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THE FORCES GENERATED WHEN DRILLING BITS ARE APPLIED VERTICALLY AND OBLIQUELY: ANALYTICAL ANALYSIS AND INFLUENCE ON NORMAL OPERATION AT ANGLES OF 15° AND 30° INCLINATION

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Abstract

In this article the system of forces generated by operation of drilling bits at angles of vertical (0°), 15° and 30° inclinations of mining enterprises is analyzed. A mathematical model of the axle load (WOB), side force (Side Force), frictional force and the oblique angle of normal force was developed on the basis of a trigonometric approach and their effect on the normal operation of the bullet was determined. The results of the study show that slope angles from 15° to 30° reduce the axle load by 3.4-13.4%, and increase the side force by 25.9-50%. This condition significantly changes the drilling velocity, drill speed, and stabilizer

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load. The article provides recommendations based on modern Scopus index scientific sources.

Keywords: Drill bit, oblique well, axle load (WOB), side force, normal force, frictional force, 15° inclination, 30° inclination, force analysis, circle dynamics, torque.

Introduction

In modern mining and oil and gas industry, the drilling process optimization remains an important technological challenge. The direction of the well, in particular the angle of the slope, will fundamentally change the system of forces influencing the drill bit (drill). A correct calculation of the force system is crucial in determining drill bit selection, operating modes, and expected operating time.

In vertical wells, the main force acting on the shaft — the Weight on Bit (WOB) — acts directly along the well axis, and its entire value is spent on breaking up the rock. However, as the well turns from a vertical direction to an angle of inclination, the system of forces becomes more complicated: part of the axle load becomes a side force, the frictional force increases, and the interaction of the shaft with the stabilizers intensifies [1, 2, 3].

In particular, angle wells of 15° and 30° inclined wells are common in open pit and oil and gas enterprises. The change in the system of forces at these angle intervals is practically important because they determine the mechanisms of the well's erosion, the drilling velocity, and the stability of the well wall. Modern scientific studies show that as the angle of inclination increases, it is required to increase the pressure on the drill rig as an effective compensation for reducing the axial load [4, 5].

The purpose of this study: to develop an analytical mathematical model of the forces influencing drill bits used at mining enterprises in vertical (0°), 15° and 30° inclined conditions and to quantify their impact on normal operation of the

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drill bit. The study was carried out on the basis of modern scientific sources included in the Scopus database [1, 2, 3, 4, 5, 6].

REVIEW OF SCIENTIFIC LITERATURE

Modern research on the system of forces acting on the drill bit

The issue of forces acting on the drill bit has been extensively studied in the scientific literature. Bembenek et al. (2006) The study performed by Energies, MDPI, 2024) developed mathematical models for vertical and oblique drilling rows and obtained analytical correlations of contact forces and frictional forces for pipes made of different materials (aluminum, titanium, steel) [1]. This work has been indexed by Scopus and is an important resource in the study of the mechanics of the interaction of the drill string with the well wall.

An analytical model of drill bit and rock interactions was developed by Zafarian, Ameri, and Dolatyari (Scientific Reports, Nature, 2024). This model makes it possible to calculate shear force and fracture angle in vertical and slanted oil and gas wells by taking into account in-situ geomechanical forces. According to the study, previous models underestimated power in vertical wells by as low as 48%; In oblique wells, however, the difference was even greater [2]. This case illustrates the practical importance of proper force analysis.

Tengesdal et al. (2016) (Simulation: Transactions of the Society for Modeling, 2023) investigated the real-time modeling of drill string dynamics in inclined wells. The study scientifically analyzed the forces generated by friction of the drill string with the well wall in sloping wells, the problems of hole cleaning, and the phenomenon of string settling [3]. This resource serves as a basis for understanding force dynamics in 3D directional wells.

Etesami et al. (Journal of Petroleum Science and Engineering/Fuel, 2022) explored the difference between surface WOB and lower WOB in predicting penetration rate (ROP) in directional drilling. The study shows that the surface WOB indicator due to the slope of the well differs significantly from the WOB

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that is actually affecting the lower dove [4]. Failure to account for this difference will lead to serious errors in ROP models.
Johancsik et al. (2006). The classic 1984 torque and drag model (the hard rope model) is also still widely used in calculating drill and drill string forces. In a study published in the ASME Journal of Energy Resources Technology (2022), this model was extended with contact forces arising from pipe stiffness, and the accuracy of application in inclined wells was improved [5]. In addition, a method for quantitatively estimating frictional drag force in shear drilling was presented in Scientific Reports (2025) [6].

THEORETICAL BASIS: THE SYSTEM OF FORCES ACTING ON THE DRILL BIT

System of forces in a vertical well (0°)
In a vertical well (angle of inclination θ = 0°), the system of forces acting on the drill bit is of the simplest form. The full classification of forces in this case is as follows:

- **Arrow Load (WOB — Weight on Bit):** The main force acting along the well axis. The full cost will go to the incision of the rock. The drill collars that form the bottom of the drill line are expressed as the difference in weight and buoyancy (lifting force) of the collars.
- **Torque (TOB — Torque on Bit): The** rotational moment around the axis of rotation of the Dolota. It is formed as a result of undercutting and friction of the rock.
- **Hydraulic force:** The force generated by a stream of drilling fluid, the reaction force of the fluid passing through the nozzles.
- **Side Force: In** a vertical well, it is ideally zero; however, due to the weight and geometry of the BHA (Well Hole Equipment), a small side force may be present.

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The effective value of WOB in a vertical well is expressed by the following equation:

$$G'arb_{O\,B_0} = q \cdot L_t \cdot \left(1) - \frac{\rho_n}{\rho_s} \right)$$

where: q is the weight (N/m) of the drill collar unit length; L_c — drill collar length (m); ρ_m — drilling fluid density (kg / m³); ρ_s — steel density (kg / m³) [4].

MATHEMATICAL MODEL OF A SYSTEM OF FORCES IN AN INCLINED WELL

Principle of force decomposition

When the angle of inclination of the well is θ (0° < θ < 90°), the weight of the drill string is divided into two constituents. This phenomenon is based on the fundamental law of mechanics, the principle of the breakdown of force on coordinate axes. This approach is widely used in the scientific literature [3, 4, 5]:

$$F_{a\,x\,ia\,l} = G'arb \cdot \cos\theta$$

$$F_{n\,yoki\,ma\,l} = G'arb \cdot \text{gunoh}\,\theta$$

where: W is the weight of the drill string segment (N); θ is the angle of inclination (degrees); F_{axial} is the force constituent in the direction of the axis (N); F is the normal force (N) that presses the well wall.

Thus, in an oblique well, the effective bullet load (the WOB with the real effect on the well) is expressed as:

$$G'arb_{O\,B_{e\,ff}} = G'arb_{O\,B_0} \cdot \cos\theta - F_f$$

where: WOB_0 is the nominal WOB(N) for a vertical well; F_f is the frictional force (N). This formula is used to calculate the real WOB at the bottom from the surface WOB [4].

Side Force (SF) is the force exerting pressure on the well wall and depends on the distance between the stabilizers and the drill, the angle between the dryer axis and

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the well axis, and the weight of the BHA. A simple analytic model is as follows [3, 5]:

$$SF = W \cdot \sin\theta + F_c$$

Here: F_c is the contact force constituent (N) arising from the stiffness BHA. Side force directly affects the flow of the wheel and the load of the stabilizer [1, 3].

The classical 'soft string' model (Johancsik et al., 1984), based on Coulomb's law of friction, is widely used. In this model, the frictional strength is dependent on the normal force and the coefficient of friction (mu) [5]:

$$F_f = \mu \cdot F_N = \mu \cdot G'arb \cdot \mathrm{gunoh}\,\theta$$

where: μ is the coefficient of friction (usually between 0.15–0.35); F_N is the normal force (N). The frictional force is directed against the bullet load, reducing the effective WOB that reaches the barrel [4, 5].

In an oblique well, an addition to the torque is generated from two sources: the first is the drilling torque (TOB) resulting from the shear of the well; The second is the additional torque (T_f generated by the friction of the drill string with the well wall. Their sum is the total torque delivered by the surface engine [1, 3]:

$$T_f = \mu \cdot r \cdot F_N = \mu \cdot r \cdot G'arb \cdot \mathrm{gunoh}\,\theta$$

Where: r is the radius of the drill string (m); F_N is the normal contact force (N). As the slope increases, F_N increases, resulting in an increase in T_f as well, which increases the overall torque load [1, 5].

QUANTITATIVE FORCE ANALYSIS AT 15° AND 30° ANGLES OF INCLINATION

Trigonometric values and basic coefficients

We determine the basic trigonometric values for the angles of 0°, 15°, and 30°. These values are used directly in power formulas:

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Table 1. Trigonometric values for 0°, 15°, and 30°

Parameter	θ = 0° (vertical)	θ = 15°	θ = 30°	Unity
COSΘ	1,0000	0,9659	0,8660	—
sinθ	0,0000	0,2588	0,5000	—
WOB_eff / WOB_0 = cosθ	1,0000	0,9659	0,8660	—
F_normal / W = sinθ	0,0000	0,2588	0,5000	—
WOB Reduction	0 %	3,41 %	13,40 %	%
Normal Strength Gain	0 %	25,88 %	50,00 %	%(from W)

Example calculation: Power values for W = 100kN

For a practical calculation, consider a conditional example. Suppose that the drilling string weight W = 100 kN, coefficient of friction μ = 0.25 (mean value, typical indicator for Scopus sources [4, 5]), diameter r = 0.15 m (for 295.3 mm diameter). Based on these values, we calculate the forces for slopes of 0°, 15°, and 30°:

Table 2. Power ratings at various angles of inclination (W = 100kN, μ = 0.25)

Sign and type of strength	θ = 0°	θ = 15°	θ = 30°
Effective bullet force, WOB_eff = W×cosθ, kN	100,00	96,59	86,60
Normal power, F_N = W×sinθ, kN	0,00	25,88	50,00
Frictional force, F_f = μ×F_N, kN	0,00	6,47	12,50
Real WOB in Dolota = WOB_eff - F_f, kN	100,00	90,12	74,10
Sideload (SF ≈ F_N), kN	0,00	25,88	50,00
Frictional torque T_f = μ×r×F_N, N·m	0,00	971	1875
Decrease in real WOB, %	0 %	9,88 %	25,90 %

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As can be seen from the table, at an angle of 30° inclination, the WOB affecting the doleta is reduced by 25.9%. This has a direct impact on the speed of drilling. Simultaneously the side force doubles and the frictional torque reaches 1875 N·m. To compensate for these forces, it is necessary to increase the surface WOB and use special rheological drilling fluids [4, 6].

Effect of oblique angle on rop (drill speed)

The Rate of Penetration (ROP) of drilling is directly related to the actual WOB affecting the drill. In directional drilling, the lower WOB should be used instead of the surface WOB when predicting ROP. Etesami et al. The WOB correction for oblique is expressed by S. et al. (2022) as follows [4]:

$$G'arb_{O\,B_d} = G'arb_{O\,B_s} \cdot (\cos\theta - \mu \cdot \text{gunoh}\,\theta)$$

$$G'arb_{O\,B_d} = G'arb_{O\,B_s} \cdot \cos\theta - \mu \cdot G'arb_{O\,B_s} \cdot \text{gunoh}\,\theta$$

Here: WOB_d is the real WOB in the bottom panel; WOB_s is a surface indicator. For 15°: WOB_d = WOBs × (0.9659 - 0.25 × 0.2588) = 0.9012 × WOBs. For 30°: WOB_d = WOBs × (0.8660 - 0.25 × 0.5000) = 0.7410 × WOBs [4].

5. EFFECT OF FORCES ON THE NORMAL FUNCTIONING OF THE DOLOTA

Reduced Axis Load and Impact on Drilling Efficiency

Reduced effective bullet load affects drilling efficiency in several ways. First, ROP declines: the dolota can't provide enough depth to penetrate the rock. Scientific studies show that approximately 9-10% of the surface WOB at an angle of inclination of 15° is unaffected by the drilling speed (friction and power are lost due to direction changes). At a slope of 30°, this loss reaches 25–26% [4].

Second, there is a need to revise the type and design of the dolota. A study conducted in the wells of the Majnoon field (Iraq) (Scientific Reports, 2025) indicates that in the process of maintaining a slope of 32.9°, it will be necessary

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to optimize the drilling parameters (WOB, not RPM). J-shaped wellways increased the penetration rate by 50–100% compared with S-shaped ones [7].

Third, the issue of choice of dolota becomes more important in sloping conditions. Scientific studies have shown that the directional performance and resistance to side loading of the drill bit play an even more important role with the increase in slope. In particular, optimizing the catter geometry at a slope of 15° to 30° for PDC dolates reduces the uneven wear caused by side force [2].

Effect of normal force and side force on the absorption of the circle

The normal force (the force pressing the well wall) increases dramatically with an increase in slope. At an angle of 30°, it is 50% of the weight of the circle. This condition causes the following physical consequences:

- **Uneven Feeding:** Side force causes one-way loading of the catters (at the PDC end) or teeth (at the waterfall end). The underside of the dolota (at the end of the well) is eaten faster. Zafarian et al. The analytical model of S. et al. (2024) shows that as the angle of inclination increases, the shear strength and the angle of fracture of the rock change significantly [2].

- **Dolota Shift (Bit Walk):** As the slope increases, the dolota tends to deviate from the well axis. This phenomenon complicates directional drilling and requires a reconfiguration of the BHA (well well equipment) system [3].

- **Increase in stabilizer load:** Normal force is transmitted to the stabilizers. At a slope of 30°, the pressure on the stabilizer surface doubles compared to 0°. Bembenek et al. (2006) In the analytical-numerical model of S. et al. (2024), this relationship was confirmed by experimental data [1].

- **Dynamic instability: An** increase in lateral force exacerbates lateral oscillation (whirl) and stick-slip phenomena. According to research, the time spent in stick-slip oscillation in deep wells is more than half of the total drilling time [16].

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Table 3. The effect of forces at the slopes of 0°, 15° and 30° on the consumption of the circle

Impact Area	θ = 0°	θ = 15°	θ = 30°
Real WOB (relative)	100%	90,1%	74,1%
Normal Strength (Relative)	0%	25,9%	50,0%
Frictional strength (relative)	0%	6,5%	12,5%
Stabilizer Load	Minimal	Medium	High
The danger of uneven eating of dolota	Low	Medium	High
Stick-slip probability	Medium	High	High
Risk of Borehole Wall Erosion	Low	Medium	High
Drilling fluid requirement (washing)	Standard	Enhanced	Intensive

The Frictional Force and the Drag Problem

Frictional force — drag — in oblique wells becomes one of the most important problems of drilling operations. Tengesdal et al. (2016) The numerical model of S. et al. (2023) shows that in sloping wells, the continuous contact of the drill line with the wall is increased; This reduces the efficiency of axial transmission [3]. The frictional drag force resulting from the Johancsik model is calculated based on formula 6.

Practical example: In a well at a well with a slope of 30° at a depth of 2500 m, the frictional drag force if the weight of one metre of drill line **q = 200 N/m**, μ = 0.25 and the length of the row in the well L = 200 m, is as follows:

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$$F_{drag} = 0{,}25 \times 200 \times 200 \times \text{gunoh}\,30$$

$$F_{drag} = 0{,}25 \times 200 \times 200 \times 0{,}5$$

$$F_{drag} = \mathbf{5000\ N} = \mathbf{5\ kN}\ \checkmark$$

This value is of great value in practical terms: additional drill rig power is required to overcome this drag force in lift-and-drop operations (SPO). As the sloping increases, the drag strength also increases, and the duration of the SPO is extended. An ASME (2022) study noted that drag forces at a slope of 30° were 2-3 times higher than in a vertical well in stuck-pipe (stuck row) cases [5].

Hydraulic power change under oblique conditions

The flow of the drilling fluid also varies with respect to the angle of the slope. In oblique wells, the efficiency of removing shear particles (cutting transport) decreases because gravity creates sediment on the underside of the drill line. Bembenek et al. (2006) S. et al. (2024) modeled the optimal flow rate for different angles of inclination; The results showed that an increase of 30–40% in speed would be required to remove particles at an angle of 30° [1].

The critical velocity for the removal of liquid pests in an oblique well **v_c** is estimated by the following equation:

$$v_c(\theta) = v_c(0^\circ) \times (1) + k \times \text{gunoh}\,\theta)$$

Where k is the empirical coefficient (typically 0.3–0.5). For 30° $v_c(30°) \approx 1.15$–$1.25 \times v_c(0°)$. This requires increasing the capacity of drilling pumps [1].

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PRACTICAL RECOMMENDATIONS FOR MINING ENTERPRISES

Recommendations for an angle of inclination of 15°

Since the angle of inclination of 15° is relatively small, any changes in the power system remain within the acceptable limit, but must be taken into account. The following recommendations were developed based on Scopus index sources [1–6]:

- **Surface WOB Correction: It** is recommended to increase the surface WOB by approximately 11% of the required value to compensate for the WOB with a higher value of 9-10% that has a real impact on the dolota. Formula: WOB_s = WOB_d / 0.9012.
-
- **Friction monitoring:** Continuous monitoring of drag and friction force requires the use of MWD (Measurement While Drilling) instruments. At a slope of 15°, the frictional force is 6.5% of W — not a level that cannot be ignored.

- **Drilling fluid:** It is desirable to increase the fluid flow rate by 10-15% above standard in order to remove particles. Rheological properties must be optimized.

- **Catter Layout for PDC Pods:** To reduce uneven wear in sloping conditions, it is recommended to choose dolates with asymmetrical catter layouts [2].

Recommendations for an angle of inclination of 30°

At a slope of 30°, the change in the power system is noticeable: the real WOB is reduced by 25.9%, the side force is 50% of the weight of the wheel. This situation requires more complex technical measures:

- **Large correction of surface WOB: To** maintain the real WOB in the dolota as desired, it is necessary to increase the surface WOB by 35%: WOB_s = WOB_d/0.7410.

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- **Special BHA Construction:** It is recommended to use additional stabilizers or RSS (Rotary Steerable System) to manage the increased side force. Tengesdal et al. (2016) The model of S. et al. (2023) proved the need for real-time monitoring of BHA dynamics at a slope of 30° [3].

- **Lowering the coefficient of friction:** Application of special friction additives (lubricants) and nano-additive drilling fluids can decrease the coefficient of friction to μ = 0.25 to 0.15. This reduces drag power by 40%.

- **Drilling pump capacity:** It is necessary to increase the flow rate by 25 to 30% to remove the particles. It is desirable that the flow regime be in a turbulent state.

- **Drill speed control:** It is more effective to optimize the RPM than WOB at a 30° inclination. A study in the Majnoon field showed that reducing RPM in stiffer formations yields a better result than increasing WOB [7].

DISCUSSION AND COMPARATIVE ANALYSIS

It is also worth to compare the obtained results with modern scientific sources Scopus. Zafarian et al. An analytical model of (Scientific Reports, 2024) showed that shear force in inclined wells is underestimated by up to 48% when in-situ geomechanical forces related to the angle of inclination are not taken into account [2]. Our trigonometric model confirms this difference: at a slope of 30°, the real WOB decreases by 25.9%, while along with the frictional force is reduced by 25.9%.

Bembenek et al. (2006) The analytical-numerical model of Energies et al. (2024) presented the analytic relationships of contact forces and frictional forces for the interaction of vertical and oblique drill string cross-sections with the well wall [1]. This study shows a good agreement with our results: the fact that at a slope

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of 15° the normal force is 25.9% W and at 30° it is 50% of W, is consistent with their model.

Etesami et al. A study by S. et al. (2022) on the ROP prognosis in directional drilling also provides important information: unlike surface WOB, the lower WOB is significantly reduced due to slope and friction [4]. Our formula (9) accurately represents this correction and shows a loss of 9.88% at 15° and 25.90% at 30°. This is the important technological basis for adjusting the parameters of a drilling rig.

The ASME (2022) study based on the Johancsik model [5] and Scientific Reports' (2025) quantitative method of estimating drag power [6] also support our results. These sources also note that the increase in drag force at a slope of 30° compared to the vertical position and the prolongation of the SPO period is a critical problem from a practical point of view.

CONCLUSION

Scientific and analytical analysis of the system of forces, generated by the operation of drill bits at vertical angles (0°), 15° and 30° inclined made the following main conclusions:

1. Principle of force decay: When the angle of inclination θ is θ, the axial force acting on the bullet is $WOB_0 \times \cos\theta$ and the normal force is $W \times \sin\theta$. At 15°, the bullet force increases by 3.41% and the normal force by 25.88% from zero.

2. Decrease in real WOB: Taking into account the frictional force (μ=0.25), the real WOB at the slope of 15° decreases by 9.88% and at 30° by 25.90%. This has a direct impact on the drilling rate and ROP rate [4].

3. Side Force Effect: The Side Force (SF) is 50% of W at a slope of 30°. This leads to uneven feeding of the board, increased stick-slip vibrations, and increased stabilizer load [1, 3].

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4. Increase Torque: The extra torque ($T_f = \mu \times r \times F_N$) of friction reaches 1875 N·m at an angle of 30°. This adds a significant load to the operating mode of the drill rig motor [1, 5].

5. Increased Fluid Flow: In order to remove particles from inclined wells, it is necessary to conduct an increase of 15-25% of standard at an angle of 30°. A recalculation of the hydraulic system is required [1, 6].

6. Practical recommendations: increase the surface WOB by 11% for a 15° inclination and by 35% for 30°; use of special friction-reducing drilling fluids; it is recommended to choose RSS or enhanced stabilizer BHA at a 30° inclination [3, 7].

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