

Article

Evaluating the Effect of Stabilized Weight Transfer to the Bit on Mechanical Specific Energy in Horizontal Well Drilling

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Abstract

This study investigates the effect of stabilizing axial load transfer to the bit on mechanical-specific energy during horizontal well drilling. To analyze drilling regimes, field data on WOB, ROP, RPM, TOB, and MSE were used and processed using z-score standardization, outlier removal based on the IQR criterion, and k-means clustering. The selected number of clusters was determined using the elbow method and silhouette analysis; after filtering, the dataset included 1750 observations, and the six-cluster solution was selected for exploratory interpretation. It was found that the lowest MSE values were characteristic of clusters 0, 1, and 5, among which cluster 5 demonstrated the most favorable combination of WOB, ROP, and energy efficiency. Clustering the modeled data confirmed the possibility of identifying drilling regimes with reduced MSE under a stabilized-load scenario. The predicted MSE reduction should be interpreted as a scenario-based, idealized model-based estimate obtained under quasi-steady assumptions rather than as a field-validated performance gain. The results may be used to support the selection of rational drilling parameters and to guide the further development of drilling control systems for horizontal well drilling.

Keywords: mechanical specific energy; weight on bit; hydraulic thruster; k-means clustering; horizontal drilling; drilling optimization



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1. Introduction

Mechanical specific energy (MSE) is a relevant and methodologically sound criterion for drilling efficiency because, in its original formulation, it is defined as the work required to destroy a unit volume of rock. MSE reflects the energy expenditure associated with well deepening during the drilling process. In the study by R. Teale, it was shown that specific energy can be used as an index of rock breaking efficiency and that its magnitude is related to the strength properties of the material being destroyed [1].

The relevance of MSE stems from the fact that this parameter integrates the contributions of axial and rotational work at the bit into a single value and is expressed through routinely recorded parameters, including WOB, TOB, RPM, and ROP, which allows MSE to be used as a quantitative indicator of energy efficiency [2]. MSE also serves as a metric for

comparing drilling intervals across different wells and can be applied to optimization by minimizing specific energy consumption subject to operational constraints [3].

A distinctive feature of MSE as a tool for monitoring rock breaking efficiency is its diagnostic sensitivity to energy losses that do not result in an equivalent increase in the volume of rock removed. An increase in MSE under unchanged geological and technical conditions indicates inefficient WOB transfer or an inappropriate WOB level, increased resistance forces, vibrations, poorer borehole bottom cleaning, and progressive bit wear. Its practical applicability was confirmed in the studies by Dupriest and Koederitz [4], which demonstrated that real-time MSE monitoring makes it possible to evaluate drilling efficiency, identify optimal drilling regimes, and justify changes in well design and drilling technology.

In the context of horizontal and highly deviated wells, the importance of MSE as a fundamental metric increases, since the wellbore trajectory of such wells is associated with greater energy losses caused by the difficulty of transferring load to the bit, friction, and bottom-hole assembly (BHA) dynamics. MSE makes it possible to quantitatively assess energy losses that increase in proportion to the deviation from the vertical and to distinguish them from losses arising due to other causes.

When drilling horizontal and highly deviated wells, the transmission of WOB from the surface is hindered by increasing contact forces between the drill string and the wellbore wall, which leads to higher friction forces, axial drag, and torque [5]. As the inclination angle and the length of the horizontal section increase, the total resisting forces also increase. Load transfer becomes a limiting factor in achieving the target depth required for the efficient development of oil and gas fields [6,7]. An additional limitation is associated with the loss of axial stability due to buckling and deformation of the drill string, when the weight of the drill string can no longer be effectively transmitted to the bit in the amount required for rock breaking [8]. This necessitates specialized solutions aimed at reducing friction and improving load transfer to the bit.

A further challenge is the difficulty of stabilizing WOB during trajectory control, especially in oriented drilling with downhole motors, when the drill string does not rotate and is prone to uncontrolled slipping. Under such conditions, torsional vibrations and irregular axial movements of the drill string lead to fluctuations in WOB, which complicates the maintenance of a constant and uniform WOB and impairs wellbore trajectory control [9], especially during sliding drilling.

Reviews of MSE applications indicate that most studies use the MSE parameter as an objective function for the selection and adjustment of drilling regimes rather than as a tool for analyzing WOB and TOB trends. Most studies indicate that mechanical specific energy is primarily used to optimize ROP through the selection of WOB and RPM, to evaluate rock strength properties, and to identify zones of energy loss, with the main emphasis placed on reducing average MSE values by adjusting drilling parameters [10,11]. Similarly, in studies on drilling optimization using machine learning, MSE is included in the optimization criterion, while the algorithms select the optimal WOB and RPM values to minimize this parameter in real time [12,13].

More broadly, recent developments in artificial intelligence and data-driven industrial optimization show that complex engineering systems can benefit from decision-support frameworks that combine monitoring data, pattern recognition, and predictive analysis [14]. In such systems, AI-assisted approaches are increasingly used not only for process automation but also for operational efficiency improvement, anomaly detection, and support of engineering decision-making under uncertainty. In this context, the clustering-based methodology proposed in the present study can be regarded as an interpretable data-driven tool for identifying drilling regimes associated with different levels of energy efficiency.

Although it is not intended as a full real-time autonomous control system, it follows the broader trend toward intelligent operational support in engineering applications.

The aim of this article is to substantiate an approach for the quantitative assessment of the effect of stabilizing axial-load transfer to the bit on rock-breaking energy characteristics of rock breaking expressed in terms of mechanical specific energy. To achieve this aim, a comparison is made between the “actual” MSE calculated from field data using the classical MSE formula and the MSE calculated for the bottom-hole assembly (BHA), which reproduces a scenario of stabilized load transfer to the bit. Thus, the objective is formalized as the evaluation of the difference between real and modeled MSE values for selected drilling intervals and operating regimes, which makes it possible to isolate the contribution of stable and uniform WOB to changes in the energy efficiency of drilling-deviated and horizontal sections [15]. The predicted MSE reduction should be interpreted as a scenario-based upper-bound estimate obtained under quasi-steady assumptions rather than as a field-validated performance gain.

2. Theoretical Background and Problem Statement

2.1. MSE as an Indicator of Rock-Breaking Efficiency

The quantitative assessment of rock-breaking efficiency during well drilling is a complex task because the effective axial and lateral forces applied cannot be determined with high accuracy. Laboratory experiments show that [16,17] for a single PDC cutter, the proportion of the axial force relative to the rotational force is on the order of 83% at an entry angle of 50° from the vertical. MSE is also widely used to identify drilling complications [18]. MSE analysis has been proposed for detecting low-level vibrations, inefficient drilling regimes, and related drilling dysfunctions. The energy efficiency of rock breaking by a PDC bit is achieved when the MSE value approaches the uniaxial compressive strength (UCS); thus, efficiency can be expressed as follows [19]:

$$\eta = \frac{UCS}{MSE}, \quad (1)$$

where η is the rock-breaking efficiency and UCS is the uniaxial compressive strength:

$$MSE = \frac{P}{Q_v}, \quad (2)$$

where P is the total mechanical power delivered to the bit, including the axial and rotational components, and Q_v is the volumetric rock-breaking rate.

$$MSE = \frac{WOB}{A_b} + \frac{2\pi TOB \cdot n}{60 A_b \cdot ROP} \quad (3)$$

Equation (3) expresses MSE as the mechanical energy supplied to the bit per unit volume of rock removed. For PDC bits, WOB and TOB are coupled through bit-rock interaction, usually under a quasi-steady cutting assumption [20]. Reliable MSE estimation therefore requires bit-level TOB and RPM. Surface torque may overestimate the energy delivered to the bit in deviated and horizontal wells because it includes drill string friction and drag [21]. When a positive displacement motor is used, the bit RPM must include both top-drive rotation and motor rotation [22,23]. In heterogeneous formations or during dynamic drilling dysfunctions, MSE should therefore be interpreted as an integral indicator of drilling efficiency rather than as a direct measure of rock strength. Under comparable geological conditions, the minimum MSE indicates the most energy-efficient regime, whereas an increase in MSE without a proportional increase in ROP indicates additional energy losses (Figure 1) [24].

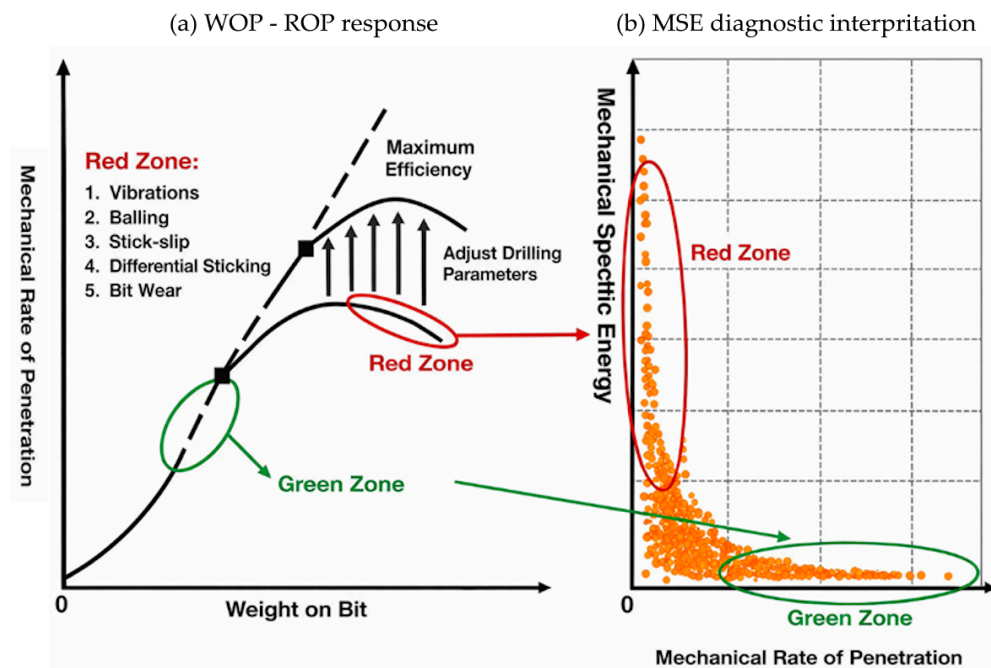


Figure 1. Identification of inefficient drilling regimes using MSE: (a) conceptual relationship between WOB and mechanical rate of penetration; (b) distribution of MSE versus mechanical rate of penetration, showing the efficient and inefficient operating regions. The Green Zone denotes the efficient drilling regime, characterized by effective WOB transfer, a relatively high ROP, and comparatively low MSE, whereas the Red Zone corresponds to inefficient drilling conditions associated with excessive energy consumption and drilling dysfunctions [25].

2.2. Limitations of Axial Load Transfer to the Bit in Horizontal Wells

The difficulty of controlling WOB lies in the fact that the bit load cannot be determined directly and reliably from surface hook-load measurements alone in real time from the hook-load sensor. This is because the hook load is determined by the weight of the drilling assembly, whereas the actual load acting on the bit remains unknown [26]. When drilling horizontal well sections with BHAs incorporating a PDM, once the bit contacts the borehole bottom and load is applied, feed from the surface is temporarily suspended. At the surface, the drill string remains stationary, whereas rock breaking at the borehole bottom continues. Under these conditions, the bit is subjected to the elastic force generated by drill string deformation and directed toward the bottom of the borehole.

In Figure 2a, the drill string moves toward the bottom of the borehole under the action of axial forces (gravity-induced axial forces) F , while the sliding friction forces $f_0 N$ and the bottomhole reaction force $WOB_0 = W_0$ act in the opposite direction. At a certain moment, feed from the surface is stopped, whereas the distribution of friction forces remains unchanged:

$$F = W_0 + f_0 N L \quad (4)$$

where F is axial force, f_0 is the friction coefficient, N is the linear contact force between the drill string and the wellbore wall, and L is the drill string length.

In Figure 2b, as rock breaking progresses and as the bit advances, the compressed drill string undergoes elastic recovery, and WOB_0 decreases to WOB , causing the drill string to elongate by ΔL . The section of the drill string that resumes forward sliding has a length S . The friction coefficient increases from f_0 to f :

$$F = W + f_0 N (L - S) + f N S \quad (5)$$

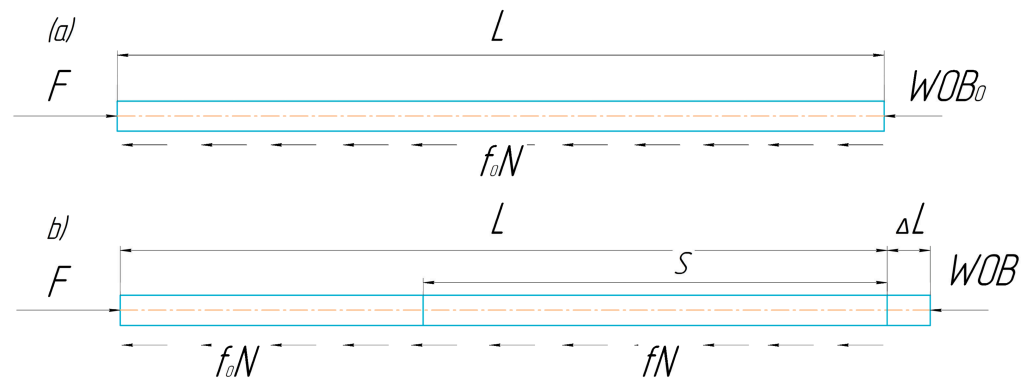


Figure 2. Principle of drill string elongation during load transfer: (a) compressed state; (b) tensioned state [compiled by the authors].

From Equations (4) and (5), the following expression is obtained:

$$S = \frac{W_0 - W}{N(f - f_0)} \quad (6)$$

The longitudinal deformation of the drill string is determined according to Hooke's law, while, from Equation (6), the length of the section, S , is expressed through the difference in weight on bit and the contact parameters.

For a rod subjected to a variable axial force $F(x)$, the elastic longitudinal deformation (in absolute value) is given by the following:

$$\delta_0 = \int_0^L \frac{F_0(x)}{EA} dx = \int_0^L \frac{W_0 + f_0 N(L - x)}{EA} dx = \frac{1}{EA} \left(W_0 L + \frac{f_0 N L^2}{2} \right) \quad (7)$$

$$\delta = \int_0^{L-S} \frac{F_0(x)}{EA} dx + \int_{L-S}^L \frac{F(x)}{EA} dx = \frac{1}{EA} \left(W L + \frac{f_0 N L^2}{2} + N(f - f_0) \left(L S - \frac{S^2}{2} \right) \right) \quad (8)$$

where δ_0 is the deformation in state (a), δ is the deformation in state (b), E is the elastic modulus, and A is the cross-sectional area of the drill string. For the left segment, $0 \leq x \leq L - S$, the friction coefficient is f_0 ; for the right segment, $L - S \leq x \leq L$, the friction coefficient is f .

After integration and substitution of the corresponding values, the expression is reduced to the final form of Equation (9), which relates the increase in drill string elongation to the change in weight on bit:

$$\Delta L = \delta_0 - \delta = \frac{(W_0 - W)^2}{2EAN(f - f_0)} \quad (9)$$

where E is the elastic modulus and A is cross-sectional area of the drill string.

It follows from Equation (4) that the greater the initial WOB, the greater the depth of cut per revolution of the drilling tool; likewise, the closer the instantaneous friction coefficient f is to the running-in friction coefficient f_0 , the greater the advance per cycle. In addition, a higher initial WOB provides a higher rate of penetration.

Thus, it can be seen that, during drilling, the load applied to the bit is not transmitted uniformly and may fluctuate over a fairly wide range. This causes vibrations and impacts that adversely affect both the rate of penetration and the equipment, potentially leading to drilling complications and failures. In sliding mode, a reduction in hook load cannot be interpreted as a direct measure of the actual bit load, because the transfer of axial force is affected by drill string stretch, friction, and wellbore contact conditions [27,28]. Moreover, the contact friction forces may become so high that, without drill string rotation, advancing the drill string toward the bottom of the borehole becomes impossible, and the load is not

transmitted to the bit in an amount sufficient for rock breaking [29]. This is one of the factors that may limit the drilling of extended horizontal intervals.

2.3. Technical Means of Load Transfer to the Bit

Nevertheless, various technical and operational measures aimed at reducing friction are used to overcome static friction and resistance forces. In some cases, lubricating additives are employed, whereas in others, special devices and engineering solutions are required. According to their mechanism of action, such technical solutions can reasonably be classified into two functional groups: (1) direct WOB generation devices installed in the lower section of the BHA (Direct WOB), and (2) weight-transfer devices, which reduce frictional losses but do not act as independent sources of load.

Studies by M. Reich [30], V. Buslaev [31], D. Baldenko [32], Z. Li and C. Wang [33], J. Zhao and X. Cui [34], B. Mohamed [35], and others describe various devices designed to generate additional load on the bit. A schematic of the hydraulic thruster and its operating principle is presented in Figure 3. The general concept of these devices is to generate axial force using the hydraulic energy of the drilling fluid flow [36,37]. The axial force is generated by a piston due to the pressure drop below the device. In the study by M. Reich, the axial force is expressed in the simplified form $W_t = \text{pressure} \times \text{area}$. In the study by Li and Wang, the operating load parameter was introduced as follows:

$$W_t = pA_0 \quad (10)$$

where p is the combined pressure drop across the PDM and the bit, and A_0 is the piston-face area.

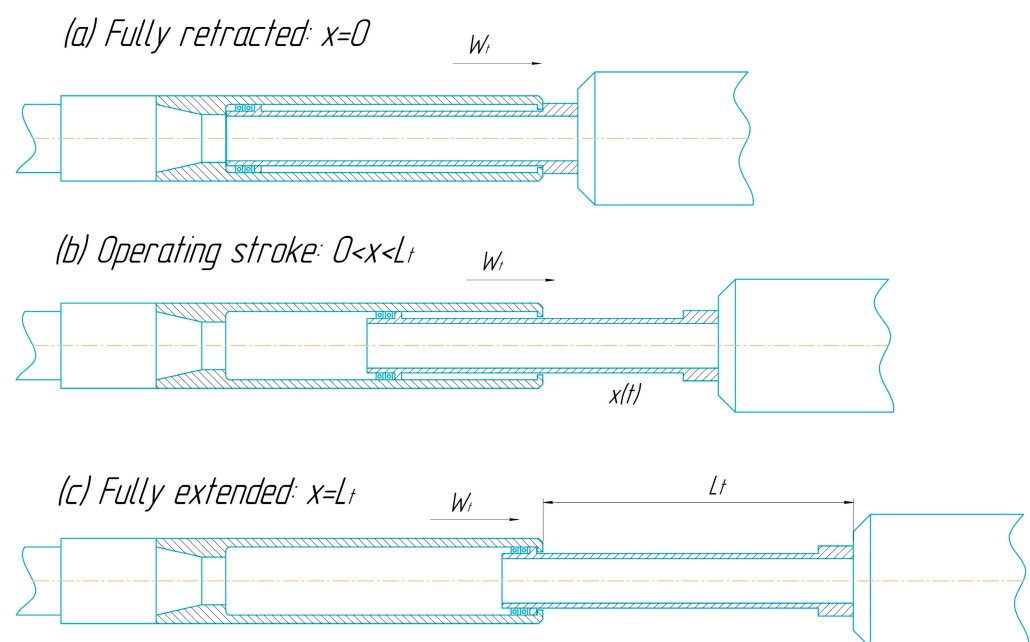


Figure 3. Hydraulic thruster operating states: (a) fully retracted, $x = 0$; (b) operating within the piston stroke, $0 < x < L_t$; and (c) fully extended, $x = L_t$. [compiled by the authors].

A structurally important consideration is that, in addition to generating axial force, the hydraulic thruster must also reliably transmit torque; for this purpose, guide grooves and keys are provided on the piston face to ensure mechanical engagement [38].

When a hydraulic thruster is incorporated into the BHA, the assembly is represented by an upper section connected to the thruster housing and a lower movable section carrying the bit. Let $u_t(t)$ and $u_b(t)$ denote the axial displacements of the upper and lower sections,

respectively. With the positive direction taken toward the bottom of the borehole, the thruster extension is defined as

$$x(t) = u_b(t) - u_t(t) \quad 0 \leq x \leq L_t \quad (11)$$

where L_t is the maximum piston stroke. Within the working stroke, the pressure-generated axial force acts on the lower section and stabilizes WOB. At $x = 0$ or $x = L_t$, the corresponding end-stop reaction becomes active.

Three operating regimes of the hydraulic thruster can be distinguished according to the relationship between the actual WOB (W) and the hydraulically generated load W_t :

1. If $W > W_t$, the thruster is in a fully charged state and, as an actuating device, is effectively inactive, the load is generated by the component W_b , i.e., by the weight of the upper drill string section.
2. If $W = W_t$, the thruster is in the operating state: the piston pushes the lower movable section of the BHA, and the load on the bit is maintained nearly constant, $W_t = \text{const.}$ This corresponds to a quasi-steady operating regime [39].
3. If $W < W_t$, the thruster is fully discharged and is again considered inactive.

In the operating regime, $R_0 = R_L = 0$, therefore, F_{tb} represents the force by which the thruster transmits load between the upper and lower sections of the BHA:

$$F_{tb} = W_t(Q, x) \approx W_t(Q), \quad (12)$$

where Q is the drilling pump flow rate.

Within the axial model, the interaction between the hydraulic thruster and the lower part of the assembly can conveniently be described through the internal force $F_{tb} = W_t$. In the form of Newton's second law, the governing equation can be written as follows:

$$m_b \ddot{u}_b = W_b + (W_t(Q, x) + R_0 - R_L) - F_f(\dot{u}_b) - W, \quad (13)$$

where m_b is the equivalent mass of the lower section, F_f is the friction force between the lower BHA section and the wellbore wall, and R_L is the constraint force associated with the piston stroke limit, which arises only when the device is fully charged or fully discharged.

$$F_{tb} = W_t(Q, x) + R_0 - R_L, \quad 0 \leq x \leq L_t, \quad R_0 \geq 0, \quad R_0 x = 0, \quad R_L \geq 0, \quad R_L(L_t - x) = 0 \quad (14)$$

Hydraulic thrusters are not the only means of reducing MSE. Axial-oscillation and agitator tools can reduce static friction and improve WOB transfer; controlled pipe rocking or drill string rotation can similarly mobilize the string during sliding [40,41]. Lubricating additives can reduce the drill string–wellbore friction coefficient [42], while optimized trajectory design, BHA selection, rotary-steerable drilling, improved hole cleaning, and closed-loop adjustment of WOB, RPM, and flow rate can reduce energy losses through different mechanisms. These approaches are complementary rather than interchangeable: friction-reduction methods do not necessarily generate a constant local WOB, whereas a thruster does not eliminate torsional or lateral dysfunctions.

Beyond purely mechanical modeling, recent studies show that complex engineering systems increasingly rely on artificial-intelligence-driven decision-support frameworks for operational decision-making, process optimization, and adaptive control [43]. In such environments, the role of AI is not limited to full automation; it also includes pattern recognition, predictive analysis, and the structured interpretation of multidimensional process data to support engineering judgment under uncertainty. From this perspective, the clustering-based methodology used in the present study can be regarded as an interpretable

data-driven decision-support tool for distinguishing drilling regimes associated with different levels of mechanical specific energy. Although the proposed approach is narrower in scope than full autonomous optimization systems, it is consistent with the broader trend toward intelligent support of engineering operations in complex industrial environments.

2.4. Problem Statement

Thus, the theoretical considerations discussed above show that *MSE* is a convenient integral metric of the energy efficiency of rock breaking; however, its practical interpretation in horizontal wells fundamentally depends on the actual *WOB* profile. During slide drilling with a positive displacement motor (PDM), the transfer of axial load from the surface is impeded by increasing friction and axial drag, which leads to non-uniform *WOB* transfer due to the elastic deformation of the drill string and significant fluctuations in bit load. These fluctuations increase the proportion of energy expended on friction and dynamic effects rather than on useful rock breaking, which is manifested by an increase in *MSE*. Therefore, reducing *MSE* and improving drilling efficiency requires a scenario with stabilized load transfer. One possible solution is the use of technical devices in the BHA, such as hydraulic thrusters, whose operating mode maintains a nearly constant *WOB*.

3. Data and Methods

3.1. Field Data and Data Preprocessing

The study was based on field drilling data from wells, and rock cutting was performed using PDC bits [44]. Unified datasets were compiled, including drilling depth, weight on bit, torque at the bit, rotational speed, rate of penetration, drilling pump pressure and flow rate, and the geometric characteristics of the well trajectory. The datasets also included drilling fluid properties, bottom-hole assembly configuration, and bit type and size.

Time series obtained from different measurement subsystems were synchronized and aligned by drilling depth. The measured depth (MD) was used as the reference axis. When necessary, the data were interpolated onto a regular time-depth grid with increments of Δt and Δh , ensuring consistent discretization for subsequent *MSE* calculations and statistical analysis.

Prior to calculating the actual mechanical specific energy, the original time series were subjected to a multistage cleaning procedure. The filtering aimed to exclude operating regimes inconsistent with steady-state rock cutting and to remove obvious measurement anomalies [45]. Intervals corresponding to unstable drilling conditions were excluded from the analysis, including those in which the bit stuck or briefly stopped and then accelerated sharply, accompanied by simultaneous spikes in *WOB* and *TOB*. These intervals were identified by pronounced fluctuations in *RPM*, torque, and *WOB*. The actual *MSE* was calculated using the classical Teale equation (Equation (3)).

3.2. Clustering of Drilling Regimes

To prevent features [46] with larger magnitudes from dominating the Euclidean distance used in k-means, *WOB* and *ROP* were standardized using the z-score method, whereby each value was converted into a dimensionless quantity.

For weight on bit,

$$WOB_{\text{normal},i} = \frac{WOB_i - \overline{WOB}}{s_{WOB}} = \frac{WOB_i - \frac{1}{n} \sum_{i=1}^n WOB_i}{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (WOB_i - \overline{WOB})^2}} \quad (15)$$

where $\overline{WOB}$ is the mean weight on bit and s_{WOB} is the sample standard deviation.

For the rate of penetration,

$$ROP_{normal,i} = \frac{ROP_i - \overline{ROP}}{s_{ROP}} = \frac{ROP_i - \frac{1}{n} \sum_{i=1}^n ROP_i}{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (ROP_i - \overline{ROP})^2}} \quad (16)$$

Thus, drilling regimes were identified using the k-means algorithm in a two-dimensional feature space.

$$x_i = (WOB_{normal,i}, ROP_{normal,i}) \quad (17)$$

The k-means objective function minimizes the total within-cluster variance:

$$\min_{\{C_j\}_{j=1}^k} \sum_{j=1}^k \sum_{x_i \in C_j} \|x_i - \mu_j\|^2 \quad (18)$$

where C_j is the set of points belonging to the j -th cluster and μ_j is the cluster centroid, i.e., the mean vector in the normalized feature space.

The clustering framework is intentionally exploratory and uses only two operational variables, WOB and ROP . It does not explicitly include TOB , RPM , inclination angle, mud properties, lithology, bit wear, vibration indicators, or hydraulic parameters; therefore, the identified clusters should be interpreted as simplified operating regimes rather than exhaustive physical classes.

3.3. Simulation of Stabilized Load Transfer to the Bit

After processing and analyzing the field data, the data were modeled taking into account the use of a hydraulic thruster in the bottom-hole assembly to transfer weight to the bit during drilling [39]. The objective of this stage was to model the axial load profile on the bit that could be achieved under stabilized weight transfer and then to compare the actual and modeled MSE values.

It was assumed that the hydraulic thruster operated in a quasi-steady regime, remaining within the piston working stroke and generating a uniform axial force governed solely by the hydraulic pressure differential.

Modeling was carried out only for intervals corresponding to constant circulation and steady-state rock cutting. The analysis accounted for drilling fluid flow rate, stable pressure, bit contact with the bottom, and the absence of anomalous spikes in torque, RPM , and ROP . In this way, operating regimes in which the behavior of the hydraulic thruster could not be interpreted were excluded from the analysis. The thruster state was described by a piston-stroke variable that changed over time according to the difference between the displacements of the drill string and the lower BHA:

$$x_i = \min\{\max[x_{i-1} + (\Delta u_{b,i} - \Delta u_{t,i}), 0], L_t\} \quad (19)$$

The displacement of the lower BHA was determined from the rate of penetration:

$$\Delta u_{b,i} = ROP_i \Delta t \quad (20)$$

The displacement of the upper assembly $\Delta u_{t,i}$ was prescribed based on the surface-applied feed regime over the selected drilling interval. Under the operating regime, the weight on bit was taken to be equal to the force generated by the thruster. This yielded a simulated time series corresponding to a stabilized weight-transfer scenario. The simulated mechanical specific energy was then calculated at each time step using the Teale equation, as for the actual data, except that the actual weight on bit was replaced by the simulated value.

The effect of the thruster was evaluated by comparing both the field-derived and simulated mechanical specific energy values over the entire interval and within the clusters previously identified using k-means in the space of normalized features, $WOB_{normal,i}$ and $ROP_{normal,i}$. This allowed drilling regimes to be compared under statistically similar loading and rate-of-penetration conditions.

It should be noted that the proposed modeling approach primarily describes the axial component and does not explicitly account for lateral vibrations or impact interactions. Therefore, the results are interpreted as a scenario-based estimate of the maximum effect of stabilized weight transfer to the bit under otherwise identical conditions, rather than as a full dynamic model of the entire drill string. The model isolates the effect of reduced axial-load variability and does not quantify vibration-related energy losses.

Within this modeling framework, any apparent stabilization of TOB arises indirectly from the imposed stabilization of WOB and the assumed quasi-steady bit-rock interaction law. This should not be interpreted as evidence that torsional dysfunctions would necessarily be suppressed under field conditions, because stick-slip, torsional oscillations, and other downhole dynamic effects are not explicitly represented in the present one-dimensional axial model.

4. Results

4.1. Clustering Results for the Initial Dataset

The initial dataset contained 1765 observations. Before clustering, the WOB and ROP features were standardized using the z-score method (Equations (15) and (16)), after which outliers were removed based on the interquartile range criterion ($IQR \times 1.5$). A total of 0.8% of the observations were excluded because they were characterized by anomalously high ROP values or extremely low/high WOB values. The cleaned dataset comprised 1750 observations. The number of clusters, $k = 6$, was selected based on a combined analysis of the inertia curve (the elbow method) and the mean silhouette coefficient, as shown in Figure 4. At $k = 6$, a pronounced slowdown in the decrease in inertia is observed, while the silhouette coefficient is $S = 0.398$, which corresponds to a moderately separated cluster structure in the two-dimensional (WOB_i, ROP_i) space.

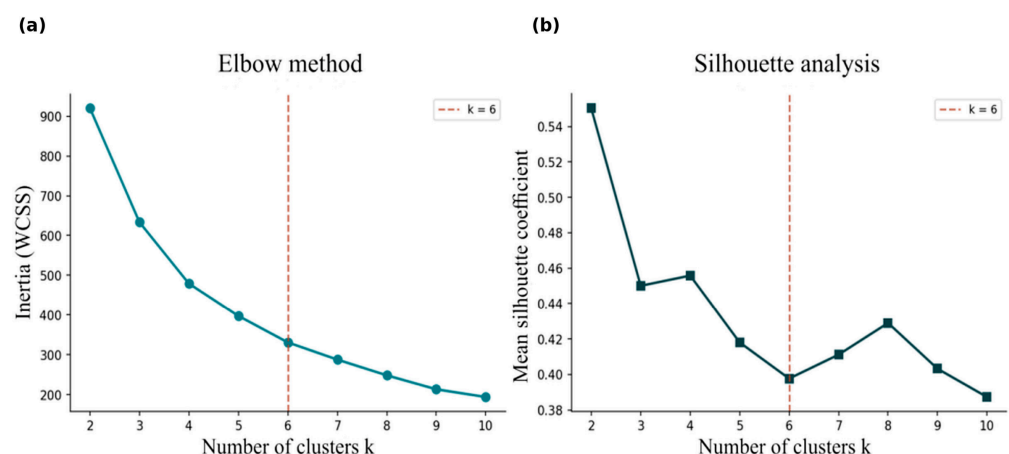


Figure 4. Selection of the number of clusters: (a) elbow method based on the within-cluster sum of squares; (b) mean silhouette coefficient. The circular markers in (a) and square markers in (b) indicate the calculated metric values for each tested number of clusters, k . The dashed line marks the exploratory selection of $k = 6$ [compiled by the authors].

Table 1 presents the statistical characteristics of the identified clusters in physical units. The clusters differ substantially both in the range of operating parameters (WOB, ROP, RPM, and TOB) and in the level of mechanical specific energy, MSE.

Table 1. Statistical characteristics of the drilling regime clusters.

Cluster	n	Share, %	WOB, t ($M \pm \sigma$)	ROP, m/h ($M \pm \sigma$)	RPM, rpm	TOB, N·m	MSE _{mean} , MPa	MSE _{med} , MPa
0	347	19.8	2.75 ± 0.92	36.4 ± 6.7	84.4	4139	108	111.0
1	303	17.3	8.36 ± 0.78	11.3 ± 4.6	88.4	12,157	103.9	101.6
2	314	17.9	5.23 ± 0.76	36.4 ± 6.4	83.0	7969	206.1	198.5
3	221	12.6	8.23 ± 1.06	30.8 ± 6.2	84.5	12,258	274.8	266.6
4	399	22.8	10.87 ± 0.81	9.5 ± 4.8	88.5	15,760	114.3	104.1
5	166	9.5	5.39 ± 1.35	15.2 ± 6.0	90.2	7772	93.1	97.7

WOB, t ($M \pm \sigma$)—mean $\pm$ standard deviation of the cluster weight-on-bit value. ROP, m/h ($M \pm \sigma$)—mean $\pm$ standard deviation of the cluster rate of penetration. The k-means clustering was performed on z-score-normalized features, whereas in Table 1, the values were converted back to physical units to improve interpretability. MSE_{mean}—arithmetic mean of all MSE values within a given cluster. MSE_{med}—median of all MSE values within a given cluster. The median is less sensitive to outliers. If the mean and median are close, as in clusters 0, 1, and 5, the MSE distribution within the cluster is approximately symmetric. If they diverge, this indicates the presence of a tail of high values that increases the mean. The visualization of the clusters is presented in Figure 5.

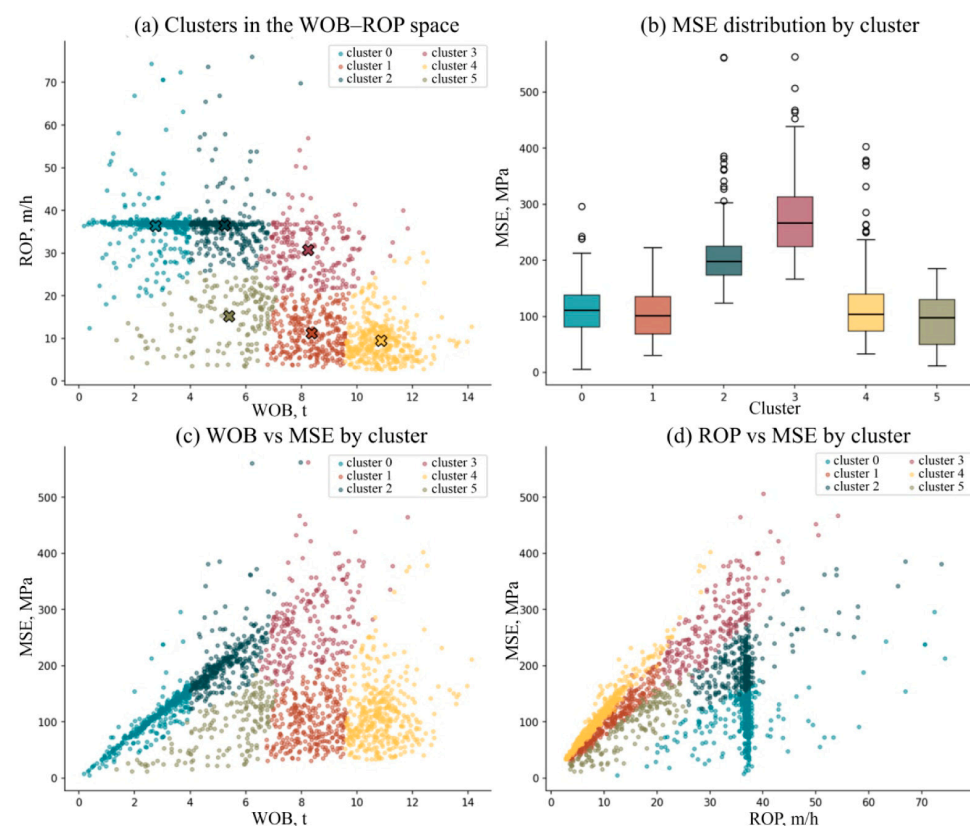


Figure 5. Cluster visualization panel: (a) WOB–ROP space, where colored points represent individual observations and crosses (×) indicate the centroids of the corresponding clusters; (b) MSE boxplot by cluster; (c) WOB–MSE distribution by cluster; (d) ROP–MSE distribution by cluster [compiled by the authors].

Three clusters with the lowest mean *MSE*, namely clusters 0, 1, and 5, were identified as the low-*MSE* regimes selected for further analysis. Collectively, these regimes comprise 816 observations, corresponding to 46.6% of the cleaned dataset. Cluster 5 is characterized by a moderate load ($WOB \approx 5.4$ t) and a medium rate of penetration ($ROP \approx 15.2$ m/h) at the lowest $MSE \approx 93$ MPa, which indicates the most efficient conversion of energy into rock breaking. Cluster 1 comprises regimes with an increased load ($WOB \approx 8.4$ t) and $ROP \approx 11.3$ m/h at $MSE \approx 104$ MPa. The low *MSE* values observed in cluster 0 despite the low load may indicate intervals of softer rock, a well-matched drilling regime in which efficient energy transfer is achieved at low weight on bit, or the absence of vibrations or impacts of the drill string against the wellbore wall.

4.2. Depth Distribution of the Identified Clusters and Selection of Intervals for Simulation

Heatmaps were constructed to evaluate the distribution of clusters along the wellbore trajectory (Figures 6 and 7). Figure 6 shows the localization of all six clusters across depth intervals, whereas Figure 7 presents only the low-*MSE* clusters. The analysis shows that cluster 0 predominates in the upper part of the section, which is consistent with the occurrence of less competent formations. Cluster 1 dominates within the 400–700 m interval, corresponding to stronger formations for which a higher weight on bit is required to achieve effective rock breaking. Cluster 4 is concentrated in the lower part of the section and is characterized by a low rate of penetration. By contrast, the cluster associated with inefficiently high *MSE* is distributed mainly within the 550–700 m interval, which may indicate non-stationary drilling conditions in transition zones. This interpretation is further supported by the reduction in rate of penetration and its substantial standard deviation.

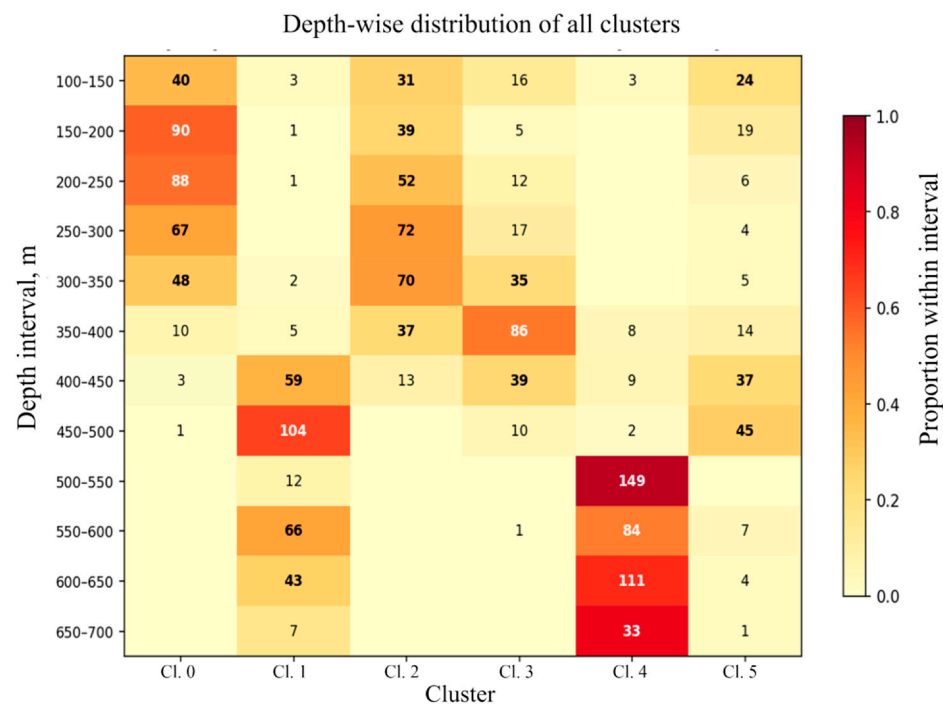


Figure 6. Spatial localization of all clusters by depth interval (number of observations in each cell; color indicates the proportion within the interval) [compiled by the authors].

The selected efficient regimes (clusters 0, 1, and 5) were used in the subsequent analysis as the basis for comparing the actual and modeled mechanical specific energy. These intervals, which are characterized by the lowest energy losses under the current drilling conditions, were chosen for simulation of the hydraulic thruster scenario. Comparing the actual *MSE* with the modeled *MSE* under stabilized loading ($WOB = \text{const}$) makes it

possible to qualitatively assess the potential for reducing energy consumption through the elimination of axial-load fluctuations at the bit.

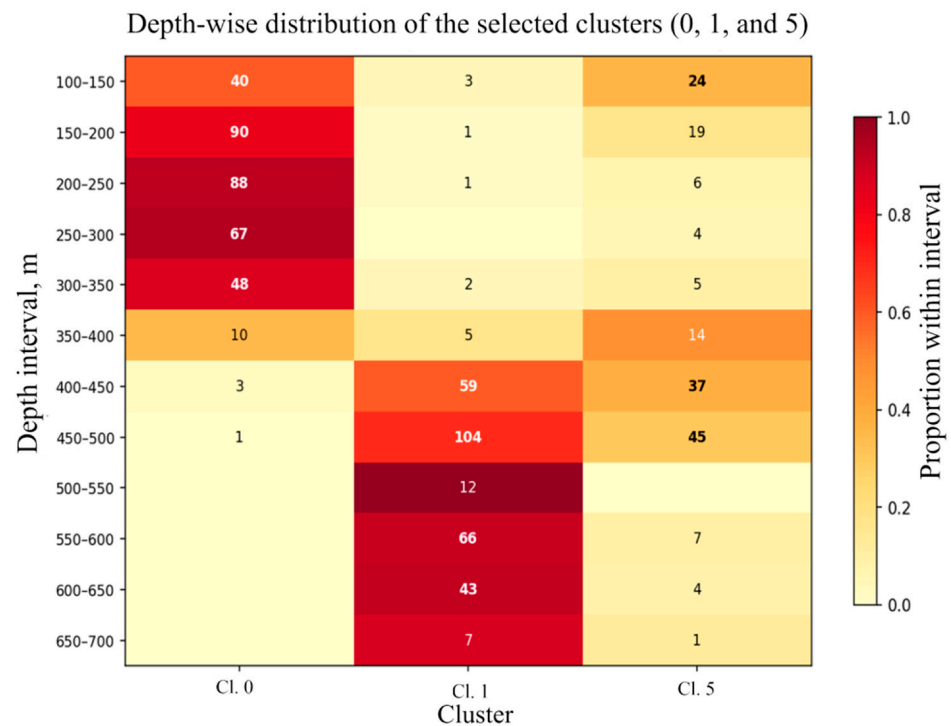


Figure 7. Spatial localization by depth of the clusters corresponding to the most efficient drilling regimes (0, 1, and 5) [compiled by the authors].

Because lithology was not included explicitly in the clustering feature space, the inferred relation between cluster distribution and formation competence should be regarded as interpretive rather than demonstrative.

4.3. Results of Simulation of Stabilized Load Transfer to the Bit

The WOB was modeled taking into account the total pressure drops across the bit and the PDM. Because the modeled load differed from the actual load, torque and rate of penetration were corrected to their predicted values. The modeling was carried out on a subset of 816 observations from clusters 0, 1, and 5 listed in Table 1, after additional outlier removal and the application of filtering criteria. Table 2 summarizes the results of the cluster analysis for the resulting dataset, which contained 400 observations for the $k = 3$ solution.

Table 2. Statistical characteristics of the clusters identified from the simulated dataset [compiled by the authors].

Cluster	n	Share, %	WOB _{model} , t ($M \pm \sigma$)	ROP _{model} , m/h ($M \pm \sigma$)	RPM rpm	TOB N·m	MSE _{model_mean} MPa	MSE _{model_med} MPa
0	149	37.2	6.16 $\pm$ 0.28	19.1 $\pm$ 2.6	84.2	7754	75.3	82.7
1	126	31.5	6.44 $\pm$ 0.15	9.5 $\pm$ 2.9	90.0	7773	67.9	62.4
2	125	31.2	5.83 $\pm$ 0.16	10.6 $\pm$ 3.4	87.1	7686	57.8	57.7

The modeled data differ primarily in the markedly reduced variability of weight on bit. According to Table 2, the standard deviation of WOB, $\sigma(WOB)$, is 0.15–0.28 t, whereas in Table 1 it reaches 0.78–1.35 t. Overall, the variability of WOB was reduced by 69.6% in

cluster 0 and by as much as 88.1% in cluster 2. These results quantitatively confirm the stabilizing effect of the hydraulic thruster on the axial load applied to the bit.

Across all clusters in Table 2, the mean MSE is 67.5 MPa, whereas the weighted mean MSE of the recommended clusters in Table 1 is 103.4 MPa. Thus, the modeled scenario yields a reduction in MSE of 35.9 MPa, or 34.7%. Cluster 2 is the most efficient, with $MSE_{\text{model_mean}} = 57.8$ MPa and $MSE_{\text{model_med}} = 57.7$ MPa, and is additionally characterized by an almost symmetric distribution (symmetry coefficient, 0.998) and the lowest coefficient of variation (7.5%). A further feature of the modeled dataset is the narrowing of the TOB range relative to the field data. In the present quasi-steady axial model, this tendency follows from the imposed stabilization of WOB and the assumed bit–rock interaction law. However, this result should be interpreted only as a model-based tendency and not as direct evidence that torsional dysfunctions would be eliminated in actual drilling.

A heatmap was constructed to assess the distribution of the modeled clusters along the wellbore trajectory (Figure 8). The Y-axis shows depth intervals with a 50 m increment, whereas the X-axis represents the clusters. The color of each cell indicates the proportion of the corresponding cluster within a given interval, and the number in each cell denotes the count of observations.

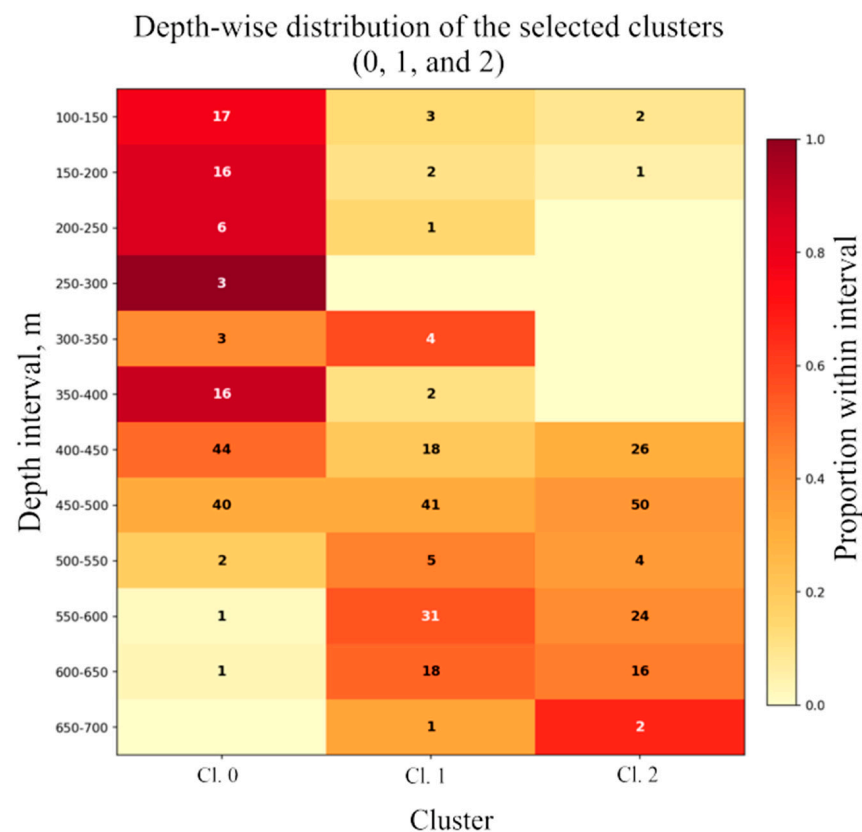


Figure 8. Spatial localization of the clusters identified from the modeled drilling parameters across depth intervals [compiled by the authors].

The cluster distribution shows a clear depth-related zonation pattern. Cluster 0 predominates in the upper part of the section, accounting for 61 of 76 observations (80.3%) within the 100–400 m interval. Its share reaches 84–86% in the 150–200 m and 200–250 m intervals and 100% in the 250–300 m interval. This pattern corresponds to a drilling regime with a high rate of penetration and a relatively elevated MSE of 75.3 MPa.

The 400–500 m interval represents a transition zone in which all three clusters are present in comparable proportions. Within the 400–450 m interval, cluster 0 remains the

most abundant, although clusters 1 and 2 together account for approximately half of the observations. In the 450–500 m interval, the distribution becomes nearly uniform: cluster 2 accounts for 38.2%, cluster 1 for 31.3%, and cluster 0 for 30.5%. The co-occurrence of all three clusters suggests that the observed distribution may reflect a combination of geological and operational factors that allow multiple drilling regimes to occur.

In the lower part of the section (550–700 m), clusters 1 and 2 are predominant, together accounting for 97.9% of the observations. Cluster 1 dominates the 550–650 m intervals, while the proportion of cluster 2 increases steadily with depth. The concentration of these two lower-ROP clusters in the deeper part of the section may be consistent with increased rock strength and/or changing operational conditions and higher friction forces at greater depth. Meanwhile, the low *MSE* values suggest that stabilized transfer of load to the bit promotes efficient conversion of mechanical energy into rock breaking. Because *WOB* fluctuations are suppressed, energy losses due to dynamic effects are minimized, and a larger share of the mechanical work is directed toward useful rock breaking rather than friction and vibration.

5. Discussion

The simulation results make it possible to evaluate the potential reduction in mechanical specific energy (*MSE*) achievable through stabilization of the axial load applied to the bit. Comparison of the field-derived dataset with the modeled dataset and with the simulated hydraulic-thruster scenario revealed several patterns that are important from both theoretical and practical perspectives.

5.1. Interpretation of the Main Results

Thus, the results obtained from the analysis of the actual and modeled data indicate the following. The clustering of field data demonstrated substantial heterogeneity of drilling regimes, with *MSE* ranging from 93.1 to 274 MPa, and the efficient clusters (0, 1, and 5) comprising 46.6% of the dataset. Under the modeled stabilized load-transfer scenario, the *WOB* range became narrower, as reflected by a 69–88% reduction in standard deviation, while the weighted-average *MSE* decreased by 34.7%. This value is higher than the 10–20% improvement reported in studies for drilling optimization based on the selection of operating parameters [47,48]. The spatial analysis suggests that load stabilization promotes energy-efficient drilling regimes in the lower part of the section, where the transfer of *WOB* during actual drilling is most strongly impeded by increasing friction forces. These results indicate the potential of hydraulic thruster application for *WOB* stabilization and reduction in mechanical specific energy.

5.2. Physical Interpretation and Practical Implications

The physical origin of the observed effect lies in the elimination of load fluctuations described in the theoretical section (Equations (4)–(9)). In the absence of load stabilization, *WOB* fluctuates with a standard deviation of 0.78–1.35 t, corresponding to a relative variability of 10–25%. Each fluctuation in the borehole bottom load causes inefficient redistribution of energy between the axial and rotational components of power at the bit [49]. According to Equation (3), *MSE* is proportional to the ratio between the total mechanical power delivered to the bit and the volumetric rate of rock breaking. When *WOB* fluctuates, the axial power component varies with both *WOB* and *ROP*, while the rotational component depends on *TOB* and bit rotational speed. This gives rise to intervals in which total energy input does not translate into an equivalent volume of rock removal.

WOB stabilization using a hydraulic thruster markedly suppresses *WOB* fluctuations: in the operating regime $WOB = W_t = \text{const}$, the standard deviation $\sigma(WOB)$ decreases to

0.15–0.28 t, which corresponds to a 69–88% reduction in variability. The observed decrease in *MSE* is in quantitative agreement with the elastic-drill string model, while the amplitude of longitudinal oscillations is also reduced.

The transition from the field-derived dataset to the modeled dataset is accompanied by a reduction in the number of clusters from $k = 6$ (Table 1) to $k = 3$ (Table 2), indicating a physically meaningful simplification of the regime space. Whereas the actual data exhibit a six-cluster structure because of the wide variability in *WOB* and *ROP*, the model constrains the *WOB* range to 5.83–6.44 t and can therefore be represented by three clusters that differ mainly in drilling rate.

Cluster 0 in Table 2 ($ROP = 19.1 \pm 2.6$ m/h, $MSE = 75.3$ MPa) corresponds to a high-penetration-rate regime. The positive correlation between *ROP* and *MSE* within this cluster ($r = 0.40$) suggests that, even under stabilized loading, higher penetration rates are accompanied by higher specific energy. A plausible explanation for this is either insufficient borehole bottom cleaning at elevated *ROP* or entry into intervals of stronger rock.

Cluster 2 in Table 2 ($WOB = 5.83 \pm 0.16$ t, $ROP = 10.6 \pm 3.4$ m/h, $MSE_{\text{mean}} = 57.8$ MPa) corresponds to the regime with the most efficient energy conversion into rock breaking. Its *MSE* coefficient of variation is only 7.5%, markedly lower than those of clusters 0 and 1, which reach 20.3% and 20.8%, respectively. In addition, the near coincidence of $MSE_{\text{mod,med}}$ and $MSE_{\text{mod,mean}}$ (57.7 and 57.8 MPa) points to an almost symmetric distribution and, hence, to a steady drilling regime without pronounced asymmetry in the modeled *MSE* distribution.

Within the adopted quasi-steady bit-rock interaction relationship, stabilization of *WOB* produces a narrower modeled *TOB* range. This result is a consequence of the model assumptions and should not be interpreted as evidence that stick-slip or other torsional dysfunctions would be suppressed under field conditions.

The modeled data show that the friction coefficient μ remains within a narrow range, from 0.146 to 0.153, with a standard deviation of 0.014 across all clusters. This indicates that load stabilization maintains the bit in a stable rock-interaction regime and prevents transition to an inefficient drilling mode.

The present study does not include a formal techno-economic analysis because tool-cost and rig-time data were not available. Nevertheless, the practical value of a hydraulic thruster would depend on whether the reduction in *MSE* is accompanied by increased *ROP*, reduced vibration-related damage, longer bit life, and lower nonproductive time sufficient to offset the additional tool cost and operational complexity. A dedicated cost-benefit analysis should therefore be included in future field trials.

5.3. Limitations

The simulation results suggest that the use of a hydraulic thruster could reduce *MSE* by 30–35% compared with the actual drilling regimes characterized by the lowest specific energy. It should be emphasized, however, that the simulation was carried out under several assumptions, namely a quasi-steady operating regime of the hydraulic thruster, constant circulation, and the absence of lateral vibrations: conditions that may not hold over certain drilling intervals. Even so, reducing *WOB* variability from $\sigma = 0.78$ –1.35 to $\sigma = 0.15$ –0.28 t appears to be physically achievable for hydraulic thrusters of various designs. A critical requirement is to sustain an operating regime in which $W = W_t$ (Equations (10) and (12)); this, in turn, requires appropriate selection of the pressure drop and piston face area.

From a practical perspective, distinguishing three drilling regimes under stabilized load conditions (Table 2) facilitates decision-making in drilling control. Within the investigated dataset and the adopted modeling assumptions, an *MSE* below approximately

60 MPa characterized the lowest-MSE modeled cluster. This value should not be interpreted as a universal operational threshold.

A limitation of the present clustering framework is that it uses only two variables, WOB and ROP, to identify drilling regimes. Other potentially influential drilling parameters, including torque-on-bit (TOB), RPM, inclination angle, mud properties, bit wear condition, lithology, vibration indicators, and hydraulic parameters, were not explicitly incorporated into the feature space. Consequently, the resulting clusters should not be regarded as exhaustive or uniquely distinct physical classes of drilling behavior, but rather as simplified operational groupings useful for exploratory interpretation. This constraint should be considered when assessing the representativeness of the identified regimes and their relationship to MSE.

More advanced AI-based optimization strategies, including reinforcement learning, constrained model-predictive control, and hybrid physics-informed optimization, may in the future support real-time selection of WOB, RPM, and flow rate under operational constraints [50]. In contrast to clustering, which primarily provides an interpretable partition of historical operating regimes, such approaches could potentially support adaptive control policies aimed at minimizing MSE while simultaneously accounting for ROP, vibration risk, and equipment limitations. However, these methods require larger labeled datasets, reliable downhole telemetry, and explicit safety constraints before field deployment.

5.4. Future Research

Future research may focus on: (1) validating the simulation results against field data from wells drilled using a hydraulic thruster; (2) incorporating dynamic effects, such as vibrations and stick-slip, into the model; and (3) using downhole telemetry data to expand the clustering feature space through the inclusion of trajectory-related parameters and drilling fluid properties.

The next stage should include controlled field trials with downhole WOB, TOB, pressure, vibration, and piston-position measurements. A paired before/after or alternating-BHA design within comparable formations would reduce geological confounding. Dynamic model extensions should include transient hydraulics, end-stop impacts, torsional and lateral drill string motion, bit wear, hole cleaning, and formation-dependent bit-rock parameters. Validation should report not only MSE but also ROP, vibration severity, bit life, tool reliability, nonproductive time, and cost per drilled meter. Future models may incorporate gamma ray and directional survey data to better account for lithology and well trajectory effects in drilling-regime classification and optimization.

Beyond clustering-based regime identification, more advanced AI-based optimization approaches may be considered for future drilling applications. In particular, reinforcement learning may offer a framework for sequential decision-making in which drilling parameters such as WOB, RPM, and flow rate are adjusted in real time in response to changing downhole conditions and operational constraints. In contrast to clustering, which primarily provides an interpretable partition of historical operating regimes, reinforcement-learning-based strategies could potentially support adaptive control policies aimed at minimizing MSE while simultaneously accounting for rate of penetration, vibration risk, and equipment limitations. At the same time, the application of such methods to drilling requires large and reliable datasets, careful reward-function design, and strict safety constraints, which means that their practical implementation should be preceded by substantial field validation.

6. Conclusions

Field data were partitioned into six exploratory WOB-ROP regimes, of which clusters 0, 1, and 5 exhibited the lowest MSE and comprised 46.6% of the cleaned observations. Cluster

5 yielded the lowest mean MSE (93.1 MPa) at moderate WOB and ROP. In an idealized quasi-steady hydraulic-thruster scenario, the standard deviation of WOB decreased by approximately 69–88%, and the weighted mean MSE decreased from 103.4 to 67.5 MPa (34.7%). This predicted reduction in MSE should be interpreted as a scenario-based upper-bound estimate derived under quasi-steady assumptions, constant circulation, and without explicit representation of lateral or torsional drill string dynamics; accordingly, it should not be regarded as a field-validated performance gain, but rather as an indication of the theoretical potential of stabilized weight transfer to the bit. Overall, hydraulic thrusters may improve axial-load transfer and reduce modeled energy losses in deviated and horizontal drilling, although field trials are still required to establish their actual effects on ROP, vibration mitigation, reliability, and economic performance. Future work should integrate downhole measurements, geological and directional data, dynamic drill string modeling, and constrained AI-based control.

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