



Dynamic Evaluation and Assessment of Horizontal Wellbore

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ABSTRACT

This paper addresses the issue of wellbore cleaning during horizontal well drilling. A dynamic evaluation and assessment system for wellbore cleaning in horizontal wells has been developed using numerical simulation and the Analytic Hierarchy Process (AHP). First, numerical simulations were conducted using Fluent software to analyze the factors influencing the movement of rock cuttings in horizontal wells, such as drill string rotational speed, annular return velocity, drilling fluid properties, drill string eccentricity, and wellbore inclination angle. The effects of these factors on the cuttings transport behavior were investigated. First, numerical simulations were conducted using Fluent software to analyze the factors influencing the movement of rock cuttings in horizontal wells, such as drill string rotational speed, annular return velocity, drilling fluid properties, drill string eccentricity, and wellbore inclination angle. The effects of these factors on the cuttings transport behavior were investigated.

KEYWORDS

Horizontal Well; Wellbore Cleaning; Dynamic Evaluation.

1. INTRODUCTION

The cleaning of the wellbore in horizontal wells is crucial for drilling and production activities in the petroleum industry. With the continuous development of oil and gas resources, horizontal well technology has become an important direction in oil and gas exploration and development. However, the issue of wellbore cleaning in horizontal wells has also become more prominent. It directly affects the safety, efficiency, and final cost of drilling operations, as well as the production performance and economic benefits of oil and gas wells[1].

The purpose of establishing a dynamic evaluation system for horizontal wellbore cleaning is to summarize the advantages and disadvantages based on the algorithms of the aforementioned scholars, improve upon them, and monitor and evaluate changes in borehole cleanliness[2]. This, in turn, reduces the risks of drill bit wear and stuck pipe, improves drilling speed, and reduces drilling costs. The established dynamic evaluation system can assist drilling engineers in better understanding the borehole cleaning conditions, thus optimizing drilling parameters more effectively[3].

2. THE PRIMARY CONTROLLING FACTORS INFLUENCING THE MIGRATION OF CUTTINGS IN HORIZONTAL WELLS

The migration of cuttings in horizontal wells significantly affects drilling efficiency, wellbore safety, cementing quality, environmental protection, and economic benefits. It can reduce drilling speed, accelerate bit wear, increase the risk of stuck pipe, alter wellbore pressure distribution, lower cementing efficiency, damage casing, contaminate formations and water resources, as well as increase drilling costs and reduce oil and gas production[4]. Therefore, effective measures should be

implemented to optimize cuttings migration and ensure the smooth progression of drilling operations. Through Fluent simulation methods, the primary influencing factors of cuttings migration in horizontal wells are analyzed, and the following conclusions are drawn:

(1) Higher drill string rotation speeds increase the agitation around the drilling fluid, aiding in the suspension of cuttings. This is especially important in horizontal wells, where gravity's effect on the settling of cuttings is diminished, necessitating additional agitation to maintain their suspension. The rotation of the drill string helps draw the cuttings into the flow of the drilling fluid, thereby more effectively transporting the cuttings from the drill bit to the wellhead.

(2) Higher annular return rates of drilling fluid can improve wellbore cleaning efficiency. A sufficiently high circulation rate aids in the effective transport of cuttings within the drilling fluid. In horizontal wells, this helps ensure that cuttings located further from the wellhead are effectively transported to the wellhead, reducing accumulation of cuttings in the wellbore by increasing the flow rate.

(3) The properties of the drilling fluid play a crucial role in the migration of cuttings in horizontal wells. First, viscosity affects the flow characteristics of the drilling fluid. An appropriate viscosity reduces the turbulence intensity of the fluid, helping to control the transport of cuttings and reduce their redeposition. Second, a moderate increase in the density of the drilling fluid not only helps balance formation pressure but also enhances the carrying capacity of the fluid, aiding the effective transportation of cuttings from the wellbore to the wellhead. However, excessively high density can accelerate the settling of cuttings particles, thus reducing the efficiency of cuttings transport.

(4) During the drilling process in horizontal wells, variations in eccentricity directly affect the flow characteristics of the drilling fluid and the distribution of shear forces, thus impacting the efficiency of cuttings suspension, transport, and removal. As eccentricity increases, the annular cross-section becomes uneven, resulting in an uneven distribution of flow rate and shear forces within the annulus. This may cause flow rates to be too low in certain areas, increasing the risk of cuttings deposition, particularly in the horizontal section, where it becomes difficult to effectively suspend and carry the cuttings.

(5) As the wellbore inclination angle approaches horizontal, the circumferential oscillation of the cuttings bed becomes increasingly pronounced. In the near-horizontal section of the well, the height of the cuttings bed in the annulus significantly decreases, and the oscillation induced by the rotation of the drill string becomes more noticeable, leading to improved wellbore cleaning.

Taking the analysis of the impact of drill pipe rotation speed on cuttings transport in horizontal wells as an example[5].

As shown in Figure 1 and Table 1, the numerical simulation results are presented under different drill pipe rotation speeds, with a drilling fluid density of 1250 kg/m^3 , annular return velocity of $0.55 \text{ m}^2/\text{s}$, fluid viscosity of $50 \text{ mPa}\cdot\text{s}$, a well inclination angle of 90° , and an eccentricity of 0.4. It can be clearly observed from the figure that, as the drill pipe rotation speed increases, the volume fraction of cuttings in the annulus significantly decreases, and the flow state of the cuttings-carrying drilling fluid begins to exhibit circumferential oscillations. This type of flow not only alters the distribution pattern of the cuttings but also causes the cuttings bed to oscillate, meaning that the bed's height is higher on one side than the other[6].

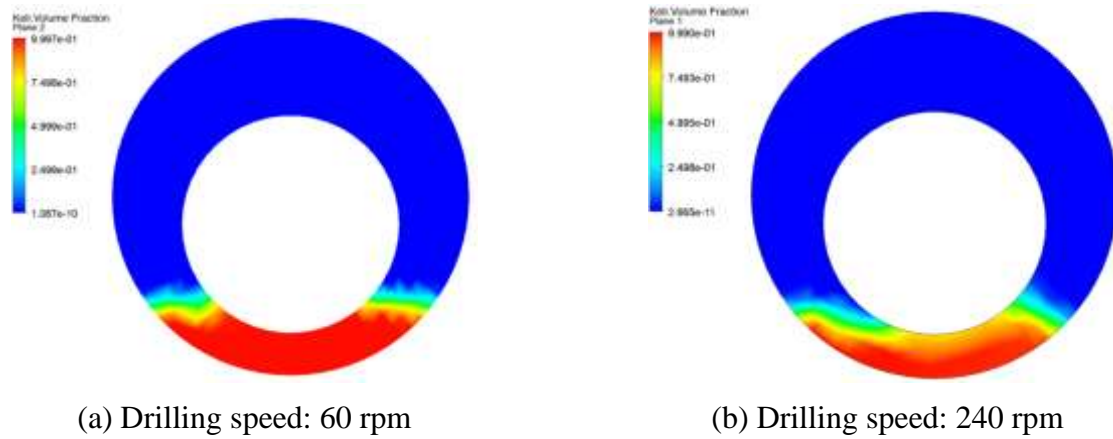


Fig. 1 Percentage of finite element cuttings content under different drill string rotation speeds.

Table 1 Simulation Results

Annular Cuttings Concentration(%)	Drill Pipe Rotational Speed(rpm)
19.8	60
16.5	120
14.2	180
10.3	240

Figure 2 shows the finite element velocity contour map of the annular local area at four different drill string rotational speeds. From the figure, it can be observed that as the drill string rotational speed increases, the stirring effect of the drilling fluid intensifies, which enables more effective suspension of the cuttings. High rotational speeds can generate stronger centrifugal forces and axial flow, helping to transport the cuttings from the bottom of the well to a higher position in the borehole. The dynamic characteristics of cuttings migration change. Within a certain range of rotational speeds, the lifting and carrying efficiency of the cuttings increases with the rotational speed, as the stirring and suspension effects of the cuttings in the drilling fluid are enhanced, reducing the likelihood of cuttings deposition, especially in horizontal well sections. However, beyond a certain critical rotational speed, the turbulence intensity of the fluid flow may become too high, causing the cuttings to deposit again.

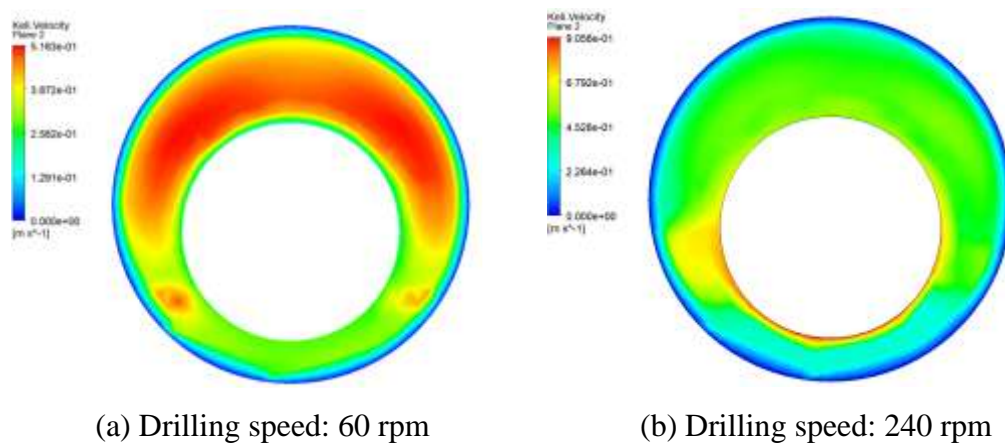


Fig. 2 Finite Element Velocity Contour Plot at Different Drill Pipe Rotational Speeds

Further analysis indicates that under different rotational speed conditions, the velocity vector distribution of cuttings movement in the annular region is shown in Figure 3. When the drill string

speed is low, the drilling fluid can only provide limited transportation velocity, so only the cuttings particles at the surface of the cuttings bed receive the transport velocity provided by the drilling fluid. The cuttings at the bottom of the cuttings bed, due to dense accumulation and obstruction from the overlying cuttings, have difficulty being resuspended and transported[7].

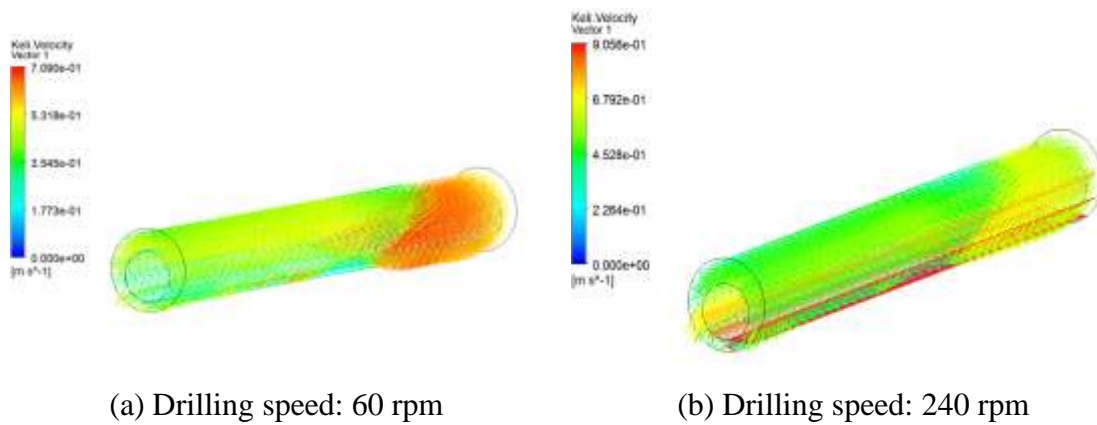


Fig. 3 Vector Diagram of Cuttings Transport Velocity at Different Drill Pipe Rotational Speeds

As a result, their movement velocity is lower, leading to the gradual formation of a stable fixed bed region. The formation of the fixed bed region may obstruct the flow of drilling fluid, thereby reducing the cuttings removal efficiency. Therefore, the movement velocity of these cuttings is low, leading to the gradual formation of a stable fixed bed region. As the drill string speed increases, the tangential velocity of the drilling fluid in the annular space increases, enhancing the chances of cuttings moving upward, thereby promoting the migration of the cuttings and reducing sedimentation. As the drill string speed increases, the height of the cuttings bed gradually decreases, and both the upper layer particles of the cuttings bed and the particles at the lower edge, caused by the shift in the cuttings bed due to the rotation of the drill string, can achieve higher transport velocities.

3. ESTABLISHMENT OF A DYNAMIC EVALUATION MODEL FOR WELLBORE CLEANING IN HORIZONTAL WELLS

3.1. Evaluation System for the Wellbore Cleaning Condition of Horizontal Wells

The core of evaluating the wellbore cleanliness of horizontal wells lies in constructing a rational indicator system, which should objectively reflect the structure of influencing factors during horizontal well drilling operations and the inherent relationships between them [8].

In the previous section, a comprehensive and detailed analysis of the factors influencing the cleanliness of the horizontal wellbore was conducted. Three models were established, namely the horizontal well ECD dynamic evaluation model, the dynamic monitoring wellbore cleanliness model based on the wellhead load, and the dynamic monitoring model based on cuttings weight analysis. It was concluded that the main factors influencing the cleanliness of the horizontal wellbore include basic data, wellbore trajectory, drilling tool combination, hydraulic parameters, and cuttings weight. These influencing factors are further impacted by several specific factors. The key factors in basic data include well depth, vertical depth, displacement, and mechanical drilling speed; the main factors in wellbore trajectory include azimuth, dogleg severity, and inclination angle; the key factors in the drilling tool combination include bit wear, bit size, and drill string specifications; the main hydraulic parameters include drilling fluid density, drilling fluid viscosity, and annular return speed of the drilling fluid; the factors in cuttings weight include average wellbore diameter, wellbore enlargement ratio, cuttings density, and cuttings size. Based on the fundamental principles of the Analytic

Hierarchy Process (AHP), the evaluation index system for the cleanliness of the horizontal wellbore is shown in Figure 4.

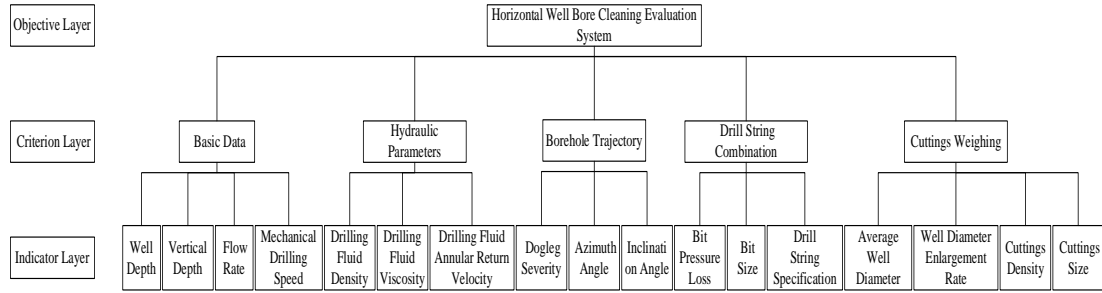


Fig. 4 Diagram of the evaluation system for horizontal wellbore cleaning condition

3.2. Determining the Weight of Factors for Horizontal Wellbore Cleaning Assessment

3.2.1. Establish a hierarchical structure for wellbore cleanliness conditions.

Based on the characteristics of the evaluation index system, the Analytical Hierarchy Process (AHP) is employed to establish a hierarchical structure [9]. The dynamic evaluation system for horizontal wellbore cleanliness is mainly divided into three levels: the goal level, the criterion level, and the factor level.

(1) Goal Level: Represents the ultimate objective of the overall evaluation, i.e., the subject of the evaluation, marked as the highest level X , containing only one element. In the evaluation of horizontal wellbore cleanliness, this level refers to the evaluation of wellbore cleanliness.

(2) Criterion Level: Specifies the main factor types that constitute the evaluation object, marked as X_k . In the evaluation of horizontal wellbore cleanliness, it primarily includes three models: the dynamic evaluation model for horizontal wellbore ECD, the dynamic monitoring model for wellbore cleanliness based on surface load, and the dynamic monitoring model based on rock cuttings weight analysis.

(3) Factor Level: Derived from the factors in the criterion level, it includes specific indicators used to achieve the criteria, marked as X_{kj} . It encompasses five main categories and related evaluation index factors: basic data, drill string configuration, hydraulic parameters, well trajectory, and rock cuttings weight.

3.2.2. The Dynamic Evaluation Factor Set for Wellbore Cleaning Conditions in Horizontal Wells

Based on the wellbore cleaning condition evaluation system for horizontal wells shown in Figure 3-1, the factor set at the criterion level, X , and the factor set at the indicator level, X_k , are defined as follows:

$$X = (X_1, X_2, X_3) \quad (1)$$

$$X_k = (X_{k1}, X_{k2}, \dots, X_{km}) \quad (2)$$

Among them, m represents the number of individual factors contained within the criterion level factor of type [10].

3.2.3. Determination of Evaluation Factor Weights

Since each evaluation factor affects the wellbore cleanliness of horizontal wells to varying degrees, it is necessary to rank them according to their importance to determine the weight coefficients, thereby establishing the weight sets for the criterion and indicator layers.

Table 2 Relative Importance Value Table

Scale	Meaning
1	Relative Importance Value Table: The impact of X_i compared to X_j is comparable
3	The impact of X_i compared to X_j is slightly important
5	The impact of X_i compared to X_j is moderately important
7	The impact of X_i compared to X_j is highly important
9	The impact of X_i compared to X_j is critically important
Even numbers between 1 and 9	The median impact of adjacent X_i compared to X_j

The expert panel constructs a judgment matrix based on the relative importance of each influencing factor in wellbore cleanliness, thereby assessing the relative importance of the criterion layer elements. The scale for importance classification is shown in Table 2.

Using the scale of classification shown in Table 3-1, the comparison results are filled into each element of the judgment matrix for both the criterion and indicator layers. The judgment matrix is a square matrix, where the rows and columns represent the factors being compared, and each element in the matrix represents the relative importance between the corresponding factors.

3.2.4. Construction of the Evaluation Matrix

When conducting a comprehensive evaluation, the first step is to determine the relative membership degree of each factor and its corresponding weight coefficient. The specific method is as follows: First, based on the specific evaluation criteria, the evaluation object is classified and an evaluation grade set is formed. For the movement characteristics of the cuttings bed within the horizontal wellbore, five levels are set, and the corresponding evaluation grade set includes: good cleanliness, relatively good cleanliness, average cleanliness, poor cleanliness, and very poor cleanliness. Each member of the expert panel is requested to determine the level corresponding to each evaluation factor in the criterion layer and fill it in Table 3.

Table 3 Cleanliness Status Rating Table

Evaluation Levels \ Evaluation Factors	Good	Fairly Good	Average	Below Average	Poor
X_1					
....					
X_{n_k}					

Each element in the evaluation matrix represents the degree of membership of the influencing factor. Constructing the evaluation matrix for the criterion layer can make the decision-making process more transparent and traceable, allowing the decision results to be interpreted and understood, and providing a reference for subsequent decisions. The matrix is shown below.

$$R_k = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{15} \\ r_{21} & r_{22} & \cdots & r_{25} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n_k 1} & r_{n_k 2} & \cdots & r_{n_k 5} \end{bmatrix} \quad (3)$$

3.2.5. First-Level Fuzzy Comprehensive Evaluation

The first-level fuzzy comprehensive evaluation serves to identify the primary objectives of the decision-making process, namely the ultimate goals or overarching direction to be achieved. Decomposing the entire decision-making problem into several relatively independent yet interrelated sub-objectives or key aspects facilitates a clearer understanding of the problem's complexity and structure. The evaluation procedure is as follows:

$$B_k = W_k \bullet R_k = \begin{bmatrix} w_{k1} & w_{k2} & \cdots & w_{kn_k} \end{bmatrix} \cdot \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{15} \\ r_{21} & r_{22} & \cdots & r_{25} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n_k 1} & r_{n_k 2} & \cdots & r_{n_k 5} \end{bmatrix} = [b_{k1} \ b_{k2} \ b_{k3} \ b_{k4} \ b_{k5}] \quad (4)$$

3.2.6. Second-Level Fuzzy Comprehensive Evaluation

The second-level fuzzy comprehensive evaluation focuses on sub-objectives or criteria under the first-level objectives. By conducting fuzzy comprehensive evaluations for each sub-objective or criterion, the optimal choice or best decision-making solution for each main objective can be ultimately determined. This approach enables decision-making assessments at a more refined level. The evaluation process is as follows:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} \end{bmatrix} \quad (5)$$

A fuzzy matrix operation is performed on R to obtain the membership vector of the target layer relative to the evaluation grade set.

$$B = W \bullet R = \begin{bmatrix} w_1 & w_2 & w_3 \end{bmatrix} \cdot \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} \end{bmatrix} = [b_1 \ b_2 \ b_3 \ b_4 \ b_5] \quad (6)$$

According to the maximum membership principle of fuzzy comprehensive evaluation, the highest component in vector B corresponds to the hole-cleaning efficiency level.

3.3. Determination of Whole-Well Cleanliness Level and Acceptance Criteria

The established single-factor cleanliness membership vectors were applied to the hierarchical model of wellbore cleanliness in horizontal wells, thereby determining the overall well cleanliness membership vector as follows:

$$r = [r_5 \ r_4 \ r_3 \ r_2 \ r_1] \quad (7)$$

The maximum membership principle was adopted to determine the cleanliness status of the entire well.

Based on practical drilling engineering considerations and the established standards for wellbore cleanliness levels in horizontal wells, the following acceptance criteria were defined:

Level 5 (Unacceptable): Must be avoided under all circumstances;

Level 4 (Unacceptable): Requires heightened vigilance;

Level 3 (Undesirable): Should be mitigated using appropriate control measures;

Level 2 (Conditionally Acceptable): Permissible under specific conditions but requires enhanced dynamic monitoring of wellbore cleanliness;

Level 1 (Acceptable): Generally permissible, but proactive measures should be taken to prevent deterioration of wellbore cleanliness.

3.4. Case Analysis

Taking the Shunbei A Well as an example, the standardized calculation results of various factors are as follows: well depth 6.3112, vertical depth 5.1203, discharge 5.6657, mechanical drilling speed 5.2012, drilling fluid density 4.1516, drilling fluid viscosity 4.0217, annular return speed of drilling fluid 4.5142, dogleg severity 4.1528, azimuth angle 4.0226, inclination angle 4.8911, bit weight loss 3.1262, average well diameter 4.1612, well diameter expansion rate 4.8987, cuttings density 5.8727, and cuttings size 5.1723. Based on the relative weights calculated above, the cleanliness level coefficient of this wellbore is 4.6214.

The quantitative assessment result for the Shunbei A Well is 4.6214. To interpret this result within specific cleanliness levels, it is necessary to calculate the average cleanliness assessment result for the block where the well is located. By comparing the assessment result derived from the drilling data with the average value, one can understand the cleanliness conditions of this well.

Using fuzzy algorithms, the average quantitative assessment result for this block is calculated to be 4.5147, while the cleanliness assessment value for this well is 4.6214, slightly above the average. According to the principle of maximum membership, its overall cleanliness condition is rated at level 3.

A comparison of the data from the rig team's daily reports and the integrated information platform with the assessment system's data shows a significant degree of consistency between the cleanliness assessment results and the actual conditions. The assessment data obtained by the system aligns with the actual conditions within the wellbore, indicating that the system demonstrates a high level of accuracy and reliability in monitoring and evaluation.

4. CONCLUSIONS

(1) Through numerical simulations using ANSYS FLUENT, a detailed analysis was conducted on the influence of five main controlling factors—annular return speed of drilling fluid, drill string rotational speed, drilling fluid properties, drill string eccentricity, and inclination angle—on the migration patterns of cuttings during horizontal well drilling. The results of this analysis can predict the cuttings migration process within the horizontal wellbore, thereby evaluating the cleanliness of the wellbore.

(2) Based on mainstream real-time monitoring evaluation models such as the ECD model, the wellhead load monitoring evaluation model, and the cuttings weight analysis evaluation model, a method using AHP (Analytic Hierarchy Process) is proposed for a comprehensive quantitative assessment of the cleanliness of horizontal wellbores. The main controlling factors affecting cuttings migration during horizontal drilling are set as the indicator layer. Fuzzy comprehensive evaluation methods are used to determine the influence degree of each factor, with the horizontal wellbore cleanliness evaluation model as the criterion layer, and the overall assessment of horizontal wellbore cleanliness as the target layer. The hierarchical structure and weights determined by AHP are applied to assess the cleanliness status of horizontal wells.

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