuming to drill a run, a section, or a well. This could be used in an energy efficiency drilling project to reduce the carbon footprint or to offset it. We find it useful to also calculate some KPIs, such as kilowatt. hour per meter, to be used in runs of different length, but that are still comparable because they belong to the same type of well, in the same field, for example. Figure 13 shows the comparison of the evolution of the total power applied to the system, cumulated energy (Kw.hr) and cumulated energy per meter (Kw.hr/m) for two runs of two different but same type wells.

The little jumps of values observed in energy curves and the different data density in power curves correspond to points where data was removed due to quality issues, such as duplicated depths, duplicated times, negative rotary speed, etc.

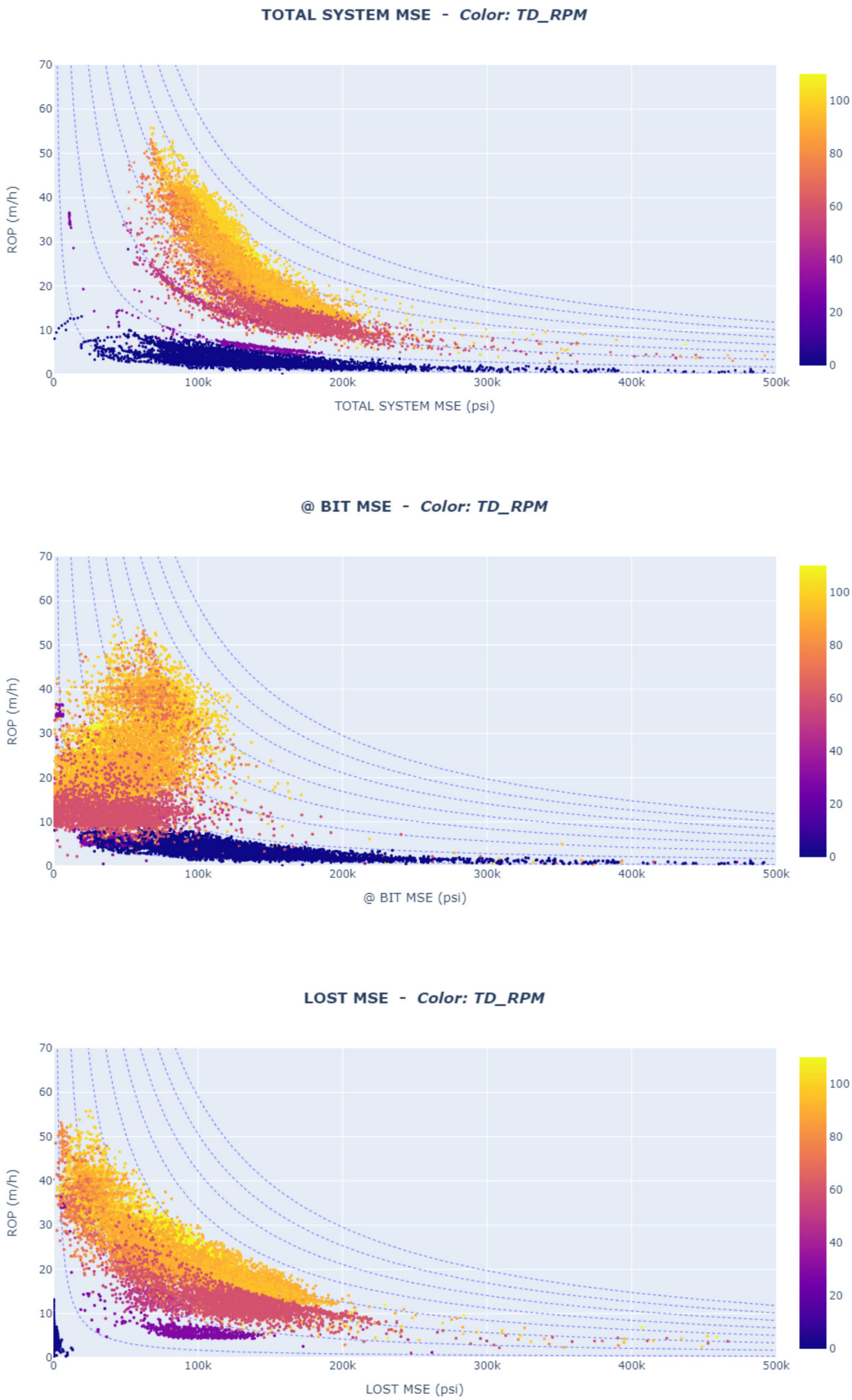

Figure 9. Influence of Surface RPM over ROP versus MSE plots.

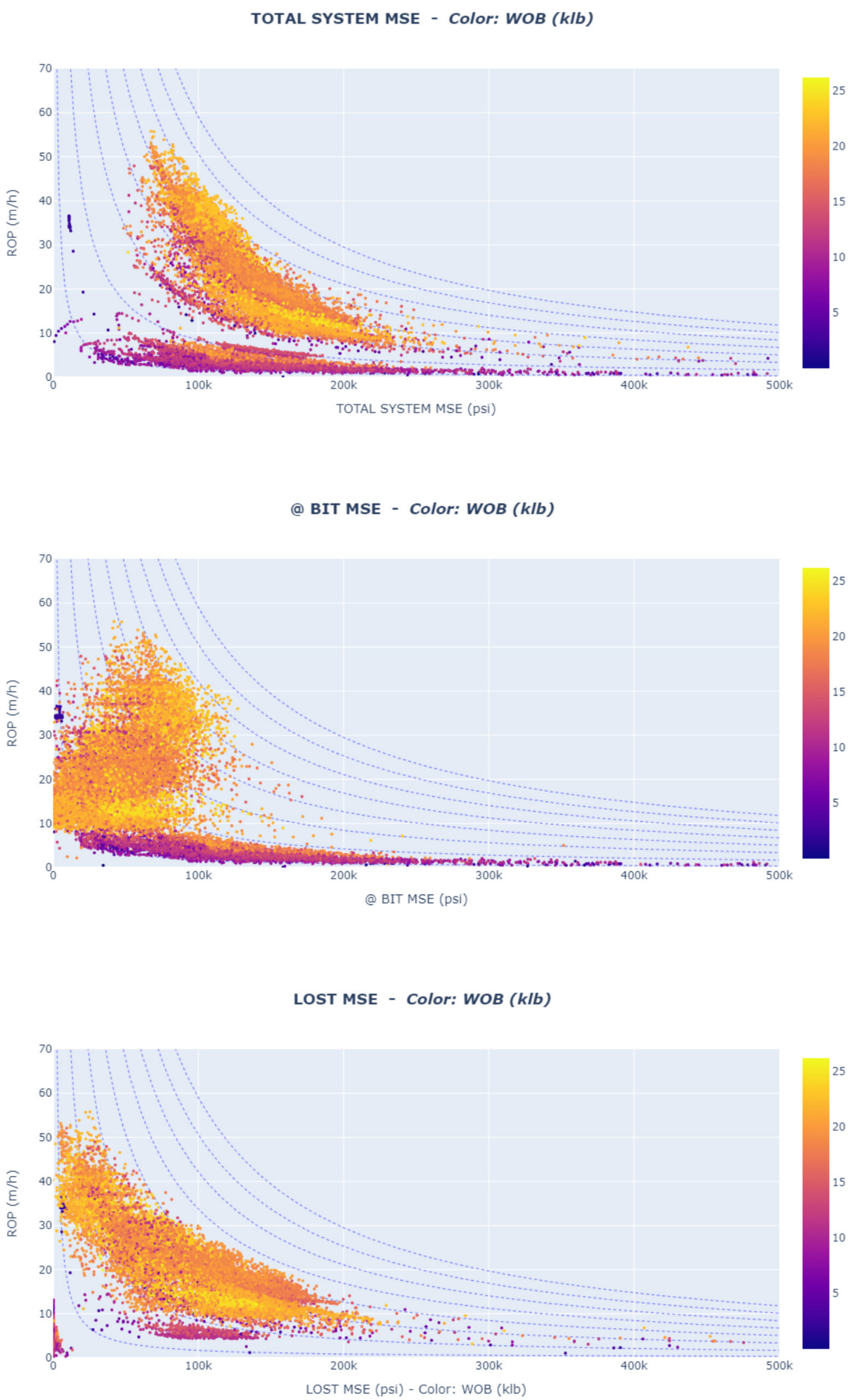

Figure 10. Influence of Surface WOB over ROP versus MSE plots.

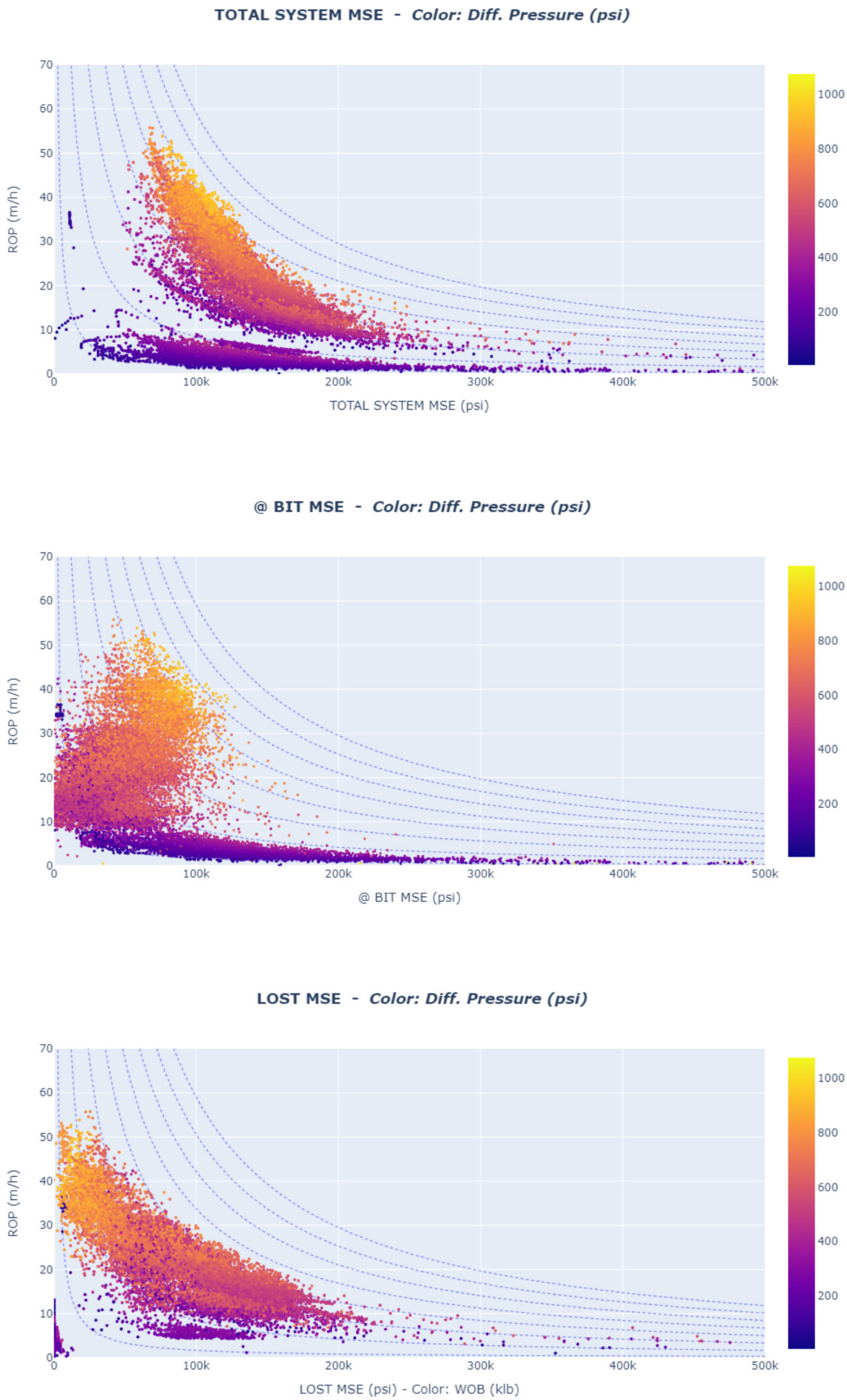

Figure 11. Influence of Differential Pressure over ROP versus MSE plots.

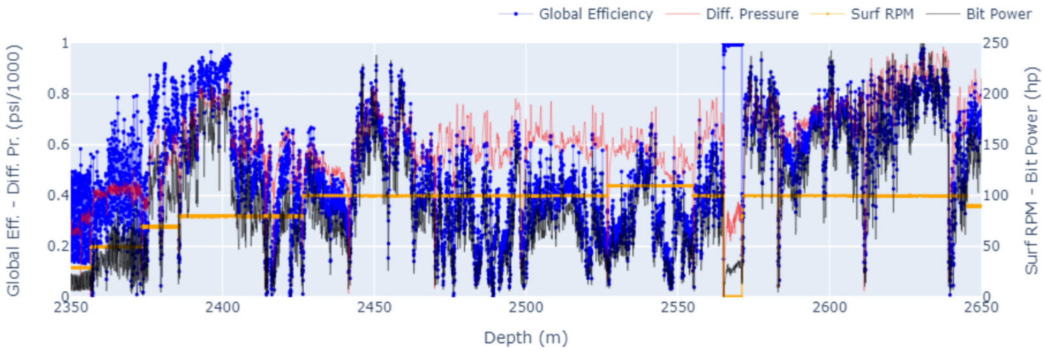

Figure 12. Evolution of Global Efficiency, Bit Power, Differential Pressure and Surface RPM with hole depth.

Figure 13. Evolution of Total Power applied to System, Cumulated Energy (Kw.hr) and Cumulated Energy per meter (Kw.hr/m).

Next table shows values of consumed energy at 2700 meters hole depth for the two cases:

Consumed energy @ 2700 m	Well 1	Well 2
Cumulated Energy (Kw.hr)	2100.9	2577.8
Cumulated Energy per meter (Kw.hr/m)	5.76	7.45

CONCLUSIONS

In the present work, equations were proposed to calculate total system MSE, effective on bit MSE and the difference between them, lost MSE. Usually, the drilling engineer only has surface instruments to measure drilling parameters. Particularly, bit MSE needs effective weight on bit, bit rotary speed and bit torque in its formula. When a motor is used, we can use the motor chart to have an estimation of motor rotary speed and motor torque as a function of differential pressure and flow rate.

Then a model was proposed to compute bit torque, and to do that some strong assumptions were made, such as rigid string with no torsional deformations and RPM oscillations on itself and steady-state with no transients. The model requires the consideration of lost torque, which in turn is the sum of the friction torque and the torque lost due to vibrations. The friction torque can be registered by the driller taking a reference torque with the bit rotating of bottom at the rotary speed to be used in the corresponding stand. If historical data is analyzed, as in the present work, a machine learning regression model can be created to estimate friction torque, using data extracted from directional driller sliding sheets of wells of the same field. To estimate the torque lost by vibrations we proposed a workflow where we look for coherent values of lost MSE and bit MSE. Particularly we correct the values of lost torque due to vibrations until we do not have negative values of lost MSE and bit MSE. In this process we found that torque lost due to vibrations is around 1.3-1.4 times the friction torque. This is a global factor found in the couple of datasets analyzed in this work. This is a particular point that can be improved from this work, how to correctly identify the lost torque due to irreversibilities other than friction, such as vibrations. We then analyzed the influence of different drilling parameters over ROP versus MSE plots, such as depth, surface rotary speed, surface weight on bit and differential pressure.

We stated that if we want to calculate the mechanical efficiency at bit level, we must compare the Confined Compressive Strength with the bit MSE values. With bit MSE and total system MSE we can calculate a Global Efficiency index, to understand how much of the total energy applied to the system reaches the drilling bit, and how much is lost in the path. Applying analytics to several wells in a particular field, could be useful to understand the best drilling bits, motors, tools, BHA and well trajectories that improve the Global Efficiency index.

Finally, we proposed to calculate the consumed energy during drilling in kilowatt.hour and, in kilowatt.hour per meter, in case we compare runs of different lengths. Understanding the evolution and quantity of consumed energy could be useful in energy efficiency drilling projects, to reduce or to offset carbon footprint.

NOMENCLATURE

A_{bit} = Bit Area (in^2)
CCS = Confined Compressive Strength (psi)
D_{bit} = Bit Diameter (in)
$MSE_{total\ system}$ = Total Mechanical Specific Energy applied to the system (psi)
MSE_{bit} = Effective Mechanical Specific Energy applied on the drilling bit (psi)
MSE_{lost} = Lost Mechanical Specific Energy (psi)
N_{surf} = Rotary Speed measured at surface (rev/min)
N_{motor} = Motor Rotary Speed (rev/min)
N_{bit} = Drilling Bit Rotary Speed (rev/min)
$POWER_{bit}$ = Effective Power that reaches the Drilling Bit (hp)
$POWER_{total\ system}$ = Total Power applied to the System (hp)
ROP = Rate of Penetration (ft/hr in equations, m/h in ROP versus MSE plots)
TQ_{surf} = Surface Torque (lbf.ft)
TQ_{motor} = Motor Torque (lbf.ft)
TQ_{bit} = Bit Torque (lbf.ft)
TQ_{lost} = Total Lost Torque (lbf.ft)
$TQ_{friction}$ = Lost Torque due to friction between drill string and borehole (lbf.ft)
$TQ_{vibrations}$ = Lost Torque due to reasons other than friction (lbf.ft)
$TQTD_{cutt}$ = Component of bit torque provided by the top drive (lbf.ft)
WOB_{surf} = Weight on Bit measured at surface (lbf)
WOB_{bit} = Weight on Bit that effectively reaches the Drilling Bit (lbf)
μ = Bit specific Coefficient of Sliding Friction

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