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Research Article

Calculation and analysis of dynamic drag and torque of horizontal well strings☆,☆☆

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Abstract

In recent years, shale gas production horizontal well types mainly include conventional horizontal well, highly deviated well and scoop-shape horizontal well. For the sake of construction decision making, it is necessary to study these three types of wells from the aspects of drag and torque characteristic, weight on bit transferring efficiency, key hole sections or links and extreme penetration length. In this paper, these three types of horizontal wells were taken as the study objects. Their drag and torque, load transfer and extended reach drilling were explored based on the dynamic model of full hole drilling string and the simulation calculation of dynamic characteristics of full hole drilling string system. And the results were applied and tested on site in three shale gas wells (a conventional horizontal well, a highly deviated well and a scoop-shape horizontal well) in the Changning area, Sichuan Basin. And the following research results were obtained. First, the contact friction strength of the deeper part of the buildup section in the scoop-shape horizontal well is very high, and it is 1.67 times that of the hold section. The total contact force of buildup section in the scoop-shape horizontal well is 1.62 times that in the highly deviated well. Second, the contact friction strength of the hold section in highly deviated well is not only higher than that of its buildup section, but also higher than any characteristic section in the three well types of the same depth. Third, the operating stress of drilling strings during the drilling of three well types is not high, but during the extended reach drilling in the curved section of the scoop-shape horizontal well, it is necessary to focus on the twist off of drilling string in the hold section. Fourth, the weight on bit transferring efficiency of scoop-shape horizontal well is lower than that of conventional horizontal well and highly deviated well. In conclusion, the research results preliminarily reveal the drag and torque characteristics and active load transferring mechanisms of conventional horizontal well, highly deviated well and scoop-shape horizontal well for shale gas production, and present important hole sections for safety assessment. They can be used as references for efficient and safe construction of shale gas horizontal wells.

Keywords: Shale gas; Conventional horizontal well; Highly deviated well; Scoop-shape horizontal well; Contact friction strength; Torque; Weight on bit transferring efficiency; Limit extended reach drilling length

According to the US Energy Information Administration (EIA), shale gas will account for 30% of global total gas production by 2040 [1]. With the increasing economic effects of shale gas, China has begun to consider and encourage oil companies to explore and develop shale gas. Rapid development in recent years has made shale gas an important support for future increase of reserves and production in the natural gas industry [2,3]. China's shale gas reservoirs are deeply buried. Horizontal wells are the main technical measures and processes in low-cost and efficient shale gas development.

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Three horizontal well types are used in China, including conventional horizontal well (inclination = 90°), scoop-shape horizontal well (inclination > 90°) and inclined wells (inclination < 90°). More systematic researches, especially quantitative comparative analyses, on drag and torque, WOB transferring, extended drilling capacity and drilling safety are needed to facilitate operation decisions [4−7].

1. Background

Shale gas well exploration and development started later in China, and there are only few researches on the drag and torque of shale gas wells. Jiang et al. [8] believed that the application of rotary steerable drilling technology and oil-based drilling fluid combined with BHA optimization can significantly improve the active load transfer of horizontal shale gas wells. Shen et al. [9] reduced the drag and torque of shale gas horizontal wells by optimizing the KOP position, hold-up section length, well inclination and the rate of overall angle change. Liu et al. [10] calculated the drag and torque of shale gas wells using the soft rod moment model, and conducted stress check of drill string of actual shale gas wells.

A lot of efforts have been put into the establishment and calculation of the drag and torque model of drill string. Based on the soft rod model proposed by Johansick in 1984 [11], researchers have developed calculation models for the directional well drag and torque. He [12] proposed a modified tensile torque model based on the theory of large deformation, taking the stiffness of drill string into consideration for the first time. Subsequently, Mitchell and Samuel [13], by considering the contact position of drill string with wellbore, established a relatively complete rigid rod model. Li and Liu [14] established a steady-state tensile torque model by studying the movement state of drill string and the influence of drilling fluid. Bai and Lin [15] proposed the beam−column theory to solve the two-dimensional model of BHA deformation, and extended the research to three dimensions in 1989 [16]. Liu et al. [17,18] established longitudinal and torsional vibration models of drill string, and solved them by finite difference method. Song et al. [19] proposed a new calculation model for drag and torque. Zhu et al. [20] established a dynamics model of full hole drill string system with three-dimensional trajectory based on Hamilton's principle and finite element method, and developed a dynamics simulation software for drill string dynamics [21]. Zhu et al. [22] established a dynamic drag and torque model for highly deviated wells based on the dynamics of the full hole drill string system, and developed its numerical simulation method, the calculation accuracy of which was verified by field data.

Based on the dynamics model and dynamic behavior numerical simulation of full hole drill string system, the drag and torque, load transfer and extended drilling of the three types of shale gas horizontal wells are studied in this paper.

2. Full-hole dynamic drag and torque calculation model

The movement state of drill string is limited by wellbore size and axial winding rate. Drilling fluid also produces viscous damping to the movement of drill string. When well inclination is too large, the contact between drill strings and wellbore becomes complicated and variable. In order to obtain the drag and torque of drill string, it is necessary to conduct dynamic analysis of full hole drill strings.

The Hertz contact theory was used to calculate the drill string−wellbore contact force. Given that the impedance coefficient of drill string and wellbore Wallis k and the drag coefficient is c, the contact force is:

$$F_{\mathrm{n}} = kr + cv_{\mathrm{r}} \tag{1}$$

where r is the distance from the drill string to the wellbore wall, m; similarly, F_{n}: the contact force, kN; v_{r}: the radial velocity of drill string joint, m/s.

Drill string has axial and circular motion during drilling, so the total friction coefficient (u_{n}) is decomposed into the axial friction coefficient (u) and the tangential friction coefficient (u_{t}):

$$\varphi = \mathrm{tg}^{-1}\frac{\pi w D_{\mathrm{d}}}{60 v_{\mathrm{a}}} \tag{2}$$

$$\begin{cases} u_t = u_{\mathrm{n}} \sin\varphi \\ u = u_{\mathrm{n}} \cos\varphi \end{cases} \tag{3}$$

where φ is the transition parameter; similarly, w: the drill string rotating speed, r/min; D_{d}: the outer diameter of drill string, m; v_{a}: the axial speed of drill string, m/s.

Based on the Coulomb friction theorem, the following formulas are obtained:

$$f = -\mathrm{sign}(v_{\mathrm{a}}) u F_n \tag{4}$$

$$f_{\mathrm{t}} = -\mathrm{sign}(v_{\mathrm{t}}) u_{\mathrm{t}} F_{\mathrm{n}} \tag{5}$$

where v_{t} is the tangential velocity of drill string, m/s.

By using the spring−mass−damping (S−M−C) system, based on the basic principle of nonlinear dynamics, the dynamic balance equation of the whole drill string system is obtained:

$$\boldsymbol{M}\ddot{\boldsymbol{U}} + \boldsymbol{C}\dot{\boldsymbol{U}} + \boldsymbol{K}\boldsymbol{U} = \boldsymbol{F} \tag{6}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$, and $\boldsymbol{K}$ is the mass group matrix, damping group matrix, and stiffness group matrix of the drill string system respectively; $\ddot{\boldsymbol{U}}$, $\dot{\boldsymbol{U}}$, $\boldsymbol{U}$ and $\boldsymbol{F}$ are the acceleration matrix, velocity matrix, displacement matrix, and load matrix of the drill string system, respectively.

By introducing the load conditions and boundary conditions and solving Equation (6) by stepwise integration using Wilson-è method, the dynamic behavior of the whole drill string system can be analyzed [23].

3. Full hole dynamics analysis

The scoop-shape horizontal well technology was adopted in shale gas wells in the Changning block, the Sichuan Basin. High drag and torque was observed during drilling operations. Numerical models of full hole drill string were established for Well H24-1 (a scoop-shape horizontal well), Well 201-X (a conventional horizontal well) and Well CN-S (a highly deviated horizontal well) in the Changning block [24,25], to comparatively analyze the drag and torque and the extend drilling capacity of the three types of wells.

The same BHA was applied in the three wells. The calculation parameters are as follows: Ø139.7 mm DP + cock + kelly + Ø139.7 mm HWDP × 84.53 m (9 joints) + Ø165 mm DC × 9.47 m + Ø205 mm stabilizer × 1.53 m + Ø172 mm PDM × 7.69 m + Ø215.9 mm drill bit × 0.34 m.

Fig. 1 shows the casing program of Well H24-1. The maximum well inclination is 105°. The TVD difference between point A (2292.92 m) and point B (1972.77 m) is 320.15 m. The maximum well inclination is 91° for Well 201-X and is 83° for Well CN-S.

3.1. Drill string contact force

Dynamic contact force data was obtained. Given the same RPM and WOB, the drill string–wellbore contact forces in the full hole of Well H24-1 (the maximum well inclination of 105°), Well 201-X (the maximum well inclination of 91°) and Well CN-S (the maximum well inclination of 83°) are shown in Fig. 2. The hold section inclination angle has a significant influence on the contact force of the buildup section. The contact force of the buildup section is reduced by 40.3% by reducing the maximum well inclination from 105° to 91°, and is reduced by 52.4% by reducing the maximum well inclination from 91° to 83°. However, the contact force of the hold section has little change of about 5%.

The contact between drill string and wellbore can be divided into high-side contact and low-side contact. A high-side contact would occur when the drill string rotates to the upper well wall, and a low-side contact may be formed when

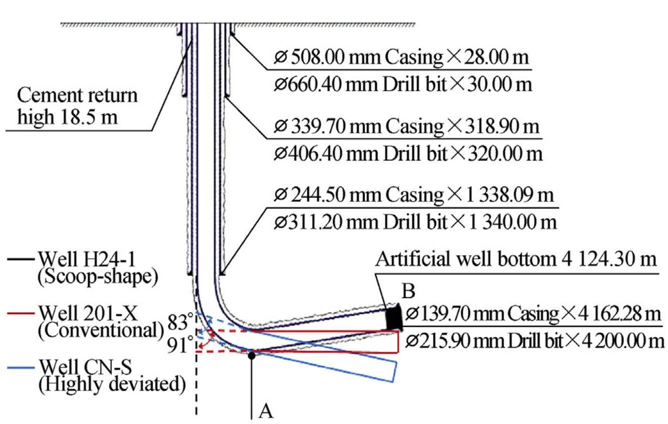

Fig. 1. Casing program of three types of wells in the Changning block.

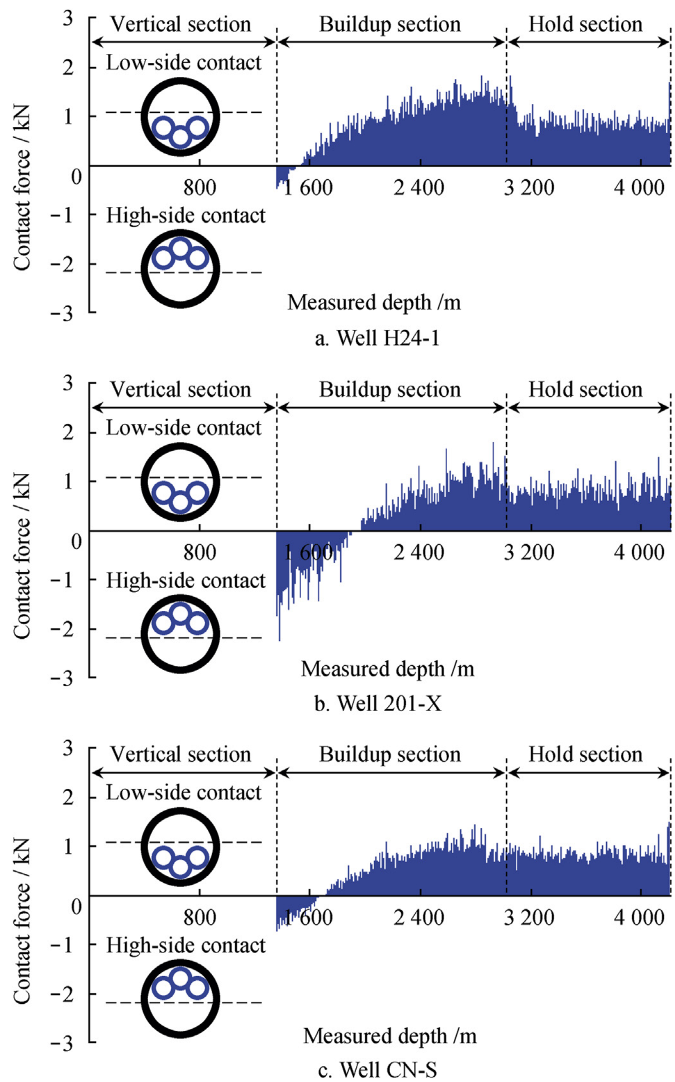

Fig. 2. Drill string–wellbore contact force in full hole.

the drill string is lying on the lower wellbore wall. In Fig. 2a–c, as the maximum well inclination decreases, the high-side contact range and contact force increase significantly. When the maximum well inclination reduces from 105° to 83°, the high-side contact range increases by 2.9 times, and the high-side contact force increases by 10.5 times. For visually comparing the contact force between drill string and borehole wall in different well sections and well types, the concept of average contact strength is defined here, that is, the average contact force between each drill string node and borehole wall in every 400 m drill string, as shown in Table 1.

It can be seen from Table 1 that the average contact strengths of three wells have little change in the hold section. In the buildup section, the average contact strength of the scoop-shape well is significantly larger than that of the other two types. The average contact strength of the deeper part of the buildup section of the scoop-shape well reached 167% of the average contact strength of the hold section.

The full bore dynamic drag and torque can be calculated based on the contact force. Generally, the friction coefficient

Table 1
Average strength of contact between the drill string and the wellbore of three types of wells in the Changning block.

Well section	Well depth/m	H24-1 (spoon-shape horizontal well)			201-X (conventional horizontal well)			CN-S (highly deviated well)		
		Average contact strength/kN	Average/kN	Difference from hold section	Average contact strength/kN	Average/kN	Difference from hold section	Average contact strength/kN	Average/kN	Difference from hold section
Buildup section	1340−1800	0.1755		25.1%	0.2051		30.1%	1.2328		181.0%
	1800−2200	0.6410		91.7%	0.3860		56.7%	0.1190		17.5%
	2200−2600	0.9666		138.2%	0.7207		105.8%	0.4505		66.1%
	2600−3000	1.1682		167.0%	0.7855		115.3%	0.7279		106.8%
Hold section	3000−3400	0.7652			0.6850			0.6997		
	3400−3800	0.6567	0.6992		0.6829	0.6814		0.6727	0.6813	
	3800−4200	0.6757			0.6761			0.6714		

between the drill string and the borehole wall is between 0.2 and 0.3 under water-based drilling fluid, and is no more than 0.1 under oil-based drilling fluid. Fig. 3 shows the variation of the average torque along the drill string in Well H24-1 under different drilling fluids. Fig. 3 indicates that the drill string in the deeper part of the buildup section is located at the maximum TVD of the full bore, where the drill string is squeezed by both ends. This section has the most significant average drag and torque rise rate, and is the very point where friction reduction measure should be adopted.

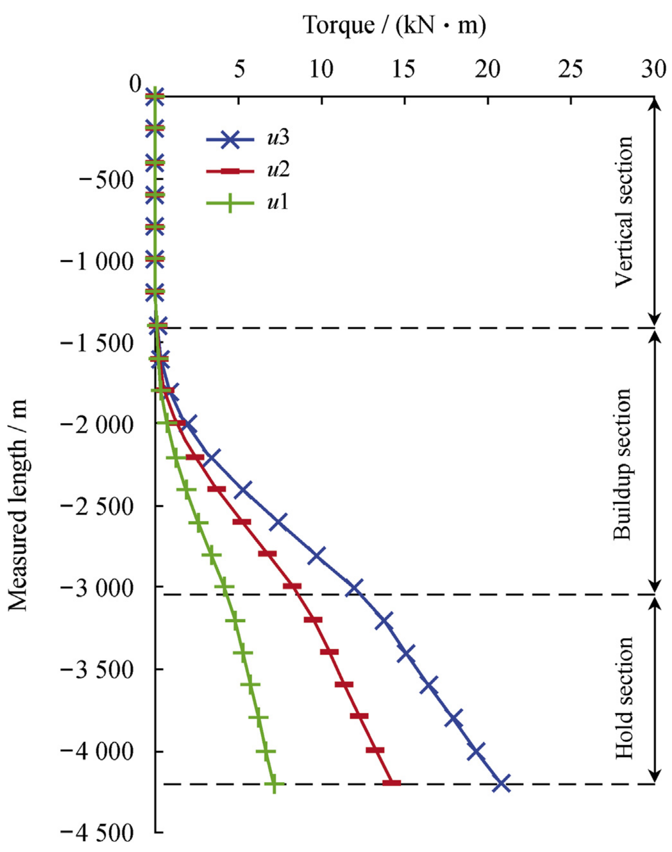

Fig. 3. Steady-state torque of the drill string of Well H24-1. Note: $u1$ refers to the friction coefficient of 0.1 under oil-based drilling fluid; $u2$ and $u3$ the friction coefficients of 0.2 and 0.3 respectively under water-based drilling fluid (similarly hereinafter).

3.2. Drill string torque and extension torque

Fig. 4 shows the transient torque variation of drill strings under different drilling fluids. As with the average torque, in the maximum vertical depth section (the deeper part of the buildup section), the fluctuation value of the transient torque of the drill string rises the fastest, and at this position the drill string contact friction with the borehole wall is the most serious. It can be also seen from Fig. 4 that the drag and torque variation amount is about 18% of its average value. Combined with the contact force in Fig. 2a, it is believed that the drill string of the deeper part of the buildup section and the hold section of the wells have a “precession” in the direction of

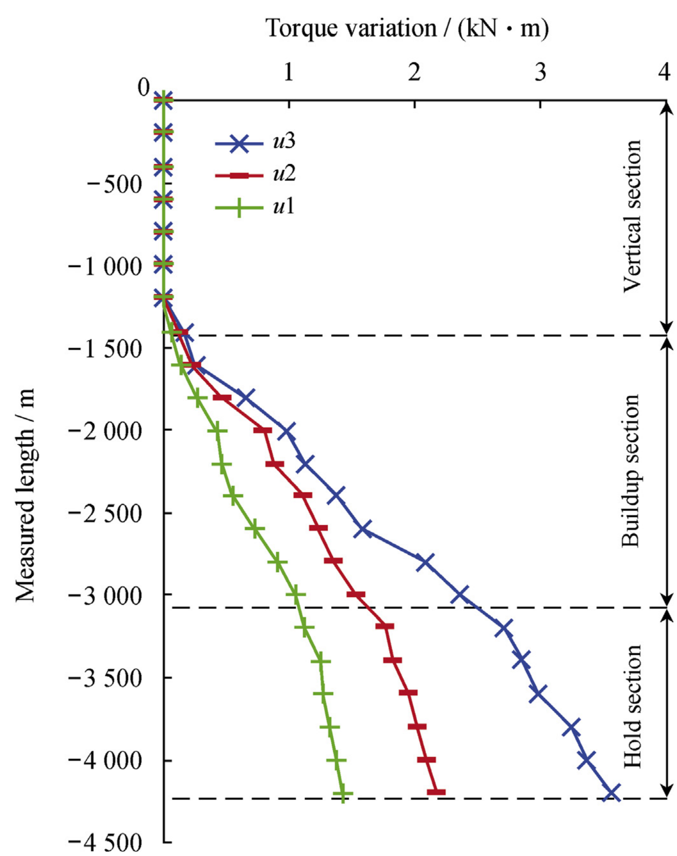

Fig. 4. Drag and torque transient variation of the drill string of Well H24-1.

Table 2
Drag and torque of the drill string of Well H24-1.

Well depth/m	Drag and torque/(kN·m)			Remarks
	$u3$	$u2$	$u1$	
4200	20.9	14.3	7.1	True depth
4200 + 600	26.7	18.0	8.0	Extended hold section prediction
4200 + 1200	32.7	21.7	10.4	
4200 + 1800	37.3	25.1	12.2	

rotation, because the drill string is subjected to the alternating continuous rising and sudden release of drag and torque. This "drill string precession" is similar to the "stick−slip vibration" of PDC bits, which is harmful to drill strings.

The industry expects to extend drilling on the basis of the current well type and TVD, but there is still no basis for calculation. Taking Well H24-1, the scoop-shape well with severe drag and torque problem as the object, this paper studied the drag and torque of drill string under different drilling fluids after extending the hold section to 600 m, 1200 m and 1800 m. The results are shown in Table 2.

According to Table 2, as the length of the hold section increases, the drag and torque rise steadily. Moreover, oil-based drilling fluid widely used in shale gas wells provides a better lubrication, making the absolute value increment of drilling friction very small.

Figs. 5 and 6 show the drag and torque of the drill string and its variation after the hold section is extended to 600 m.

It can be seen that the most severe contact between the drill string and the wellbore is still at the deeper part of the buildup section. When the buildup section was extended from 4200 m to 4800 m, the overall drag and torque increase by 24.8%, and the torque variation by 117.0%. The drag and torque variation accounts for about 32% of its average. The higher the ratio, the more serious the precession of the drill string in the direction of rotation. Most of the drill string stress checks are usually only based on the rated working load or load average, which ignores the influence of drag and torque variation on drill string, so the actual fatigue life of drill string may be greatly overestimated. Under some extreme conditions, such as severe drill string eccentric wear, well inclination change or orientation drift, overestimation can lead to drill string safety incidents.

3.3. WOB transfer

Through the simulation based on the full bore drill string dynamics model, the axial force (WOB) variation curve of the last node (drill bit) of the drill string can be obtained. The

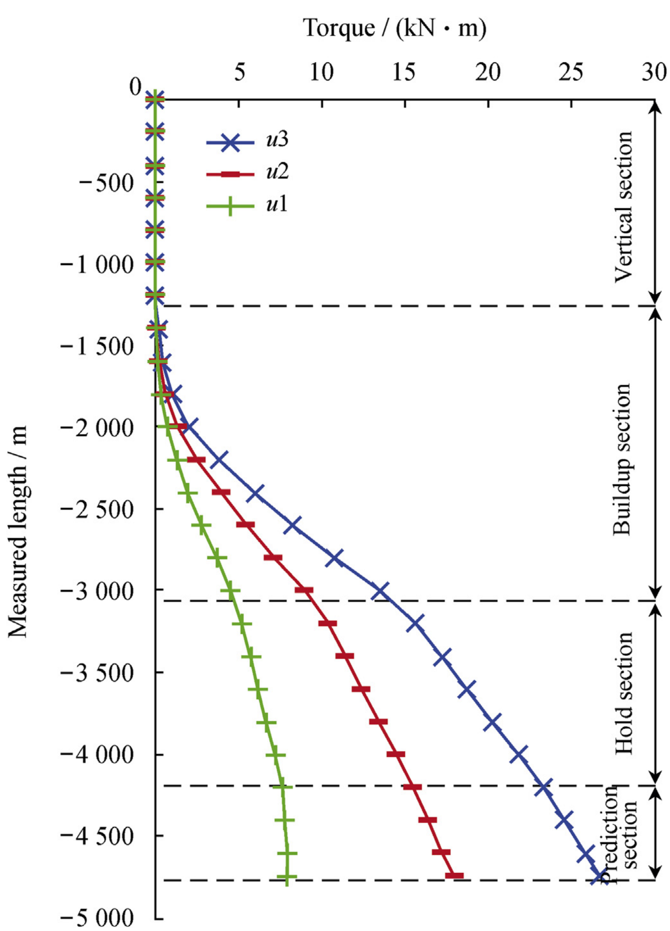

Fig. 5. Steady-state torque of drill string after extension to 4800 m.

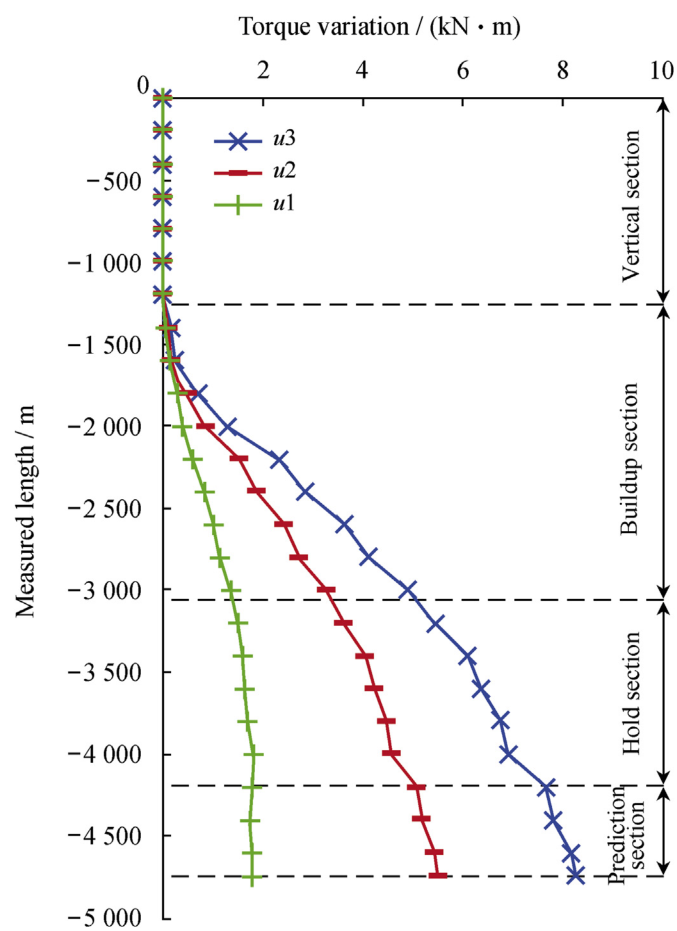

Fig. 6. Transient torque variation of drill string after extension to 4800 m.

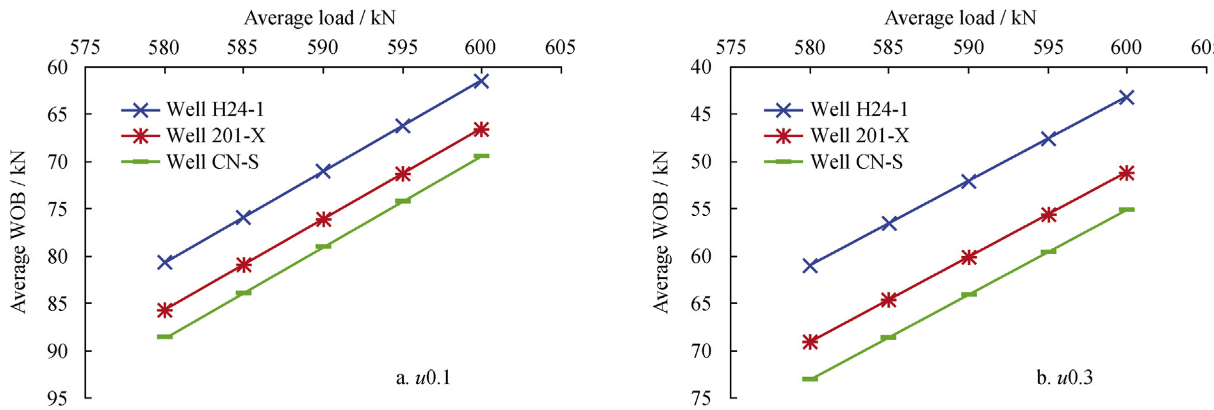

Fig. 7. WOB transfer of three wells in the Changning block.

average value represents the average WOB of various types of shale gas wells under different working conditions.

For the three types of shale gas horizontal wells, there is a big difference in the WOB transfer given the same hook load. Fig. 7 shows the WOB transfer under oil-based drilling fluid with a friction coefficient of 0.1 and water-based drilling fluid with a friction coefficient of 0.3. As the well inclination of the hold section increases, the effective WOB (the average WOB) is reduced. Under oil-based drilling fluid, given the same hook load, the average WOB is reduced by 8 kN when the hold section inclination increases from 83° to 105°. Under water-based drilling fluid, given the same hook load, the average WOB is reduced by 13 kN when the hold section inclination increases from 83° to 105°.

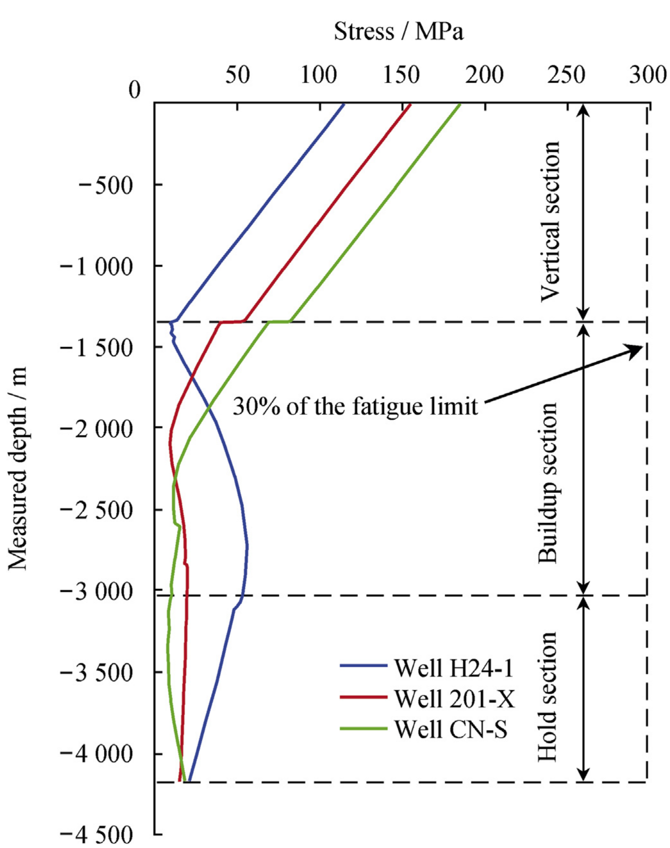

Fig. 8. Stress of drill string with the measured depth in three wells in Changning.

3.4. Check of drill string stress

The von Mises stress of the drill strings of Wells H24-1, 201-X and CN-S were calculated and analyzed, as shown in Fig. 8. Given the same WOB, the drill string of the scoop-shape well has the lowest stress at the wellhead. The stress of the scoop-shape well shows a different trend from the other two wells in the buildup section and the hold section. It increases significantly with the increase of well depth in the buildup section and decreases rapidly in the hold section. Given the drill string steel grade of S135, its yield strength is 989 MPa. The calculation results of the three wells indicate that the stress value of the drill string is much lower than the drill string yield limit and has a high safety factor (Table 3).

After the hold section of Well H24-1 is extended, the drill string stress distribution is shown in Table 4. With the extension of the hold section, the stress of the drill string at the wellhead decreases, and the stress of the drill string in the buildup section increases. However, the stress of the drill string at the bottom of the well changes a little. Essentially, when the WOB is basically the same, as the hold section of the spoon-shape well is extended, the contact force of the buildup section increases and the hook load decreases.

In recent years, failure analyses of drill strings in China indicate that more than 80% of the fracture failures of the drill string are fatigue failures or related to fatigue [26]. Therefore,

Table 3
Stress and safety factor of drill string in three wells in Changning.

Well	Wellhead stress/MPa	Average stress of curved section/MPa	Bottomhole stress/MPa	Safety factor
H24-1	113.9	42.6	21.1	8.7
201-X	154.6	16.9	16.1	6.4
CN-S	184.2	22.8	35.3	5.4

Table 4
Stress and safety factor of drill string in Well H24-1 with different extended lengths.

MD/m	Wellhead stress/MPa	Average stress of curved section/MPa	Bottomhole stress/MPa	Safety factor	Remarks
4200	113.9	42.6	21.1	8.7	True depth
4200 + 600	110.4	48.1	21.7	9.0	Extended hold
4200 + 1200	107.2	53.9	22.5	9.2	section
4200 + 1800	105.3	58.6	22.3	9.4	prediction

the fatigue life calculation of drill string has more engineering value than the drill string static stress check.

Based on the function expression (7) of the S−N (stress−life) curve, the fatigue life of the drill string can be obtained through full bore drill string dynamics calculation of the working stress amplitude [27].

$$\sigma^m N = C \tag{7}$$

where σ is the stress amplitude; similarly, N: the number of stress cycles when fatigue failure is reached; m and C: the constants of materials.

Fig. 9 shows the fatigue life of drill string in different well sections of each horizontal well, and Table 5 shows the fatigue life of drill string at the well section with the maximum load of each horizontal well, both under the assumption that the drill string is continuously working. In general, the fatigue life of the three horizontal wells in the buildup section, the upper part of the hold section and the bottom of the well is lower than that of other parts. Well H24-1 has the lowest fatigue life in the

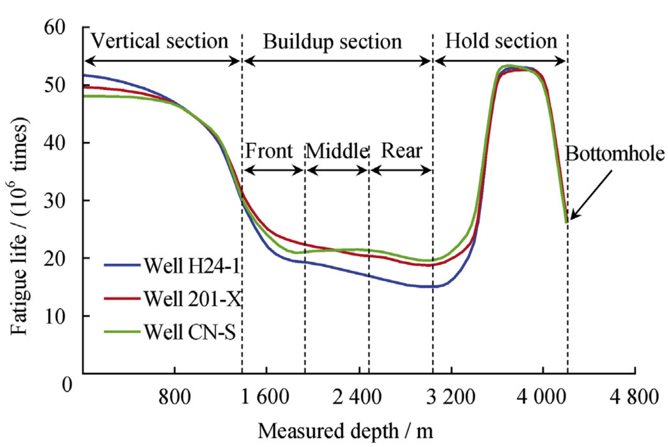

Fig. 9. Fatigue life of drill string in three wells in Changning.

Table 5
Effective working hours of the most dangerous section of the drill string in three wells at different RPMs.

Well	Drill string life/h	
	50 r/min	90 r/min
H24-1	496.7	275.9
H201-X	620.0	344.4
CN-S	650.0	361.1

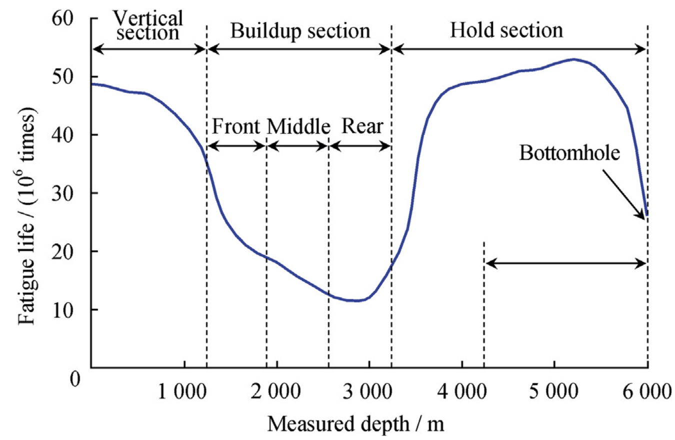

Fig. 10. Fatigue life of the drill string in the extended section of Well H24-1.

buildup section where the contact force of the drill string and the wellbore is the maximum.

Fig. 10 shows the fatigue life of the drill string in the extended section of Well H24-1, which presents a similar fatigue life distribution trend as that in Fig. 9. Moreover, due to the influence of extended drilling, the contact force of the drill string increases in the deeper part of the buildup section, resulting in a 23.1% reduction in the fatigue life of the drill string. Therefore, to increase the extension capability of the scoop-shape well, it is necessary to consider the safety of the drill string in the deeper part of the buildup section.

4. Conclusions

Three types of horizontal wells commonly used in current shale gas development were studied using the full bore drill string dynamics model and the dynamic simulation of the full bore drill string system. The following conclusions are obtained.

1) Due to the two-end extrusion, the buildup section of the scoop-shape horizontal well has a high contact friction strength, especially in the deeper part of the buildup section. The contact strength of the rear part of the buildup section is 1.67 times that of the hold section. The total contact force of the scoop-shape horizontal well in the buildup section is 1.62 times that of the highly deviated horizontal well. The contact friction strength of the hold section of the highly deviated horizontal well is not only higher than that of the buildup section, but also higher than any of the other two types of wells at the same well depth. If it is necessary to reduce friction and drag, and attentions should be paid to the buildup section of scoop-shape wells.
2) Among the three types of horizontal shale gas wells, the scoop-shape well has the lowest average WOB transfer efficiency. When oil-based drilling fluid is used, given the same hook load, the average WOB of the scoop-shape horizontal well is 8 kN smaller than that of the highly deviated horizontal well. When water-based

drilling fluid is used, the average WOB of the scoop-shape horizontal well under the same hook load is 13 kN smaller than that of the highly deviated horizontal well.

3) If extension drilling is carried out on the basis of the three types of wells, the calculations show that the working stress of the drill string in all three well types is not high and the drill string is safe. However, for the curved section of the scoop-shape well, the stress is alternating, and the drag and torque alternating amplitude is so large during a long time extension drilling that the safety issue of the drill string in curved sections needs to be noticed under the alternating bending stress and dynamic load.
4) The actual wellbore diameter (discontinuously enlarged) and the actual well trajectory (offset and adjustment) would lead to new friction problems and safety risks. It is necessary to conduct feasibility analysis and safety assessment of the extension drilling based on the actual drilling string.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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