Trajectory Optimization of Deep Shale Gas Horizontal Wells

Wenzhe Li¹, Dewei Gao¹, Feng Dai¹, Pengcheng Wu², Hairui Lin³*, and Jianhong Fu³

¹Sichuan Changning Natural Gas Development Co., Ltd, Chengdu, Sichuan 610051, PR China
²Shale gas Research Institute, Southwest Oil and Gas Branch of Petro China, Chengdu, Sichuan 610051, PR China
³State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, PR China

*Corresponding author email: 201821000583@stu.swpu.edu.cn

Abstract. The development mode of deep shale gas “Pad drilling” cluster horizontal wells could greatly reduce the single-well drilling cost and is also the significant measure for scale benefit development of shale gas. For pad drilling, the small wellhead distance of cluster well group, complicated well profile and long horizontal section result in such engineering problems as high well collision probability in upper well section, high trajectory control difficulties and large drill string torque and drag. A reasonable 3D horizontal well profile and the reasonable profile parameters are the premise for the safe and rapid drilling of shale gas horizontal well. Therefore, optimizing type and the well profile parameters suitable for deep shale gas horizontal well could help improve drilling efficiency, lower drilling risk and save drilling cost. In this paper, the three types of trajectory profile, including 3D trajectory in spatial oblique plane (large 3D), dual 2D trajectory and dual 2D and small 3D combined trajectory profile were developed, and under the same surface location and target zone, three different types of shale gas horizontal well were planed; the differences of these three trajectories in well depth, drill string torque and drag and well separation factor were compared through drill string torque and drag analysis and collision prevention analysis. The analysis results show: Dual 2D trajectory or dual 2D and small 3D combined trajectory is featured by small drill string drag and torque, low trajectory control difficulty and low well collision probability and is therefore more suitable for trajectory plan of deep shale gas horizontal wells.

Keywords: Shale Gas; Horizontal Well; Dual 2D; Well Factory; Torque and drag; Collision Prevention.

1. Introduction

Pad drilling [1-5] is generally adopted to lower the drilling cost of shale gas horizontal well and improve drilling efficiency. Pad Drilling can reduce well field occupation area, improve equipment utilization rate and shorten non-working time and well building time, which, furthermore, could lower drilling cost significantly. Pad drilling, 6-12 cluster horizontal wells are usually drilled in the same platform, and thus a collision risk occurs among wells in the upper section. Most of horizontal wells in cluster horizontal well group on the identical platform are 3D long departure horizontal wells, with large drill string torque and drag and many trajectory control difficulties [6]. Therefore, it is of great necessity to optimize the profile type and trajectory parameter of shale gas cluster horizontal well, so as to prevent inter-well collision, lower drill string torque and drag and trajectory control difficulty and finally realize safe and rapid drilling.
2. Types of Shale Gas Horizontal Wells

2.1. Profile of Large 3D Trajectory in Spatial Oblique Plane

There are many profiles about 3D horizontal well trajectory [7-10]. In the design process of deep shale gas horizontal well, in consideration of the deep burial depth of shale gas reservoir and deep kick-off point of horizontal well, the trajectory is composed of vertical section, build and turn section, hold section, build and turn section and horizontal section; upper and lower build and turn sections are not in the same plane, but the build and turn section in an identical plane is an arc in spatial oblique plane. Suppose borehole curvature radius of upper build and turn section is $R_1$ and borehole curvature radius of lower build and turn section is $R_2$, the 3D trajectory profile in a spatial oblique plane will be obtained, as shown in Figure 1.

![Figure 1. Geometric Model for 3D Trajectory Design of Spatial Oblique Plane Method.](image)

Establish an O-XYZ global coordinate system by taking wellhead O as origin, where, X stands for north coordinate (Northing), Y for east coordinate (Easting) and Z for true vertical depth (TVD). After knowing the coordinate, inclination and azimuth ($X_A$, $Y_A$, $Z_A$, $\alpha_A$, $\Phi_A$) of point A and coordinate, inclination and azimuth ($X_T$, $Y_T$, $Z_T$, $\alpha_T$, $\Phi_T$) of target point T and the length of hold section before entering target T, take the initial value of length $u_0$ on the reverse extension line of horizontal section to determine the position of point D; the coordinates of point D are shown below:

$$
\begin{align*}
X_D &= X_T - (\Delta l + u_0) \sin \alpha_T \cos \Phi_T \\
Y_D &= Y_T - (\Delta l + u_0) \sin \alpha_T \sin \Phi_T \\
Z_D &= Z_T - (\Delta l + u_0) \cos \alpha_T 
\end{align*}
$$

(1)

The determined coordinate of point D constitutes a spatial oblique plane with borehole tangent, i.e., $\xi\eta$ coordinate plane of coordinate system A-$\xi\eta\zeta$ (shown in Figure 2). On this spatial oblique plane, a upper borehole trajectory can be designed in a 2D plane.

Through the coordinate transformation, the coordinate of point D in the local coordinate system A-$\xi\eta\zeta$ will be obtained:

$$
\begin{align*}
\begin{bmatrix}
\xi_D \\
\eta_D \\
\zeta_D
\end{bmatrix} &= \begin{bmatrix} a_X & a_Y & a_Z \\ b_X & b_Y & b_Z \\ c_X & c_Y & c_Z \end{bmatrix} \begin{bmatrix} X_D - X_A \\ Y_D - Y_A \\ Z_D - Z_A \end{bmatrix} 
\end{align*}
$$

(2)

$a_X$, $a_Y$, $a_Z$, $b_X$, $b_Y$, $b_Z$, $c_X$, $c_Y$, and $c_Z$ in Formula (2) are the quantities related to point A coordinate, point D coordinate and inclination and azimuth of point A, all of which constitute the transformation matrix from a global coordinate into the local coordinate in spatial oblique plane.

It can be obtained according to the geometrical relationship shown in Figure 2:
Thus the corresponding full angle $\theta_1$ of the first spatial arc trajectory section is expressed as:

$$\tan \frac{\theta_1}{2} = \begin{cases} \frac{\xi_D - (\xi_D^2 + \eta_D^2 - 2R_i\eta_D)^{1/2}}{2R_i - \eta_D} & \text{when } \eta_D \neq 2R_i \\ \frac{\eta_D}{2\xi_D} & \text{when } \eta_D = 2R_i \end{cases}$$

The directional vector of hold section BD in Figure 1 is expressed as formula (5)

$$\vec{w} = (\cos \theta_1 a_x + \sin \theta_1 b_x)\vec{i} + (\cos \theta_1 a_y + \sin \theta_1 b_y)\vec{j} + (\cos \theta_1 a_z + \sin \theta_1 b_z)\vec{k}$$

Then, the inclination $\alpha_w$ and azimuth $\varphi_w$ of hold section can be calculated.

$$\cos \alpha_w = \cos \theta_1 a_z + \sin \theta_1 b_z$$

$$\tan \varphi_w = \frac{a_y + b_y \tan \theta_1}{a_x + b_x \tan \theta_1}$$

Thus overall angle of the lower build and turn section is calculated.

$$\cos \theta_2 = \cos \alpha_w \cos \alpha_f + \sin \alpha_w \sin \alpha_f \cos (\Phi_f - \varphi_w)$$

After $\theta_2$ is obtained this way, the length of new tangent section of the second arc section can be obtained according to the geometrical relationship shown in Figure. 3:

$$u = R_2 \tan \frac{\theta_2}{2}$$

Since the above process is executed after determining position of point D via $u_0$, this method is an iterative solution process. For the calculation accuracy $\varepsilon$ given in advance, if $|u-u_0|<\varepsilon$, iterative calculation will end. Otherwise, suppose $u_0=u$ and repeat the above calculation until the accuracy requirement is met.

The length of new tangent will be determined after the completion of iterative computation; then, length of the first arc section and length of hold section can be obtained according to the geometrical relationship method shown in Figure. 3:

$$\Delta L_1 = \theta_1 R_1$$

$$\Delta L_w = \left(\xi_D^2 + \eta_D^2 - 2R_i\eta_D\right)^{1/2} - u$$

Obtain the length of the second arc section according to the geometrical relationship shown in Figure. 3:

$$\Delta L_2 = \theta_2 R_2$$

Thus the key parameters on 3D profile are determined.
2.2. Profile of Dual 2D Trajectory

The horizontal well of dual 2D trajectory is different from that of the 2D and 3D profiles. Well trajectory of dual 2D horizontal well is in two intersected vertical plane and every vertical plane has a 2D trajectory profile. First, establish two intersected vertical planes ABDC and BDFE in space rectangular coordinate O-XYZ. Of which, ABCD is called the first vertical plane and BDEF the second vertical plane, as shown in Figure 4. In Figure 4, the surface location I is original point, X is north coordinate, Y is east coordinate, Z is vertical depth and \( \varphi \) is the included angle between the two planes; J and K respectively represents the target point and end point of horizontal section and M means the intersection point of trajectory with the first and second vertical plane.

First at all, plan the upper S shaped trajectory in the first vertical plane ABDC: Adopting “vertical-build-hold-drop-horizontal section” profile. To lower the risk of collision with adjacent wells, it is required to build up in advance in the vertical plane ABCD and the maximum inclination after building does not exceed 16°, decrease hole inclination to 0° after holding in the definite length, drilling vertically to point M where it is kick of point of in the second vertical plane BDFE. Since the inclination of M point is 0°, the design in the second vertical plane can be made directly by 2D profile plan. The only constraint is that the projection of point M in horizontal plane is on the reverse extension line of horizontal section. The key of dual 2D trajectory design lies in determining the horizontal displacement of the upper S-shaped trajectory, i.e., the distance \( S_1 \) from point M to vertical line through surface location point I in the horizontal projection plane, as shown in Figure 5. In Figure 5, coordinates of the surface location I, target point J and end point K of horizontal section are known and the azimuth of the horizontal section JK relative to due north is \( \Phi_T \); therefore, the following equation can be obtained:

\[
tg \Phi_T = \frac{E_K - E_J}{N_K - N_J}
\]

(13)
Where, $\Phi_T$ is the azimuth of the horizontal section JK relative to due north, rad; $N_K$ is the northing of point K, m; $N_J$ is the northing of point J, m; $E_K$ is the easting of point K, m; $E_J$ is the easting of point J, m. Suppose the offset distance of the horizontal section relative to well head is $H$, initial azimuth of the upper S-shaped trajectory in the first vertical plane is $\Phi_S$, as shown in Fig. 5.

The horizontal displacement $S_1$ of upper S-shaped profile is calculated as formula (14):

$$S_1 = \frac{H}{\sin(\Phi_T - \Phi_S)}$$  \hspace{1cm} (14)

Where $S_1$ is determined, the borehole trajectory in the first vertical plane can be designed by adopting S profile. In the coordinate system where wellhead is original point, the coordinate of M point will be expressed as:

$$N_M = S_1 \cos \Phi_S$$ \hspace{1cm} (15)

$$E_M = S_1 \sin \Phi_S$$ \hspace{1cm} (16)

Projected length $S_2$ of MJ in the horizontal plane:

$$S_2 = \left[\left(N_J - N_M\right)^2 + \left(E_J - E_M\right)^2\right]^{1/2}$$ \hspace{1cm} (17)

Well trajectory in the second vertical plane can be designed by taking $S_2$ as horizontal displacement and adopting single arc or dual-build and hold profile.

The advantage of dual 2D well trajectory is that turn section does not exit neither in the first nor the second vertical plane, which therefore reduces the trajectory control difficulty

2.3. Profile of Dual 2D and Small 3D Combined Trajectory

Profile of dual 2D and small 3D combined trajectory is composed of the upper modified S-shaped profile and lower 3D trajectory with shorter turning direction section and horizontal section. The upper well section is featured by a modified S-shaped 2D profile in which the inclination of final hold section is not 0° but a certain smaller inclination, then turn a shorter 3D well section to the azimuth of horizontal section. Finally, build to inclination of horizontal section to hit the target point J and continue to extend to end point K.

![Figure 6. Structural Diagram of 2D and Small 3D Combined Trajectory Profile.](image)

The upper 2D modified S-shaped trajectory can be established by referring to the design method of dual 2D trajectory and the lower 3D trajectory design can be established by referring to the design method of 3D trajectory. Figure 6 shows the spatial relationship of dual 2D and small 3D combined profile. Compared with dual 2D profile, the dual 2D and small 3D combined profile has a short turning section between the two vertical planes. The disadvantage is that turning direction operation is required.
3. Profile Design and Evaluation of Shale Gas Horizontal Well

3.1. Basic Design Parameters
12 shale gas horizontal wells are drilled on one platform and well heads are arranged in two rows; spacing of well heads in the same row is 5 m and distance between the two well heads in different rows is 30 m. By taking the three wells W1, W2 and W3 in the single row for instance, the azimuth of horizontal section is 190°, the direction of wellhead connecting line is 100° and the length of the horizontal section is 1,900 m. the offset distance of the three wells is 150 m, 450 m and 750 m respectively. Keep the coordinate of target point and length and inclination of horizontal section unchanged, plan the trajectory of the three shale gas horizontal wells W1, W2 and W3 respectively as per large 3D, dual 2D and dual 2D and small 3D combined profiles; of which, the sectional data of large 3D, dual 2D and small 3D profiles of W3 are respectively shown in Table 1~ Table 3.

Table 1. Sectional Data for Large 3D Profile of W3.

| Well Depth (m) | Inclination (°) | Azimuth (°) | TVD (m) | Northing (m) | Easting (m) | Vertical Section (m) | Dogleg Severity (°/30m) | Target |
|----------------|-----------------|-------------|---------|--------------|-------------|----------------------|-----------------------|--------|
| 2,900          | 0               | 0           | 2,900   | 0            | 0           | 0                    | 0                     |        |
| 3,255.18       | 71.04           | 103.91      | 3,170.93| -46.49       | 187.71      | 73.99                | 6                     |        |
| 3,570.46       | 71.04           | 103.91      | 3,273.38| -118.18      | 477.13      | 188.07               | 0                     |        |
| 3,986.01       | 81              | 190         | 3,400   | -422.21      | 666.82      | 517.01               | 6                     | A      |
| 5,886.01       | 81              | 190         | 3,729.93| -2,264.92    | 341.9       | 2,290.58             | 0                     | B      |

Table 2. Sectional Data for Dual 2D Well Profile of W3.

| Well Depth (m) | Inclination (°) | Azimuth (°) | TVD (m) | Northing (m) | Easting (m) | Vertical Section (m) | Dogleg Severity (°/30m) | Target |
|----------------|-----------------|-------------|---------|--------------|-------------|----------------------|-----------------------|--------|
| 300            | 0               | 0           | 300     | 0            | 0           | 0                    | 0                     |        |
| 447.1          | 12.26           | 104.7       | 445.98  | -3.98        | 15.16       | 6.2                  | 2.5                   |        |
| 655.88         | 12.26           | 104.7       | 650     | -15.23       | 58.04       | 23.72                | 0                     |        |
| 700.87         | 17.51           | 104.7       | 693.47  | -18.16       | 69.21       | 28.29                | 3.5                   |        |
| 2,586.4        | 17.51           | 104.7       | 2,491.65| -162.1       | 617.88      | 252.51               | 0                     |        |
| 3,204.32       | 0               | 0           | 3,100   | -185.87      | 708.49      | 289.54               | 0.85                  |        |
| 3,218.27       | 0               | 0           | 3,113.95| -185.87      | 708.49      | 289.54               | 0                     |        |
| 3,623.83       | 81              | 190         | 3,400   | -422.25      | 666.81      | 517.05               | 5.918                 | A      |
| 5,523.83       | 81              | 190         | 3,729.93| -2,264.96    | 341.9       | 2,290.62             | 0                     | B      |

Table 3. Sectional Data for 2D and Small 3D Combined Well Profile of W3.

| Well Depth (m) | Inclination (°) | Azimuth (°) | TVD (m) | Northing (m) | Easting (m) | Vertical Section (m) | Dogleg Severity (°/30m) | Target |
|----------------|-----------------|-------------|---------|--------------|-------------|----------------------|-----------------------|--------|
| 500            | 0               | 0           | 500     | 0            | 0           | 0                    | 0                     |        |
| 602.74         | 8.56            | 107.85      | 602.35  | -2.35        | 7.29        | 2.52                 | 2.5                   |        |
| 954.3          | 8.56            | 107.85      | 950     | -18.39       | 57.11       | 19.71                | 0                     |        |
| 962.88         | 9.26            | 117.98      | 958.48  | -18.91       | 58.33       | 20.26                | 6                     |        |
| 3,234.7        | 9.26            | 117.98      | 3,200.67| -190.47      | 381.26      | 199.27               | 0                     |        |
| 3,524.47       | 81              | 190         | 3,400   | -370         | 376.3       | 378.64               | 8                     | A      |
| 5,424.47       | 81              | 190         | 3,729.93| -2,212.71    | 51.38       | 2213.3               | 0                     | B      |

3.2. Well Depth Comparison
On the basis that the same target, the same horizontal section length(1900m), total depths of W1,W2,W3 with different offset distance of 150 m, 450 m and 750 m respectively adopting 3 different profile of the dual 2D, dual 2D and small 3D combined and large 3D profiles are showed in Figure. 8. As shown in
Figure. 7, with the increase of the offset distance, total well depth difference is very little between dual 2D profile and dual 2D and small 3D combined profile, but the total well depth difference is great between large 3D profile and dual 2D profile. For the horizontal well W3 with an offset distance of 750 m, with coordinate of target point unchangeable, large 3D well is 389 m deeper than dual 3D well, a 6.3% growth. If the target section is the same, deeper well depth will lead into higher drilling cost.

3.3. Collision Prevention Analysis
If the three wells W1, W2 and W3 are planed with the same trajectory profile, according to profile data, a scanning analysis is made by minimum distance scanning method and trajectory error analysis model, Figure. 8 shows the separation factor comparison of the three profiles. As shown in Figure. 8, the separation factors of dual 2D profile and dual 2D and small 3D combined profile are above 2.0, meeting the collision prevention demand. But the separation factor of large 3D profile decreases with increased well depth within vertical section, separation factor is less than 1 when well depth exceeds 1,500m and borehole collision probability is very high, failing to meet the collision prevention requirement. Therefore, large 3D well profile is unsuitable for cluster horizontal wells with small wellhead spacing.

3.4. Analysis on Drill String Torque and Drag
Figure. 9 shows the drill string accumulative drag under different operating conditions of the three trajectory profiles. Figure. 10 shows wellhead torque under the operating conditions of rotary drilling and back reaming.

According to Figure. 9 and 10, under the conditions of trip-out and sliding drilling, the accumulative drag of large 3D trajectory profile is the largest among 3 profiles. and drag difference between dual 2D and dual 2D and small 3D combined trajectories profile is small; but the wellhead torque for dual 2D profile under rotating drilling and back reaming is slightly large. In general, influence of drag under sliding drilling on drilling operation is the largest, and from the point of view of drill string torque and drag, the dual 2D and 2D and small 3D combined profile is superior to large 3D profile.
4. Conclusions

(1) The separation factor both of dual 2D and dual 2D and small 3D combined profiles is above 2.0, meeting the collision prevention demand of cluster horizontal wells. With respect to large 3D trajectory, the separation factor will be smaller than 1 when the well depth exceeds 1,500 m and borehole collision probability is very high. Therefore, large 3D well is unsuitable for cluster horizontal well trajectory design with small wellhead spacing.

(2) With the increase of the offset distance, the total well depth difference is very little between dual 2D and dual 2D and small 3D combined profiles, but the total well depth difference is great among large 3D, dual 2D profile. Where the target section is the same, deeper well depth will lead to higher drilling cost.

(3) Accumulative torque and drag of large 3D profile is the largest, but drag difference between dual 2D and dual 2D and small 3D combined profile is small. Both dual 2D and dual 2D and small 3D combined profiles are in favor of improving penetration rate and lowering well collision risk.

(4) Dual 2D or dual 2D and small 3D combined profile are recommended to plan the deep shale gas horizontal well, which helps control trajectory, avoids inter-well collision, and improve the rate of penetration.

References

[1] Qin Jia, Zhang Wei, Liu Jing, et al. Analysis on Shale Gas Development in the US [J] Petroleum Geology & Oilfield Development in Daqing, 2014,33 (4);170-174
[2] Nie Jingshuang and Wei Yuan, Research on Drilling Technology of Horizontal Well in Changning Region [D] Chengdu: Southwest Petroleum University, 2013
[3] Li Bin, Fu Jianhong, Qin Fubing and Tang Yiyuan, “Well Factory” Drilling Technology of Shale Gas in Weiyuan Region [J] Petroleum Drilling Techniques, 2017,45(5);13-18
[4] Zhao Guoying. “Factory Oriented” Deployment and Design Optimization of Horizontal Well – Taking Shale Gas Reservoir of Weiyuan, Sichuan for Example [J] 2018, 41(1); 51-57
[5] Xu Yunlong, Xu Dui, Xia Wenan and Zhang Xiaoming, Well Factory Drilling Practice for Large Cluster Well Group in Bailu Lake [J]. Drilling & Production Technology. 2017, 40(6);4-7
[6] Fan Haofu, Zang Yanbin, Zhang Jincheng and Zhang Haiping. Difficulties and Countermeasures of Deep Shale Gas Drilling Technology [J] Drilling & Production Technology, 2019,42(3) :20-23
[7] McMillian W H.Planning the directional well-a calculation method[J].Journal of Petroleum Technology,1981,33(06):952-962
[8] Liu Z,Samuel R.Wellbore-Trajectory Control by Use of Minimum Well-Profile-Energy Criterion for Drilling Automation[J].SPE Journal,2015
[9] Jiang Shengzong and Feng Enmin, Optimum Control Model and Calculation of Borehole Trajectory Design of 3D Horizontal Well [J] Journal of Dalian University of Technology, 2002,42 (3); 261-264.
[10] Ilyasov R R, Svechnikov L A, and Karimov M R, et al. Automation of Optimal Well Trajectory Calculations[R].SPE171326,2014.
[11] Ruszka, Jon. Technology Focus: Horizontal and Complex-Trajectory Wells [J].SPE Journal,2009.