Enhancing the benefit of slide steering drilling systems in horizontal wells of unconventional reservoirs

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The slide steering drilling system consisting of a bent positive displacement motor (PDM) and measurement while drilling (MWD) system is widely used to continuously implement all wellpath control operations by alternately applying the slide and compound drilling modes. Due to the large friction force on the drilling string during slide drilling in the horizontal section, there is a significant adverse impact on both the drilling speed and horizontal extension ability. To efficiently and economically drill long horizontal sections, it is essential to increase the compound drilling proportion and decrease the alternative times of the two drilling modes. According to the features of wavy or tortuous horizontal sections and wellpath calculation models, a prediction and control method for the compound drilling proportion of horizontal sections is first established, and subsequently, its influencing factors and laws are analyzed and verified using an example. Theoretical research and drilling practice have shown that the compound drilling proportion of the horizontal section depends on the build-up rate of slide drilling and the inclination and azimuth change rates of compound drilling and is independent of the target area parameters and wellpath fluctuation ratio. In order to increase the compound drilling proportion and reduce the slide drilling frequency in the horizontal section, it is necessary to increase the build-up rate of slide drilling properly and reduce the inclination and azimuth change rates of compound drilling to the greatest extent. This paper is helpful to enhance the benefit of slide steering drilling systems in horizontal wells of unconventional reservoirs.

KEYWORDS

slide steering drilling system, compound drilling, slide drilling, horizontal section, wellpath control, build-up rate, inclination change rate

1 Introduction

A horizontal well is an important method to develop unconventional reservoirs, like shale gas (Guo et al., 2019; Lu et al., 2021), tight oil, gas hydrate (Zhang et al., 2022a), and even deep reservoirs (Zhang et al., 2022b; Cao et al., 2022). The slide steering drilling system composed of a bent positive displacement motor (PDM) and measurement while drilling (MWD) system is widely used in horizontal wells. This system has two working modes, namely, slide drilling mode and compound drilling mode (Samuel et al., 2005;

Guan et al., 2021). By alternatively applying these two modes, it can continuously implement wellpath control operations without tripping operations. Currently, longer horizontal wells are being drilled to develop unconventional oil and gas (Guo et al., 2019; Lu et al., 2021; Yu et al., 2021; Ma et al., 2022). Because the drillstring does not rotate in the slide drilling mode, the friction force on the drillstring not only decreases the weight-on-bit transmission efficiency and causes low drilling speed but also influences the horizontal extension ability (Maidla and Haci, 2004; Samuel, 2010; Zhu et al., 2019).

Some researchers have pointed out that the actual wellpath of a horizontal section drilled by the slide steering drilling system is always in a wavy or tortuous shape, and the wellpath tortuosity influences the wellpath calculation, drag, and torque on the drillstring (Samuel et al., 2005; Samuel, 2010; Brands and Lowdon, 2012; Noshi and Schubert, 2019; Samuel et al., 2021). Some models have taken the wellpath tortuosity into account to enhance the calculation precision of the wellpath (Samuel et al., 2005; Noshi and Schubert, 2019) and the prediction precision of drag and torque on the drillstring (Samuel, 2010; Brands and Lowdon, 2012). Some researchers have realized that the wellpath tortuosity and drilling efficiency are influenced by the build-up rate of slide drilling and the inclination and azimuth change rates of compound drilling. Some models have been established to predict the build-up rate of slide drilling (Williams et al., 1989; Shi et al., 2017; Liu et al., 2019) or inclination and azimuth change rates of compound drilling (Peng and Di Qinfeng, 2000; Guo et al., 2013; Koulidis et al., 2021). Although it is well known that increasing the compound drilling proportion is the key to achieving fast and cost-effective drilling, the prediction and control method for the compound drilling proportion is still lacking.

In order to enhance the benefit of a slide steering drilling system, a prediction and control method for the compound drilling proportion of horizontal sections is established, and subsequently, its influencing factors and laws are analyzed.

2 Methods (compound drilling proportion of horizontal sections)

2.1 Wellpath description of the drilled horizontal section

As shown in Figure 1, the actual wellpath of the horizontal section drilled by a slide steering drilling system is always in a wavy or tortuous shape (Samuel et al., 2005; Noshi and Schubert, 2019). Because the inclination and azimuth commonly fluctuate slowly under compound drilling, the slide drilling must be alternated to decrease (or increase) the inclination and azimuth and control the wellpath within the target area once the drill bit is near the boundary lines of the horizontal target area. For a long horizontal section, two drilling modes may alternate multiple times. Then, the actual horizontal section has more control cycles. In one wavy cycle or control cycle, two drilling modes alternate once.

Suppose that the compound drilling tends to increase inclination and azimuth simultaneously, and then take the rectangular horizontal target area and the first wellpath control cycle as an example. The target half-width is set as a, and the target half-height is b; for the compound drilling interval, the starting point is No. 0 point, the lowest point on the vertical projection plot (the far left point on the horizontal plot) is No. 1 point, and the endpoint is No. 2 point; and for the slide drilling interval, the starting point is No. 2 point, the highest point (the far right point on the horizontal plot) is No. 3 point, and the last point is No. 4 point. To reduce the alternate times of slide and compound drilling, let the inclinations of the highest and lowest points on the vertical projection plot be equal

FIGURE 1
Actual wellpath of the horizontal section. **(A)** Vertical projection plot; **(B)** horizontal projection plot.
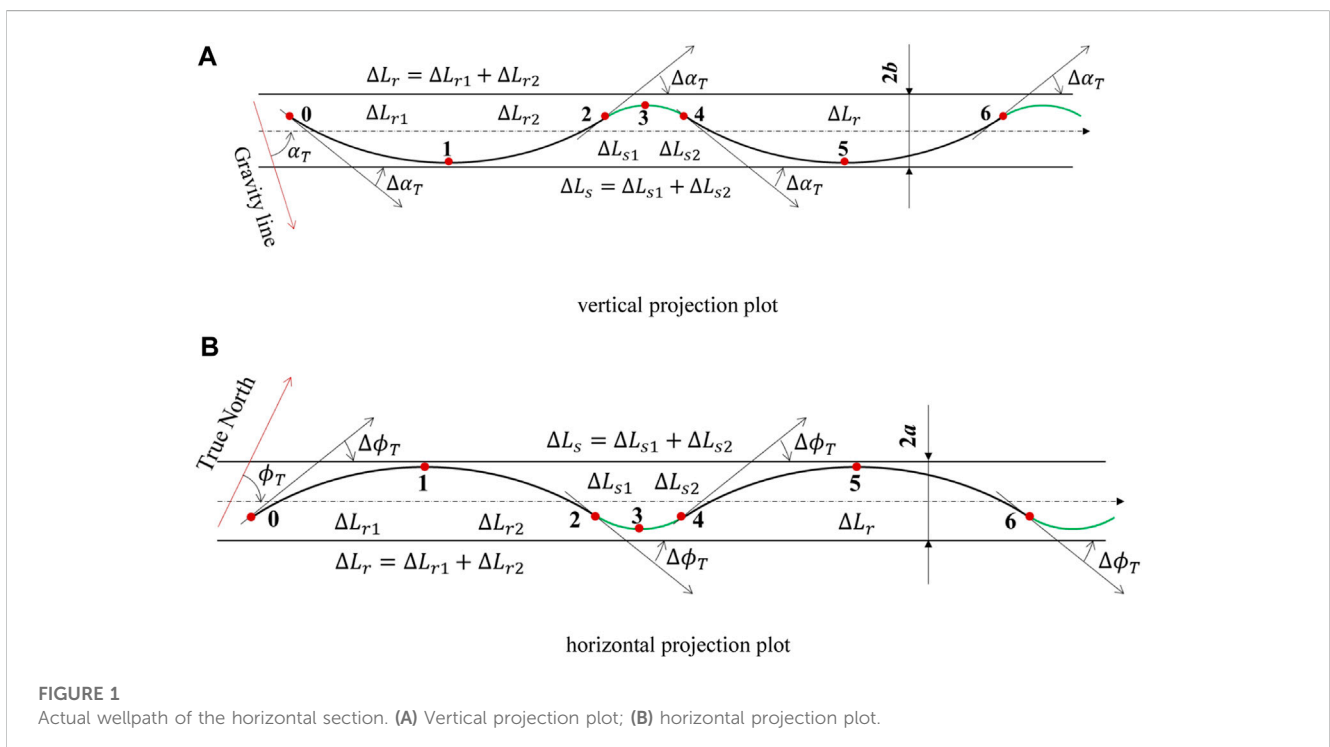
to the target inclination and the azimuths of the far left and right points on the horizontal plot be equal to the target azimuth. All node parameters of the actual horizontal section are presupposed and shown in Figure 1. For the compound drilling interval, the key parameters include the compound drilling length ΔL_r ($\Delta L_r = \Delta L_{r1} + \Delta L_{r2}$), the inclination change rate K_α, and azimuth change rate K_ϕ; for the slide drilling interval, the key parameters include the slide drilling length ΔL_s ($\Delta L_s = \Delta L_{s1} + \Delta L_{s2}$) and build-up rate K_s; and for these two intervals, the key parameters include the allowable inclination bias $\Delta \alpha_T$ and azimuth bias $\Delta \phi_T$.

2.2 Wellpath constraints of the drilled horizontal section

According to the wellpath calculation methods (Guan et al., 2021), the actual shapes of compound and slide drilling intervals are closest to the cylindrical spiral line and the inclined arc line, respectively. The cylindrical spiral method (curvature radius method) and inclined arc method (minimum curvature method) are applied alternatively to calculate all wellpath parameters of the actual horizontal section. According to the presupposed node parameters in Figure 1, the first wellpath control cycle from No. 0 point to No. 4 point can be divided into four intervals, and then all vertical depth increments ΔD_i ($i = 1$–4), N-coordinate increments ΔN_i ($i = 1$–4), E-coordinate increments ΔE_i ($i = 1$–4), and dog-leg angles γ_i can be calculated using Eqs 1–4, respectively:

$$\Delta D_i = \begin{cases} \dfrac{1}{K_\alpha}\left[\sin \alpha_i - \sin \alpha_{i-1}\right] & (i = 1, 2), \\ \dfrac{1}{K_s}\tan \dfrac{\gamma_i}{2}\left[\cos \alpha_{i-1} + \cos \alpha_i\right] & (i = 3, 4), \end{cases} \tag{1}$$

$$\Delta N_i = \begin{cases} \dfrac{1}{K_\phi \cdot \Delta \alpha_T}\left[\cos \alpha_{i-1} - \cos \alpha_i\right]\left[\sin \phi_i - \sin \phi_{i-1}\right] & (i = 1, 2), \\ \dfrac{1}{K_s}\tan \dfrac{\gamma_i}{2}\left[\sin \alpha_{i-1}\cos \phi_{i-1} + \sin \alpha_i \cos \phi_i\right] & (i = 3, 4), \end{cases} \tag{2}$$

$$\Delta E_i = \begin{cases} \dfrac{1}{K_\phi \cdot \Delta \alpha_T}\left[\cos \alpha_{i-1} - \cos \alpha_i\right]\left[\cos \phi_i - \cos \phi_{i-1}\right] & (i = 1, 2), \\ \dfrac{1}{K_s}\tan \dfrac{\gamma_i}{2}\left[\sin \alpha_{i-1}\sin \phi_i + \sin \alpha_i \sin \phi_i\right] & (i = 3, 4), \end{cases} \tag{3}$$

$$\cos \gamma_i = \cos \alpha_{i-1}\cos \alpha_i + \sin \alpha_{i-1}\sin \alpha_i \cos\left(\phi_i - \phi_{i-1}\right) \ (i = 1 \sim 4). \tag{4}$$

As shown in Figure 1, while drilling the horizontal section, the actual horizontal wellpath must be controlled within the target area, and then the actual wellpath of the horizontal section must meet the inequality constraint as follows:

$$\begin{cases} |\Delta D_2 + \Delta D_3| \sin \alpha_T \le 2b, \\ \left|(\Delta N_2 + \Delta N_3)\sin \phi_T + (\Delta E_2 + \Delta E_3)\cos \phi_T\right| \le 2a, \end{cases} \tag{5.a}$$

or

$$\begin{cases} |\Delta D_1 + \Delta D_4| \sin \alpha_T \le 2b, \\ \left|(\Delta N_1 + \Delta N_4)\sin \phi_T + (\Delta E_1 + \Delta E_4)\cos \phi_T\right| \le 2a. \end{cases} \tag{5.b}$$

If the designed target inclination $\alpha_T \ne 90°$ and/or target azimuth $\phi_T \ne 90°$, the next derivation process will be more complex. However, you can imagine that the horizontal section can be rotated in the horizontal direction on the vertical projection plot and in the east direction on the horizontal plot. After the rotation transformation, the shape of the actual horizontal section has not changed. Next, the node parameters in Figure 1 are substituted into Eqs 1–4 and then into Eq. 6. Finally, Eq. 6 can be deduced as follows:

$$\begin{cases} \dfrac{1 - \cos \Delta \alpha_T}{K_\alpha} + \dfrac{\tan \dfrac{\gamma}{2}\sin \Delta \alpha_T}{K_s} \le 2b, \\ \dfrac{\sin \Delta \alpha_T \left[1 - \cos \Delta \phi_T\right]}{K_\phi \cdot \Delta \alpha_T} + \dfrac{\tan \dfrac{\gamma}{2}\cos \Delta \alpha_T \sin \Delta \phi_T}{K_s} \le 2a, \\ \cos \gamma = \cos \Delta \alpha_T \cos \Delta \phi_T. \end{cases} \tag{6}$$

Considering the allowed inclination bias $\Delta \alpha_T$ and azimuth bias $\Delta \phi_T$, which are characterized by the parameters of the compound drilling interval (inclination change rate K_α, azimuth change rate K_ϕ, and length ΔL_r) and slide drilling interval (build-up rate K_s and length ΔL_s), Eq. 6 can be transformed into Eq. 7.

$$\begin{cases} \dfrac{1 - \sin(K_\alpha \Delta L_r)}{K_\alpha} + \dfrac{\tan \dfrac{K_s \Delta L_s}{2}\sin(K_\alpha \Delta L_r)}{K_s} \le 2b, \\ \dfrac{\sin(K_\alpha \cdot \Delta L_r)\left[1 - \cos\left(K_\phi \Delta L_r\right)\right]}{K_\phi \cdot K_\alpha \cdot \Delta L_r} \\ \quad + \dfrac{\tan \dfrac{K_s \Delta L_s}{2}\cos(K_\alpha \Delta L_r)\sin\left(K_\phi \Delta L_r\right)}{K_s} \le 2a, \\ \cos(K_s \Delta L_s) = \cos(K_\alpha \Delta L_r)\cos\left(K_\phi \Delta L_r\right). \end{cases} \tag{7}$$

From Eqs 6, 7, it can be observed that

(1) Once the target half-width a and target half-height b are given, the maximum allowed inclination bias $\Delta \alpha_T$ and azimuth bias $\Delta \phi_T$ of the horizontal section, the maximum allowed compound drilling length ΔL_r, and slide drilling length ΔL_s in one wellpath control cycle depend on the build-up rate K_s of slide drilling and the inclination change rate K_α and azimuth change rate K_ϕ of compound drilling.

(2) Once the build-up rate K_s of slide drilling and the inclination change rate K_α and the azimuth change rate K_ϕ of compound drilling are given, the maximum allowed inclination bias $\Delta \alpha_T$ and azimuth bias $\Delta \phi_T$ of the horizontal section can be solved using Eq. 6, and the maximum allowed compound drilling length ΔL_r and slide drilling length ΔL_s of the horizontal section in one wellpath control cycle can be solved using Eq. 7.

2.3 Compound drilling proportion of the horizontal section

In one wellpath control cycle of the horizontal section, the allowed compound drilling length is ΔL_r, the slide drilling length is ΔL_s, and the compound drilling proportion c_r is defined and calculated using Eq. 8.
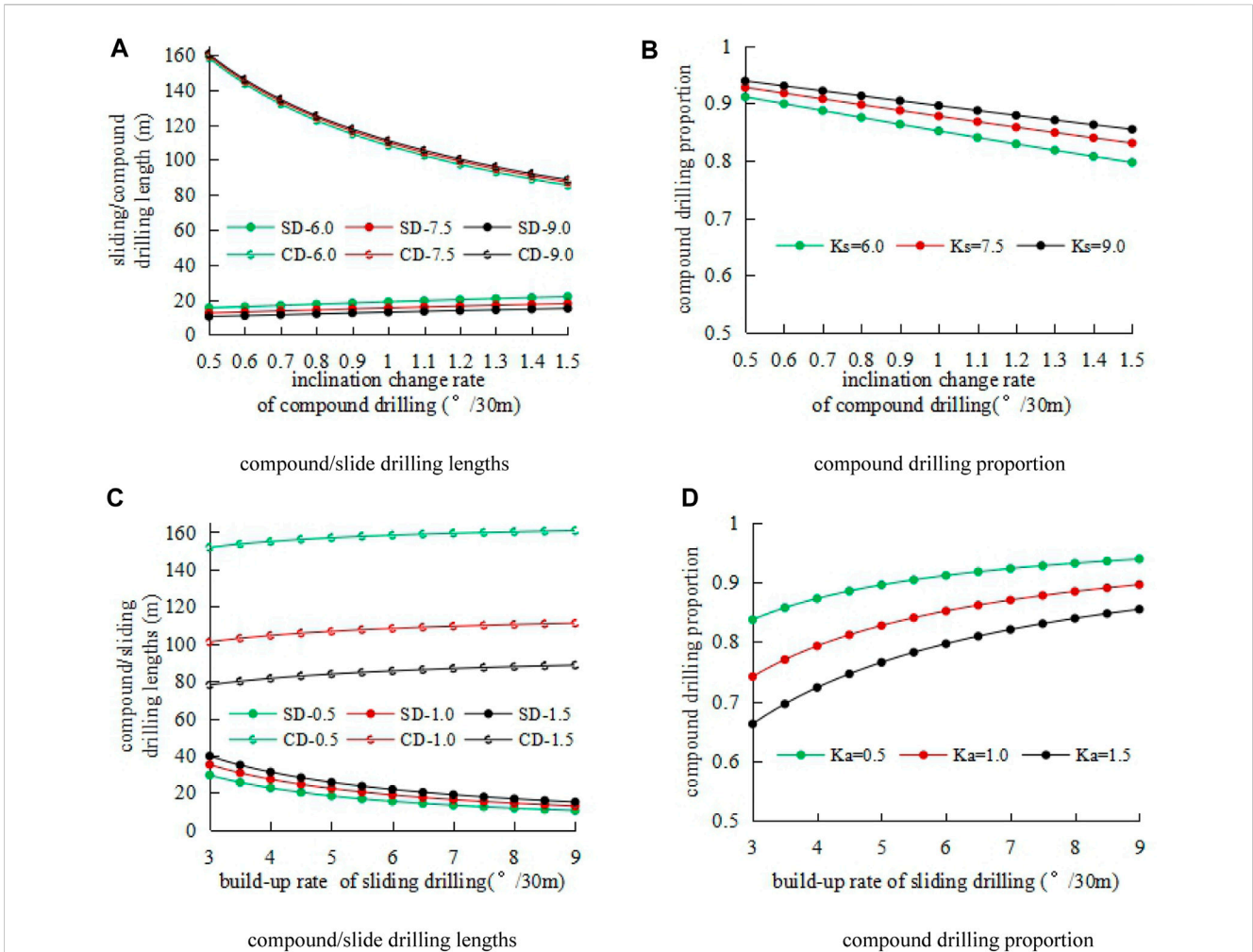
FIGURE 2
Compound drilling results vs. build-up rate. **(A)** Compound/slide drilling lengths; **(B)** compound drilling proportion; **(C)** compound/slide drilling lengths; **(D)** compound drilling proportion.

$$c_r = \frac{\Delta L_r}{\Delta L_r + \Delta L_s}. \tag{8}$$

If the build-up rate K_s of slide drilling and the inclination change rate K_α, and azimuth change rate K_ϕ of compound drilling are given, the maximum allowed compound drilling length ΔL_r and slide drilling length ΔL_s in one wellpath control cycle can be solved using Eq. 7. In fact, according to the last formula in Eq. 7, another relationship among these five characteristic parameters can be derived as follows:

$$\begin{cases} K_s \cdot \Delta L_s > |K_\alpha| \cdot \Delta L_r, \\ K_s \cdot \Delta L_s > |K_\phi| \cdot \Delta L_r. \end{cases} \tag{9}$$

According to Eq. 9, the upper limit of the compound drilling proportion c_r can be estimated as follows:

$$c_r = \frac{\Delta L_r}{\Delta L_r + \Delta L_s} < \min\left(\frac{K_s}{|K_\alpha| + K_s}, \frac{K_s}{|K_\phi| + K_s}\right). \tag{10}$$

Because the inclination change rate K_α and azimuth change rate K_ϕ of compound drilling may be positive (the inclination and azimuth increase) or negative (the inclination and azimuth decrease), these two values in Eqs 9, 10 must use their absolute values.

According to Eq. 10, it can be observed that the compound drilling proportion of the horizontal section depends on the build-up rate K_s of slide drilling and the inclination change rate K_α and azimuth change rate K_ϕ of compound drilling and is independent of the target parameters and wavy amplitude of the horizontal section. In order to enhance the compound drilling proportion for faster and more cost-effective drilling, the build-up rate K_s of slide drilling should be enhanced properly, and then the inclination change rate K_α and azimuth change rate K_ϕ of compound drilling should be reduced to the greatest extent.

3 Results (influencing factors and laws of the compound drilling proportion)

3.1 Inclination change rate of compound drilling

According to the actual horizontal drilling data, the target area is set at 1.0 m (target half-height) × 6.0 m (target half-width), and then the key parameters of slide and compound drilling are set as follows:

the build–up rates K_s = 6.0°–9.0°/30 m (6.0°/30 m for 1.0° bent PDM, 7.5°/30 m for 1.25° bent PDM, and 9.0°/30 m for 1.5° bent PDM), the inclination change rate K_α = 0.1°–1.5°/30 m, and azimuth change rate K_ϕ = 0.3°/30 m. The drilling results are estimated using Eqs 7, 8 and shown in Figures 2A, B. In the legend zone, "SD" and "CD" represent "slide drilling" and "compound drilling," respectively, and the numbers represent the build-up rate (unit: °/30 m) of slide drilling.

If the inclination change rate of compound drilling increases, the compound drilling length ΔL_r decreases significantly, but the slide drilling length ΔL_s increases slightly, and then the compound drilling proportion decreases obviously. For a given inclination change rate under compound drilling, if the build-up rate of slide drilling increases, the compound drilling length ΔL_r increases slightly, but the slide drilling length ΔL_s decreases obviously, and then the compound drilling proportion increases obviously. It is proved that increasing the build-up rate K_s of slide drilling and reducing the inclination change rate K_α and azimuth change rate K_ϕ of compound drilling contribute to increasing the compound drilling length and proportion of the horizontal section.

3.2 Build-up rate of slide drilling

Taking 1.25° bent PDM as an example, the build-up rate of slide drilling is set at 7.5°/30 m, the inclination change rate of compound drilling is set at 0.5°–1.5°/30 m, and the azimuth change rate is set at 0.3°/30 m, and then the drilling results are estimated using Eqs 7, 8 and shown in Figures 2C, D. In the legend zone, "SD" and "CD" represent "slide drilling" and "compound drilling," respectively, but the numbers represent the inclination change rates (unit: °/30 m) of compound drilling.

If the build-up rate of slide drilling increases, the compound drilling length ΔL_r increases slightly, but the slide drilling length ΔL_s decreases obviously, and then the compound drilling proportion increases obviously. For a given build-up rate under slide drilling, if the inclination change rate of compound drilling increases, the compound drilling length ΔL_r decreases significantly, but the slide drilling length ΔL_s increases slightly, and then the compound drilling proportion decreases obviously. It is proved again that increasing the build-up rate K_s of slide drilling and reducing the inclination change rate K_α and azimuth change rate K_ϕ of compound drilling contribute to increasing the compound drilling length and proportion of the horizontal section.

3.3 Case analysis

3.3.1 Drilling results
The LS3-3 horizontal well is located in China. The designed horizontal section is approximately 1200 m. The target area is 1.0 m (target half-height) × 6.0 m (target half-width). Target inclination is 88.15°, and target azimuth is 161.29°. Bottom-hole assembly (BHA) and drilling parameters are described as follows: BHA: φ152.4 mm PDC bit + φ127 mm bent PDM (1.25 for the first run and 1° for the second run) + float valve + Φ148 mm stabilizer + LWD + Φ96 mm
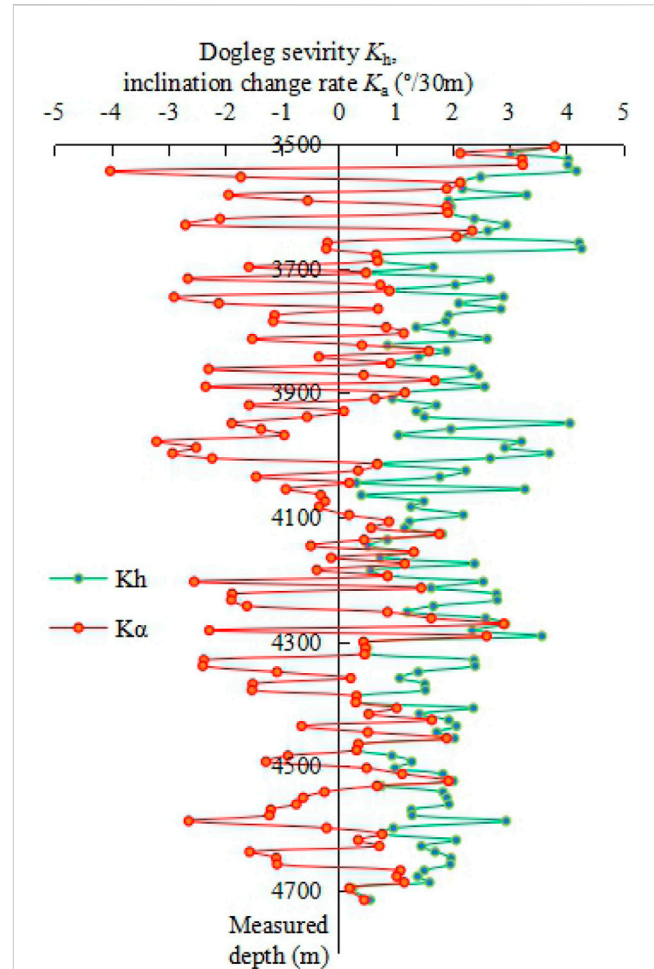

FIGURE 3
Dogleg severity and inclination change rate.

non-magnetic drill pipe. Drilling parameters: weight on bit 30 kN, top drive speed 50 r/min, and drilling fluid flowrate 18 L/s.

The statistical horizontal section length is 1,138.66 m, and the alternation time of two drilling modes is 58 in total. Wellbore curvature (dogleg severity) and inclination change rate are shown in Figure 3. For the compound drilling, the inclination mainly increases and the azimuth mainly maintains the same change rate; the average inclination and azimuth change rates are approximately 0.5°/30 m and 0.2°/30 m, respectively; the cumulative length is 1,036.9 m; the average interval length is 17.9 m/time; the maximum interval length is 66.5 m; and the compound drilling proportion is 91.1%. For slide drilling, the build-up rates are approximately 7.5°/30 m and 6.0°/30 m for the first and second runs, respectively; the cumulative length is 101.8 m; the average interval length is 1.8 m/time; the maximum interval length is 3.4 m; and the slide drilling proportion is 8.9%.

3.3.2 Verifying analysis
Based on the statistical results, the build-up rate of slide drilling is set at 6.0°–7.5°/30 m and the inclination and azimuth change rates of compound drilling are set at 0.5°/30 m and 0.2°/30 m, respectively; the wellbore fluctuation ratio (amplitude of fluctuation vs. target height) is set at 0.5–0.6. The drilling results of the horizontal section are estimated

TABLE 1 Prediction results of slide and compound drilling.

K_s (°/30 m)	c_f	ΔL_r (m)	ΔL_s (m)	c_r (%)
6.0	0.5	158.8	14.3	91.8 (92.3)
6.0	0.6	174.0	15.6	91.8 (92.3)
7.5	0.5	160.2	11.5	93.3 (93.8)
7.5	0.6	175.5	12.6	93.3 (93.8)

and shown in Table 1. Here, c_f is the wellbore fluctuation ratio equal to $\frac{\Delta D}{2b}$ (ΔD is the fluctuation amplitude along the wellbore axis on the vertical projection plot; b is the target half-height); the compound drilling proportions outside and inside brackets are estimated using Eqs 7, 10, respectively. Subsequently, the values outside brackets are set as the theoretical values; the values inside brackets are set as the estimated values.

Eq. 10 can estimate the compound drilling proportion. The theoretical prediction results show that the slide drilling length is approximately 11.5–15.6 m and the compound drilling length is approximately 158.8–175.5 m in one cycle. The compound drilling proportion is approximately 91.8%–93.3%. The actual drilling results show that the compound drilling length is approximately 17.9 m/time, the slide drilling length is approximately 1.77 m/time, and the compound drilling proportion is approximately 91.1%. The compound drilling proportion is in good agreement with the theoretical results, but the compound drilling and slide drilling lengths are less than the theoretical values. One reason is that the actual wellpath has a lagging effect while alternating compound or slide drilling modes (Su, 2000). Another reason is that the target half-height is only 1.0 m. As a result, the directional drilling engineer had to increase the wellpath adjustment frequency and shorten the interval lengths to avoid missing of the target.

3.3.3 Suggestions

The bottom-hole assembly and drilling parameters should be optimized totally to properly increase the build-up rate of slide drilling and reduce the inclination and azimuth change rates of compound drilling to the greatest extent. To achieve this purpose, BHA with two stabilizers (one stabilizer fixed near the drill bit and the other stabilizer fixed above the bent PDM) and medium weight-on-bit (WOB) are recommended (Peng and Di Qinfeng, 2000; Guo et al., 2013; Koulidis et al., 2021). At the same time, more attention should be paid to the formation. The lithology and mechanical properties of the pay zone also have a significant influence on drilling results (Yin et al., 2021; Zhu et al., 2021; Cao et al., 2022).

4 Conclusion

(1) The compound drilling proportion of the horizontal section is independent of the target parameters and the wellbore fluctuation amplitude but depends on the build-up rate of slide drilling and the inclination and azimuth change rates of compound drilling.

(2) The compound drilling proportion of the horizontal section can be estimated by the build-up rate of slide drilling and the inclination and azimuth change rates of compound drilling.

(3) To enhance the compound drilling proportion of the horizontal section and reduce the adjustment frequency of slide drilling, it is necessary to increase the build-up rate of slide drilling and reduce the inclination and azimuth change rates of compound drilling.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding authors.

Author contributions

HC: writing–original draft. CX: writing–review and editing. KH: writing–review and editing. YG: writing–original draft. YS: writing–original draft and funding acquisition. BZ: formal analysis and writing–review and editing.

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Conflict of interest

Authors HC, CX, and YG were employed by the company Engineering and Technology Research Institute, CNPC Xinjiang Oilfield Company. Author KH was employed by the company Development Company, CNPC Xinjiang Oilfield Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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