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Load-Bearing Capacity and Safe Well Depth Evaluation of Drill Strings under Wall Thickness Degradation

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Abstract: Wear-induced wall thickness reduction significantly affects the tensile bearing capacity and service safety of drill strings in deep drilling operations. Based on axial force equilibrium and hook load analysis, this study establishes a mechanical framework to evaluate the relationship between wall thickness ratio, tensile bearing capacity, and maximum safe well depth. Two typical Φ127 mm drill string grades (G105 and S135) used in the XX oilfield are analyzed as case studies. The results show that a 10% reduction in wall thickness leads to an approximately 10% decrease in tensile bearing capacity. When the wall thickness ratio decreases from 1.0 to 0.6, the maximum safe well depth decreases from 4500 m to 1000 m for G105 and from 5000 m to 3000 m for S135. Although higher-strength steel provides a larger initial safety margin, its bearing capacity remains highly sensitive to wall thickness degradation. The proposed framework provides quantitative guidance for drill string inspection, material selection, and safe depth management in deep and ultra-deep drilling engineering.
Keywords: drilling engineering, drill string inspection, drill pipe, drill string failure

I. Introduction

n deep and ultra-deep drilling engineering, the drill string serves as the primary load-bearing component in the wellbore, and its safety and reliability directly affect drilling continuity and economic performance[1-4]. As drilling depth increases, the cumulative self-weight of the drill string rises significantly, resulting in continuously increasing axial tensile load at the wellhead. Meanwhile, prolonged downhole service exposes the drill string to complex mechanical and chemical environments, including wear, corrosion, and erosion. These degradation mechanisms gradually reduce the wall thickness of the drill pipe, leading to a progressive decline in tensile bearing capacity.

When the operational load approaches or exceeds the allowable tensile capacity, the drill string may experience plastic deformation, fatigue damage, or even catastrophic fracture. Such failures not only interrupt drilling operations but also increase non-productive time and operational costs, and may pose severe safety risks. Therefore, quantitative evaluation of the tensile bearing capacity under wall thickness degradation, together with determination of the corresponding maximum safe well depth, is of critical importance for drill string management and deep-well drilling safety[5-9].

Conventional drill string safety evaluation methods are primarily based on mechanical calculation models. By establishing axial force equilibrium and considering drilling fluid buoyancy effects, the tensile bearing capacity under different wall thickness ratios can be determined and compared with the downhole hook load to identify the allowable depth range[10]. This approach possesses clear physical meaning and provides a direct representation of the relationship between structural degradation and load-bearing capacity.

However, in practical engineering scenarios, drill string safety is influenced by multiple coupled parameters, including steel grade, wall thickness ratio, drilling fluid density, and well depth[11, 12]. Under such conditions, traditional point-by-point calculation and tabular comparison methods become increasingly cumbersome and inefficient. Moreover, discrete comparison approaches may obscure the overall trend of safety margin variation with structural degradation. Therefore, a systematic mechanical framework that integrates wall thickness reduction, hook load evolution, and safety allowance into a unified analytical model is required to support rational drill string selection and operational decision-making.

Accordingly, this study establishes a tensile bearing capacity evaluation model based on axial force equilibrium, analyzes the influence of wall thickness degradation on allowable well depth, and conducts a comparative investigation of typical drill string grades used in the XX oilfield. The results aim to provide a quantitative and physically transparent basis for drill string inspection standards, service-life assessment, and drilling scheme optimization.

II. Tensile Bearing Capacity Calculation of Drill String

2.1 Force Analysis of Downhole Drill String

When the drill string is in equilibrium under the pulling force of the kelly, the axial tensile force acting on a given cross-section equals the self-weight of the drill string below that section minus the buoyant force exerted by the drilling fluid:

$$F = W - F_{\rho} \#(1.)$$

The buoyant force exerted by the drilling fluid is:

$$F_{\rho} = W\left(\frac{\rho_m}{\rho_s}\right) \#(2.)$$

Substituting the above expression yields:

$$F = W\left(1 - \frac{\rho_m}{\rho_s}\right) = W k_f \#(3.)$$

This indicates that the effective weight of the drill string in drilling fluid equals its weight in air multiplied by the buoyancy reduction coefficient k_f.

2.2 Relationship Between Wall Thickness and Tensile Bearing Capacity

The tensile stress at the wellhead cross-section of the drill string is:

$$\sigma = \frac{F}{A} \#(4.)$$

The cross-sectional area is:

$$F = \frac{\pi}{4}\phi^2 - \frac{\pi}{4}(\phi - 2\delta)^2 \#(5.)$$

Substituting into the stress expression and rearranging gives:

$$F = -\pi\sigma\delta^2 + \pi\sigma\phi\delta \#(6.)$$

This shows that the tensile bearing capacity of the drill string is a function of tensile stress, outer diameter, and wall thickness:

$$F = f(\sigma, \Phi, \delta) \#(7.)$$

When the drill string specification is fixed, the outer diameter $\Phi$is constant. Once the steel grade is determined, the allowable tensile stress $\sigma$is also fixed. During drilling operations, however, wall thickness δgradually decreases due to wear. Under this condition, the above relationship can be simplified as:

$$F = f(\delta) \#(8.)$$

This indicates that the tensile bearing capacity is directly governed by wall thickness δ. For a given wall thickness, the allowable tensile load is correspondingly determined. Therefore, drill strings with different wall thicknesses possess different tensile bearing capacities.

2.3 Influence of Wall Thickness on Tensile Bearing Capacity

After the drill string is run into the well, and when no weight on bit is applied, it is mainly subjected to axial tensile force and drilling fluid buoyancy. When weight on bit is applied, the upper section of the drill string is subjected to tensile force and drilling fluid buoyancy, while the lower section is subjected to compressive force and drilling fluid buoyancy. In general, drill collars located at the bottom of the wellbore primarily provide weight on bit to the drill bit, whereas drill pipes in the upper section bear the hook load of the entire drill string. When the weight on bit is zero, the tensile force at the wellhead reaches its maximum value.

In the XX oilfield, two types of Φ127 mm drill pipe are commonly used. One has an outer diameter of Φ127 mm, steel grade G105, and wall thickness of 9.19 mm; the other has an outer diameter of Φ127 mm, steel grade S135, and wall thickness of 9.19 mm. According to the *Drilling and Production Tools Manual*, the minimum yield strength of G105 drill pipe is 724 MPa, while that of S135 drill pipe is 931 MPa. Under normal operating conditions, the maximum allowable tensile load should not exceed 90% of the material yield strength. Therefore, the allowable tensile stress $\sigma$for G105 is

$$\sigma = 724 \times 90\% = 651.6 \text{ MPa} \#(9.)$$

and for S135 is

$$\sigma = 931 \times 90\% = 837.9 \text{ MPa} \#(10.)$$

During drilling operations, severe downhole wear and corrosion continuously reduce the wall thickness of the drill string, leading to a progressive decline in tensile bearing capacity until failure or scrapping occurs.

For comparative analysis, the tensile bearing capacity is calculated under five wall thickness ratios: 100%, 90%, 80%, 70%, and 60%, and the variation in tensile bearing capacity is examined.

2.3.1 Tensile Bearing Capacity Calculation for Φ127 mm × G105 × 9.19 mm Drill String

Substituting the corresponding parameters into the previously derived expression and rearranging yields:

$$F = -2.047\delta^2 + 259.977\delta \# (11.)$$

By substituting different values of δ, the calculated results are presented in Table 1.

Table 1: Tensile Bearing Capacity of Φ127 mm × G105 × 9.19 mm Drill String

Wall thickness ratio (%)	100	90	80	70	60
Actual wall thickness (mm)	9.19	8.271	7.352	6.433	5.514
Tensile bearing capacity (kN)	2216.31	2010.24	1800.71	1587.72	1371.28
Equivalent load (t)	226.15	205.13	183.75	162.01	139.93
Load difference (t)	0	21.02	21.38	21.74	22.08
Reduction ratio (%)	0	9.3	9.5	9.6	9.8

From Table 1, it can be observed that as wall thickness decreases, the tensile bearing capacity correspondingly decreases. Specifically, when wall thickness $\delta$is reduced by 10%, the tensile bearing capacity decreases by approximately 10%, indicating an approximately proportional relationship between wall thickness and tensile bearing capacity.

2.3.2 Tensile Bearing Capacity Calculation for Φ127 mm × S135 × 9.19 mm Drill String

Substituting the corresponding parameters into the previously derived expression and rearranging yields:

$$F = -2.632\delta^2 + 334.307\delta \# (12.)$$

By substituting different values of δ, the calculated results are presented in Table 2.

Table 2: Tensile Bearing Capacity of Φ127 mm × S135 × 9.19 mm Drill String

Wall thickness ratio (%)	100	90	80	70	60
Actual wall thickness (mm)	9.19	8.271	7.352	6.433	5.514
Tensile bearing capacity (kN)	2850	2585	2315.56	2041.68	1763.34
Equivalent load (t)	290.82	263.98	236.28	208.33	179.93
Load difference (t)	0	26.84	27.70	27.95	28.40
Reduction ratio (%)	0	9.2	9.5	9.6	9.8

Note: Reduction ratio = Load difference / 290.82 × 100%

From Table 2, it can be observed that variations in wall thickness lead to corresponding changes in tensile bearing capacity. When wall thickness δ decreases by 10%, the tensile bearing capacity decreases by approximately 10%, indicating an approximately proportional relationship between wall thickness and tensile bearing capacity.

III. Application of Tensile Bearing Capacity Calculation

3.1 Well Conditions Analysis of the XX Oilfield

A comprehensive analysis was conducted on the drill string usage conditions in the XX oilfield. The drill string assembly corresponding to the maximum loading condition during the third casing completion stage was selected as the basis for analysis. According to field statistics, the drill string configuration is as follows: 18 joints of Φ158.8 mm drill collars + Φ127 mm drill pipe + kelly.

According to the *Drilling and Production Tools Manual*, the relevant parameters are as follows: the Φ158.8 mm drill collar has a length of 9.15 m, an inner diameter of 71.44 mm, and a unit weight of 124.5 kg/m; the Φ127 mm drill pipe has a unit weight of 29.0 kg/m.

Field statistics indicate that the drilling fluid density varies with well depth as follows:
0–1000 m: 1.08–1.10 g/cm³; 1000–2000 m: 1.10–1.12 g/cm³
2000–2500 m: 1.12–1.15 g/cm³; 2500–3000 m: 1.15–1.18 g/cm³
3000–3500 m: 1.20–1.40 g/cm³; 3500–4000 m: 1.45–1.60 g/cm³
4000–4500 m: 1.55–1.70 g/cm³; 4500–5000 m: 1.65–1.85 g/cm³
These density intervals are used in the subsequent hook load calculations.

3.2 Hook Load Calculation of Drill String

The hook load refers to the tensile force borne at a given cross-section of the drill string, it can be expressed as:

$$F = Wk_f = (W_C + W_P)k_f = (q_C L_C + q_P L_P)k_f \#(13.)$$

where L_C and L_P represent the lengths of the drill collars and drill pipes, respectively. The total downhole length of the drill string is:

$$H = L_C + L_P \#(14.)$$

Thus,

$$L_P = H - L_C \#(15.)$$

Substituting into the above expression yields:

$$F = (q_C L_C + q_P H - q_P L_C)k_f \#(16.)$$

When the drill string configuration is fixed, ρ_s, q_C, L_C, and q_P are constants. The well depth H increases with drilling progress, and the buoyancy reduction coefficient k_f varies with drilling fluid density. Therefore, the functional relationship can be written as:

$$F = f(k_f, H) \#(17.)$$

Once the well depth H is determined, the corresponding drilling fluid density is also determined. Based on the above relationship, the hook load under different well depths can be calculated.

According to the block characteristics of the XX oilfield and drilling experience, a safety factor of 1.45 is adopted, and a tensile allowance of 50 t is considered. The calculated results are presented in Table 3.

Table 3: Downhole Hook Load of Drill String

H (m)	ρ_m(g/cm^3)	k_f	F (kN)	T (t)	T_a (t)	T_e (t)
1000	1.08	0.862	377.85	38.56	55.91	105.91
2000	1.10	0.86	621.39	63.41	91.94	141.94
2500	1.12	0.857	741.00	75.61	109.64	159.64
3000	1.15	0.854	859.75	87.73	127.21	177.21
3500	1.20	0.847	973.07	99.29	143.98	193.98
4000	1.45	0.815	1052.12	107.36	155.67	205.67
4500	1.55	0.803	1150.74	117.42	170.26	220.26
5000	1.65	0.79	1244.37	126.98	184.12	234.12

3.3 Analysis of Tensile Bearing Capacity

By comparing the tensile bearing capacity tables with the hook load table, the applicable well depth can be determined, thereby evaluating the drill string condition in the XX oilfield. This approach helps reduce or avoid downhole drill string accidents and ensures rational utilization of drill strings to achieve optimal operational performance.

3.3.1 Φ127 × G105 × 9.19 mm Drill String

Table 4: Load Comparison Analysis of Φ127 mm × G105 × 9.19 mm Drill String

No.	Wall thickness (mm)	Wallthickness reduction ratio (%)	Tensile bearing capacity (t)	Downhole hook load (t)	Corresponding well depth (m)
1	9.19	90%	226.15	220.26	4500
2	8.271	80%	205.13	193.98	3500
3	7.352	70%	183.75	177.21	3000
4	6.433	60%	162.01	159.64	2500
5	5.514	50%	139.93	105.91	1000

From Table 4, it can be observed that for the Φ127 mm × G105 × 9.19 mm drill string, the maximum safe well depth is 4500 m when the drill string is new. When the wall thickness ratio decreases to 90%, the maximum safe well depth reduces to 3500 m; at 80%, it decreases to 3000 m; at 70%, it decreases to 2500 m; and at 60%, it further decreases to 1000 m.

3.3.2 Φ127 mm × S135 × 9.19 mm Drill String

Table 5: Load Comparison Analysis of Φ127 mm × S135 × 9.19 mm Drill String

No.	Wall thickness (mm)	Wallthickness reduction ratio (%)	Tensile bearing capacity (t)	Downhole hook load (t)	Corresponding well depth (m)
1	9.19	90%	290.82	234.12	5000
2	8.271	80%	263.98	234.12	5000
3	7.352	70%	236.28	234.12	5000
4	6.433	60%	208.33	205.67	4000
5	5.514	50%	179.93	177.21	3000

From Table 5, it can be observed that for the Φ127 mm × S135 × 9.19 mm drill string, when the wall thickness ratio decreases to 80%, it can still be used in wells with a depth of 5000 m. When the wall thickness ratio decreases to 70%, it can be safely applied at a well depth of 4000 m. When the wall thickness ratio decreases to 60%, it can be safely used at a well depth of 3000 m.

IV. Discussion

The present study establishes a mechanical evaluation framework for analyzing the influence of wall thickness reduction on the tensile bearing capacity and maximum safe well depth of drill strings. The results reveal several important mechanical and engineering implications.

First, the approximately proportional relationship between wall thickness reduction and tensile bearing capacity degradation is consistent with the analytical formulation of cross-sectional area. Since the tensile capacity is directly governed by the effective load-bearing area, a reduction in wall thickness leads to a nearly linear decrease in tensile strength. This linearity simplifies engineering estimation and enables rapid assessment of residual bearing capacity based on measured wall thickness data during drill string inspection.

However, when the tensile capacity is further coupled with depth-dependent hook load calculations, the relationship between wall thickness ratio and maximum safe well depth exhibits nonlinear characteristics. Although the degradation of tensile capacity is approximately linear, the increase in hook load with well depth, combined with buoyancy correction and safety allowance, produces a limit-state boundary that does not follow a strictly linear trend. This indicates that drill string safety assessment cannot rely solely on isolated tensile capacity reduction percentages, but must consider the coupled effect of structural degradation and operational loading conditions.

The comparative analysis between G105 and S135 steel grades further highlights the interaction between material strength and structural deterioration. Although S135 exhibits a significantly higher tensile strength and therefore a larger safe depth range under identical wall thickness conditions, its tensile bearing capacity remains equally sensitive to wall thickness reduction. In other words, higher material strength improves the initial safety margin but does not fundamentally alter the proportional degradation behavior caused by wall thinning. This finding emphasizes that drill string inspection and maintenance remain critical even when high-strength materials are employed.

The plateau phenomenon observed in the high wall thickness ratio range for S135 drill strings indicates that, within a certain depth interval, the tensile bearing capacity significantly exceeds the equivalent design load. In this regime, structural degradation does not immediately threaten operational safety. However, once the wall thickness decreases beyond a threshold, the safety margin rapidly narrows. This transition behavior suggests that preventive maintenance decisions should not be based solely on remaining wall thickness percentage, but rather on its corresponding allowable well depth under actual operational conditions.

It should be noted that the present analysis focuses primarily on axial tensile loading conditions. In practical drilling operations, drill strings are also subjected to torsional loading, bending stresses, vibration, and fatigue effects. These additional loading modes may interact with axial tension and further reduce the overall safety margin. Therefore, the current framework provides a conservative evaluation under tensile-dominated conditions but does not represent a complete multi-axial failure analysis.

In addition, drilling fluid density is incorporated using engineering interval data rather than continuous field measurements. While this approach reflects typical operational practice, future studies may improve the precision of hook load estimation by incorporating real-time fluid density monitoring and dynamic load data.

From a methodological perspective, the mechanical formulation developed in this study provides a clear and physically interpretable safety boundary in parameter space. Future work may explore the integration of intelligent data-driven tools to enhance rapid decision-making and real-time visualization under multi-parameter coupling conditions. However, such extensions should remain grounded in rigorous mechanical consistency to ensure engineering reliability.

Overall, the results demonstrate that wall thickness degradation significantly constrains the applicable well depth of drill strings. The proposed mechanical evaluation framework offers a practical and physically transparent tool for drill string safety management, material selection, and drilling scheme optimization.

V. Conclusion

This study systematically investigates the influence of wall thickness reduction on the tensile bearing capacity and maximum safe well depth of drill strings based on axial force equilibrium and hook load analysis. The main conclusions are summarized as follows:

(1) Wall thickness is a critical structural parameter governing the tensile bearing capacity of drill strings. Due to wear and corrosion during drilling operations, wall thickness gradually decreases, resulting in a nearly proportional reduction in axial tensile capacity. For every 10% reduction in wall thickness, the tensile bearing capacity decreases by approximately 10%, indicating an approximately linear degradation relationship.

(2) When tensile bearing capacity is coupled with well-depth-dependent hook load calculations, the maximum safe well depth decreases significantly with wall thickness reduction. For the Φ127 mm × G105 × 9.19 mm drill string, the maximum safe well depth decreases from 4500 m to 1000 m as the wall thickness ratio decreases from 1.0 to 0.6. For the Φ127 mm × S135 × 9.19 mm drill string, the corresponding safe depth decreases from 5000 m to 3000 m under the same wall thickness reduction range.

(3) Although high-strength steel grades such as S135 provide a larger initial safety margin compared with G105, their tensile bearing capacity remains highly sensitive to wall thickness degradation. Material strength enhances the allowable depth range but does not alter the proportional deterioration behavior caused by structural thinning.

(4) The proposed mechanical evaluation framework enables quantitative determination of allowable well depth under different wall thickness conditions and provides a practical basis for drill string inspection, material selection, and drilling scheme optimization. The results contribute to reducing drill string failure risk and improving operational safety in deep and ultra-deep drilling engineering.

VI. Nomenclature

ρ_m— drilling fluid density (g/cm³)
W— weight of the drill string in air (N)
W_C— weight of drill collars in air (N)
W_P— weight of drill pipe in air (N)
F— tensile force borne by the drill string (N)
Φ— outer diameter of the drill string (mm)
δ— wall thickness of the drill string (mm)
σ— tensile stress of the drill string (N/m²)
F_ρ— buoyant force exerted by the drilling fluid (N)
ρ_s— density of steel (g/cm³)
A— cross-sectional area of the drill string (m²)
L— total length of the drill string below the wellhead (m)
L_C— length of drill collars (m)
L_P— length of drill pipe (m)
k_f— buoyancy reduction coefficient
q_C— unit weight of drill collars (kg/m)
q_P— unit weight of drill pipe (kg/m)
H— well depth (m)
T— equivalent load of the drill string (t)
T_a— safety factor load (t)
T_e— tensile allowance (t)

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