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Practice of Trajectory Control Technology for Directional Wells with Small Deviation in Yan'an

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Abstract. The well track irregularity, azimuth drift, and slow ROP are severe problems in the build and maintain angle sections of wells on An 7 platform. By analyzing the influences of structure factors of steerable assembly with one bend on the guiding ability, the stabilizer counts, positions and outer diameters in assembly is optimized. The BHA scheme which is suitable for small inclined directional well is proposed. Results show that some measures can be implemented, such as 1) predicting “azimuth advance angle” in directional drilling and 2) drilling 4-6m by sliding then drilling 3-5m by composite method during angle building process. These findings can improve the pertinence and operability of BHA, and enhance the ratio of composite drilling footage.

1. Introduction

The key of well path control in the directional well construction is to accurately master the build-up rate of steerable assembly, and then select and use the BHA reasonably. Since the advent of directional well, four generations of deflection tools have appeared in sequence [1]: whipstock, bending sub + downhole motor, PDM with bend and rotary steerable drilling tool. Among them, PDM with Single bend has been widely used in the well path control of directional wells with small deviation due to its advantages of simple structure, good operational performance and good economy. And in construction, the most common forms of steerable assembly are following two types, 1) steerable assembly with one stabilizer and one bend, 2) steerable assembly with two stabilizers and one bend. The key of achieving optimal drilling is how to adjust the structural parameters of BHA so as to enhance the ratio of composite drilling footage in the whole inclined section.

At the end of last century, academician Su [2] put forward the selection method of PDM, which has guiding significance for the selection and use of PDM. Di [3] found after analyzing the directional ability of commonly steerable assembly that not all of the steerable assemblies have holding-inclination or slight building-angle capability, and some of assemblies may have dropping-inclination capability. Based on the study of Di, Zhao et al. [4] used the weighted residual method to study the building-inclination capability of steerable assembly by composite drilling, and believed that steerable assembly with two stabilizers and one bend could be optimized to improve the holding-inclination capability in the maintain angle section. An et al. [5] analyzed factors which affect the directional ability of steerable assembly based on the practical application of steerable assembly with one stabilizer and one bend. Guo et al. [6] analyzed the holding-inclination capability of steerable assembly with two stabilizers and one bend and influencing factors that affect it. The results show that if the O.D. of the first stabilizer is too small, the stabilizer will have no contact with borehole. And as the increase of O.D. of the second stabilizer, the rotary side force of steerable assembly with two stabilizers and one bend decreases. In addition, the effects of the bent angle of PDM, inclination, and



WOB on the rotary side force of steerable assembly with two stabilizers and one bend are all slight.

In actual construction, the cross section of the hole drilled by steerable assembly with one bend in composite drilling is usually a regular circle, while the one drilled in sliding drilling is an irregular oval. In other words, if the ratio of sliding drilling footage in the whole inclined section is too high, it will not only delay the construction progress, but also bring many difficulties to the subsequent construction. For example, in Xinken 601 well [7] construction, excessive sliding drilling created irregular well track for upper well. This lead to the bit weight was difficultly applied on the bit by sliding drilling method in subsequent construction. Another example is the DP31H well [8] in Daniudi gas field. Due to the excessively high build-up rate by composite drilling, the actual deviation angle to be greater than the design one. It has to drop deviation by sliding drilling method, which cause the drill string to be blocked in the same section every tripping.

Through the construction of the An 7 platform, the author summarizes a set of well path control method which suitable for directional wells with small deviation in Yan'an area.

2. Engineering Background

Since 2010, a large number of cluster Wells with small deviation have been deployed in Yanchang gas field. These wells have a horizontal displacement of about 1000m and a hole depth of about 3,100m. The poor formation drillability, serious circulation loss, strong formation abrasiveness and difficult control of well track are severe problems in these constructions.

The An 7 platform is located in Yuju, Yanchuan, with an altitude of 1134m. The target layers are the Paleozoic Permian Shiqianfeng formation, Shihezi formation, Shanxi formation, Taiyuan formation, and the carboniferous Benxi formation. Geologic zonation is shown in table 1.

Table 1(a). The geologic zonation of An 7 platform.

Geologic zonation	Loose loess	Yanchang formation	Zhifang formation	Heshanggou formation	Liujiagouo formation	Shiqianfeng formation
Vertical depth	215	1116	1562	1717	2063	2384
Thickness	215	901	446	155	346	321

Table 1(b). The geologic zonation of An 7 platform

Geologic zonation	Shihezi formation	Shanxi formation	Taiyuan formation	Benxi formation	Majiagou formation
Vertical depth	2664	2779	2817	2860	2890
Thickness	280	115	38	43	30

The An 7 platform has a vertical well and 4 small-angle directional wells. According to the construction sequence, it is well An 7 (vertical well), well An 7-1, well An 7-2, well An 7-4 and well An 7-3, the specific wellhead location and drilling direction are shown in Figure 1. The design maximum deviation angle of 4 directional wells are 25°,28°,28°,30° respectively, and both are two-section structural wells. Figure 2 shows the well structure of An 7-2.

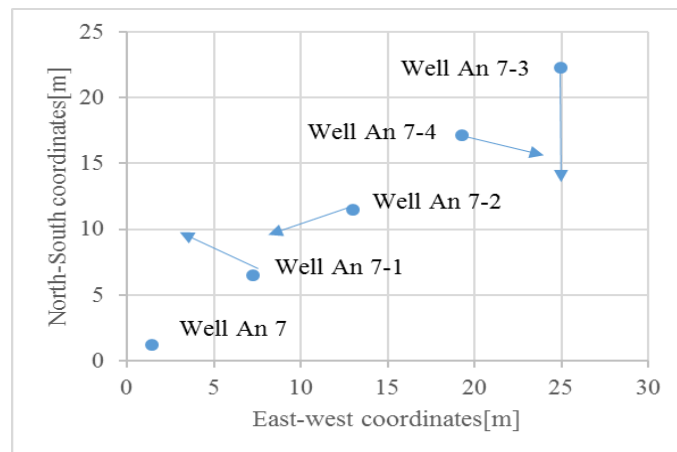


Figure 1. The schematic diagram of wellhead position of 5 wells on An 7 platform.

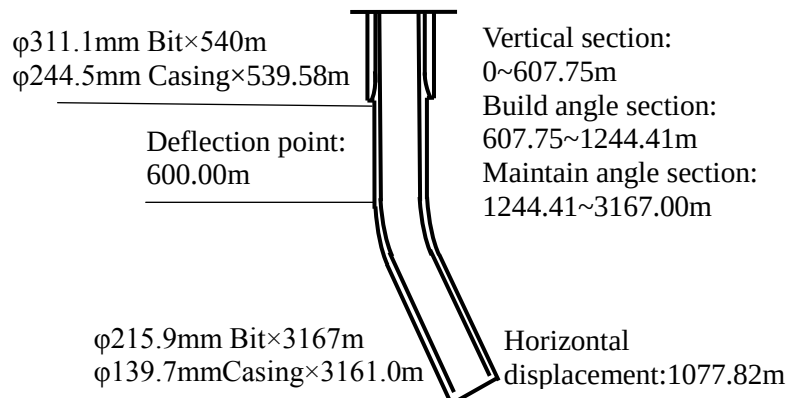


Figure 2. The schematic diagram of hole structure of An 7-2.

The problems in the construction of this platform are as follows.

- The ROP is slow in build angle section. The rock bit is used in the build angle section of An 7-1. Although the rate of build is stable, the AROP is only 6.01 m/h, which is 33.61% slower than the same section of An 7-2.
- The rate of build is instable in build angle section. In An 7-2, due to the unstable build-up rate in the inclined section, the well track is irregular. This led to resistance during the trip in some sections. For example, in the 900~925m section, the deviation angle increases from 19.24° to 22.3°, the rate of over all angle change reaches 4.23°/30m, and then in the 950~975m section, the well inclination increase from 23.14° to 23.47°, and the rate of over all angle change is only 0.35°/30m.
- Controlling inclination is difficult in maintain angle section. In the construction of the first three directional wells, the condition of the micro-increasing deviation angle appeared during the composite drilling. Therefore, we need to use sliding drilling to adjust the deviation angle, which delays the progress of the project. For example, in the initial stage of the hold angle section, the rates of build of this three wells are 0.20°/10m, 0.14°/10m, and 0.29°/10m, respectively.
- The question of azimuth drift is so prominent. In An 7-1 and An 7-4, serious problem of azimuth right drift have occurred. In order to avoid off-target, the adjusting azimuth is frequently performed. This has brought some serious effects for subsequent construction, such as problems of backing pressure and difficulty to put tool face. So we can only drill by composite drilling, resulting in a difference of 6.41° and 5.04° between the final azimuth and designed one respectively.

3. Analysis and Improvement

In order to improve the time efficiency and the wellbore quality, the BHA and the technical measures are gradually analyzed and improved during the construction of An 7 platform.

3.1. The Surface Section

The borehole size of the surface section of these 5 wells are 12-1/4 ($\phi 311.15\text{mm}$), mainly using the following two set of BHA:

BHA-1: $\phi 311.1\text{mm}$ Bit + $\phi 203.2\text{mm}$ DC $\times 3$ + $\phi 177.8\text{mm}$ NDC $\times 1$ + $\phi 177.8\text{mm}$ DC $\times 5$ + $\phi 127\text{mm}$ HWDP $\times 9\sim 15$

BHA-2: $\phi 311.1\text{mm}$ Bit + $\phi 203.2\text{mm}$ DC $\times 2$ + $\phi 308\text{mm}$ Stabilizer + $\phi 203.2\text{mm}$ DC $\times 1$ + $\phi 177.8\text{mm}$ NDC $\times 1$ + $\phi 177.8\text{mm}$ DC $\times 5$ + $\phi 127\text{mm}$ HWDP $\times 9\sim 15$

In BHA-2, the stabilizer is about 18m to 21m away from the drill bit, which can ensure sufficient pendular force under the large drill pressure, so that the deviation is controlled to a small extent. Under normal conditions, the drill pressure should be controlled below 150kN [9].

The large enlargement rate of bore diameter, upper circulation loss and large well deviation are severe problems in first three wells. The first two problems are caused by soft formation and insufficient discharge rate, respectively. And these two problems increase the difficulty of the deviation control. The maximum deviation angle of An 7 and An 7-1 are 1.62° and 1.8° respectively.

In order to drop the deviation angle and increase the ROP, the straight PDM is used in the latter two wells. That is, when the conditions permit, replace the $\phi 203\text{mm}$ drill collar near the bit with the $\phi 203\text{mm}$ straight PDM in the above two sets of BHA. The specific measures are as follows: spud in the hole with BHA-1 and then to replace the assembly with the straight PDM after drilling to the bedrock (about 120m). Drilling parameter: drill pressure, spud in the hole with 10kN drill pressure, and then increase with hole depth, gradually increase to 80kN $\sim$ 100kN; discharge rate, spud in the well with 20L / s, after drilling 2 $\sim$ 3 single joints, the discharge rate will be increased to 30L/s, and then gradually increase to 50L/s with the increase of well depth.

Results show that no mud loss occurred in the last two wells after adopting this technical measure, and the maximum deviation angle are 0.49° and 0.9° respectively. The ROP of An 7-3 reached 16.58m/h, which is 22.81% faster than the fastest An 7-2.

3.2. The Second Section

The borehole size of the second section of these 5 wells are 8-1/2 ($\phi 215.9\text{mm}$), mainly using the single bend PDM with one stabilizer or two stabilizers. The schematic diagram is shown in Figure 3. The specific structure is as follows:

BHA-3: $\phi 215.9\text{mm}$ Bit + $1.25^\circ \phi 172\text{mm}$ PDM + Absorber + Directional Sub + $\phi 165.1\text{mm}$ NDC $\times 1$ + $\phi 158.75\text{mm}$ DC $\times 5$ + Adapter Sub + $\phi 127\text{mm}$ HWDP $\times 15\sim 21$ + $\phi 127\text{mm}$ DP

BHA-4: $\phi 215.9\text{mm}$ Bit + $1.25^\circ \phi 172\text{mm}$ PDM + SDC + Stabilizer + Absorber + Directional Sub + $\phi 165.1\text{mm}$ NDC $\times 1$ + $\phi 158.75\text{mm}$ DC $\times 2\sim 5$ + Adapter Sub + $\phi 127\text{mm}$ HWDP $\times 15\sim 21$ + $\phi 127\text{mm}$ DP

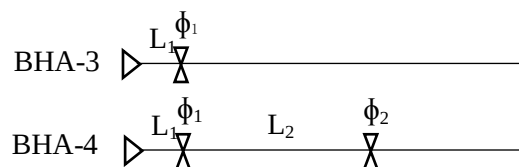


Figure 3. The schematic diagram of steerable assembly.

The size of the PDM's bend angle α has great effect for build-up rate during the sliding drilling situation, but has less effect during the composite drilling [10]. Since the design build-up rate of these four directional wells are $2.7^\circ/30\text{m}$, $3.3^\circ/30\text{m}$, $2.4^\circ/30\text{m}$ and $1.5^\circ/30\text{m}$ respectively, α is 1.25° .

For composite drilling, the position and size of stabilizer are the main factors effecting steerable ability. The first stabilizers of these two kinds of BHA are all located on the PDM, the distance from the bit is 1.0m (L_1), and the outside diameter is 212mm (Φ_1). It can be seen that the structural

parameters of BHA-3 is relatively stable. For BHA-4, mainly by adjusting the distance L_2 between the two stabilizers and the outside diameter Φ_2 of the second stabilizer to control the effect of increasing deviation angle, decreasing hole angle and maintain angle of the composite drilling, thereby improving the ratio of composite drilling footage in the whole inclined section.

3.2.1. Vertical section. The vertical section of these four directional wells are only more than 100m. Due to the small strata dip in this area, the deviation control is not difficult. The steerable assembly of increasing hole angle is used directly to drill the vertical section in order to improve the ROP. The results show that the deviation angle and the rate of over all angle change all meet the design requirements.

3.2.2. Build angle section. In An 7-1, BHA-4 with the rock bit is used. BHA parameters are $L_2 = 11.95\text{m}$, $\phi_2 = 212\text{mm}$ respectively. The results show that this assembly has a stable but a slightly higher rate of build, and the well track is regular. Drilling to the depth of 866m, due to the slow ROP, the PDC was replaced by the drill, and L_2 was adjusted to 10.66m. And other parameters were unchanged. The results show that this assembly has insufficient rate of build in composite drilling.

In An 7-2, in order to ensure the ROP and the rate of build at the same time, BHA-4 with the PDC is used. BHA parameters are $L_2 = 11.95\text{m}$, $\phi_2 = 212\text{mm}$ respectively. The construction results show that the ROP of this steerable assembly is faster, but the rate of build is unstable, and the well track is not irregular. When drilling to 1010m, we pull out of the hold, due to the MWD has no signal. Considering the drilling of maintain angle section, the L_2 is shortened to 10.66m.

In An 7-4, in order to ensure the stability of rate of build, BHA-3 with the PDC is used to drill into the build angle section. The results show that the well track is better, but the ROP is slower.

In An 7-3, BHA-3 with the PDC is first used. When drilling to 930m, we pull out of the hold and replace BHA-4, due to the MWD has no signal. The parameters are $L_2 = 10.6\text{m}$, $\phi_2 = 208\text{mm}$ respectively. The results show that the ROP is faster, the well track is smooth, and the rate of building angle is stable. They creates favorable conditions for subsequent construction.

The following is an evaluation of BHA in build angle section.

- The ROP of the rock bit + PDM with single bend is obviously slower than that of the PDC + PDM with single bend [10], but the tool surface of the former is easier to control in the sliding drilling stage, and the well track is also more regular. These features are beneficial to the geological personnel to accurately determine the horizon, especially suitable for use in horizontal sections or well sections with unclear geological conditions.
- For BHA-3, it has a simple structure and strong ability to increase the deviation angle, suitable for complex hole sections or designing hole sections with large rate of build. However, the ability to build angle in the composite drilling stage increases with the increase of the deviation angle [5]. When the deviation angle is large, it is difficult to control the well track, so this BHA is not suitable for the high angle section or horizontal section.
- For BHA-4, in the case of other conditions unchanged, L_2 and ϕ_2 are smaller, the effect of build up during the composite drilling is better.

3.2.3. Maintain angle section. In the maintain angle sections of An7-1 and An7-2, BHA used are all BHA-4 with PDC. The parameters are $L_2 = 10.66\text{m}$, $\phi_2 = 212\text{mm}$ respectively. In the actual drilling, there are micro-increasing deviation angle and azimuth drift problem in the composite drilling stage, so the adjustment of deviation angle and azimuth has to be frequently performed, resulting in the frequent changes of the borehole axis.

In An 7-4, BHA-4 with the PDC is used. The parameters are $L_2 = 10.10\text{m}$, $\phi_2 = 212\text{mm}$ respectively. During the drilling process, this steerable assembly has better effect of increasing angle, but the azimuth drift problem also occurs.

Due to the frequent adjustment of deviation and azimuth, the problems of the tool face instability and the backing pressure have occurred in the later stage of the first three directional well.

In An 7-3, according to the previous construction conditions, BHA-4 with PDC is used. The parameters are $L_2 = 9.6\text{m}$, $\phi_2 = 212\text{mm}$ respectively. The actual drilling result of this assembly in the

maintain angle section shows that the deviation is slightly increased, the problem of azimuth drift does not occur, the ROP is higher than other three wells, and the well track is smooth. It should be noted that since the problem of azimuth drift has occurred in the previous three wells, the “azimuth advance angle” is used when drilling the maintain angle section, which basically eliminated the improving azimuth operation caused by the azimuth drift.

The following is an evaluation of BHA in maintain angle section.

- According to the construction condition of An 7-3, if L_2 is further shortened, the effect of maintain angle will be better in the composite drilling. Recommended parameters: $L_2 = 9\text{m}$, $\phi_2 = 212\text{mm}$.
- If the well track is irregular, it will affect the tool face. Because the irregularity of the well track will increase the wear resistance of the borehole wall to the drill string, so that the torque cannot be smoothly transmitted to the bottom of the hole. When drilling, these torque remaining in the drill string are suddenly released, causing the tool face to be unstable. The actual drilling results show that the more frequent the adjustment of the deviation and azimuth in the upper section, the more the number of stabilizers in the BHA and the larger the diameter, the problem of tool surface instability during the sliding drilling is more prominent.
- BHA is not the main factor causing azimuth drift. Its main factors are the following two aspects. 1) Formation factor. The root cause is the nonisotropy of the formation drillability and the inclination of the formation. This factor may cause a right drift or a left drift during the drilling process. 2) The drill string rotates during the composite drilling stage. This factor can only cause a right drift [11].

3.2.4. Technical improvement. Because there are different degrees of azimuth drift in the first three directional wells, the “azimuth advance angle” [11] is used for the build angle section of An 7-3. This measure effectively improves the well quality and the time efficiency.

In build angle stage, the directional method of the whole single pipe is abandoned. And the method which drill 4-6m by sliding then drill 3-5m by composite is used. In this way, it is beneficial to drill a smooth well track, and timely understand the true rate of build of BHA through the measured data, and make a reasonable prediction of the well track accordingly.

Each time a single pipe is drilled, it is necessary to lift and lower the drill string once. On the one hand, the hole wall can be trimmed, and on the other hand, the bottom cuttings can be fully circulated to avoid regrinding.

When the deviation angle is less than 20° , the short trip is performed once every 150~200m; when the deviation angle exceeds 20° , the short trip is performed once every 100~150m. Once the turntable torque is found to increase or the friction is not normal, the constructor immediately performs a short trip.

The down hole tool should be tested on the ground before being used for drilling, and all normal can be used. If a new PDC is used, it is necessary to use a small drill pressure to shape the bottom of the hole for 30cm before normal drill pressure can be performed, which can extend the service life of the bit. (Note: Do not wear the bit when testing the PDM to avoid damage to the casing.)

4. Effect Contrast

Through the improvement of the BHA and the well path control technology, the number of adjustment deviation and azimuth in An 7-3 is greatly reduced, the problem of backing pressure is obviously relieved, and the ROP and wellbore quality is greatly improved.

4.1. Time Efficiency Contrast

The AROP of the surface and second section of An 7-3 is 22.81% and 9.04% higher than the fastest surface section of An 7-2 and second section of An7-4 respectively. The well construction period of An 7-3 is shortened by 25.47% compared with An 7-4. The time efficiency contrast of 4 wells is shown in Table 2.

Table 2. Time efficiency contrast of 4 wells.

	An 7-1	An 7-2	An 7-4	An 7-3
Total depth [m]	3063	3167	3152	3173
Actual maximum deviation angle [°]	29.24	32.52	32.75	35.38
AROP of the first drilling [m/h]	10.28	13.50	12.63	16.58
AROP of the second drilling [m/h]	6.68	7.2	7.41	8.08
Well construction period [d]	47.50	47.29	45.27	36.08

4.2. Wellbore Quality Contrast

It is generally believed that the more uniform the rate of over all angle change in each well section, the smoother the wall and the better wellbore quality. Therefore, the wellbore quality can be reflected by calculating the standard deviation of rate of over all angle change in each well section. The specific results are shown in Table 3.

Table 3. Standard deviation of over all angle change rate of 4 directional wells in each section.

	An 7-1	An 7-2	An 7-4	An 7-3
Vertical section	0.08	0.05	0.04	0.08
Build angle section	1.04	1.27	0.63	0.58
Maintain angle section	0.46	0.58	0.42	0.42

The results show that through the reasonable optimization for the steerable assembly and the well path control technology, the ratio of composite drilling footage in the whole drilling is greatly improved in the construction of An 7-3, and the well track is optimized.

5. Summary

For steerable assembly with two stabilizers and one bend, by adjusting the position and size of the second stabilizer, the build-up rate by composite drilling can be controled, so as to reduce the proportion of sliding drilling footage in the whole inclined section and increase the ROP.

In the actual drilling process, the actual rate of build should be calculated according to the measured data in time, and compared with the design rate of build. If the deviation is too large, the BHA should be replaced in time.

Predicting “azimuth advance angle” can effectively reduce the number of adjusting azimuth caused by the azimuth drift, and greatly improve well path and time efficiency.

During angle building process, drilling 4-6m by sliding then drilling 3-5m by composite method can not only drill a smooth well track, but also help predict the true rate of build of BHA in time.

6. Acknowledgement

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