Proceedings of the 3rd International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2025.28006

Research on Segmented Pressure Prediction and Drilling Boundary of Encrypted Horizontal Wells in Water Drive Ultra-low Permeability Reservoirs—Taking Oil Fields as an Example

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Abstract. This article proposes a comprehensive prediction method that combines precise geological modeling of the target area for accurate quality control and precise numerical simulation of key parameter differentiation zoning to address the difficulty of predicting formation pressure in the development of encrypted horizontal wells in ultra-low permeability reservoirs in oil fields. By establishing a three-dimensional fine geological model and combining reservoir engineering theory with numerical simulation technology, the formation pressure at the horizontal well finger, root, and middle positions was displayed with an error control of 2%, achieving high-precision prediction of the formation pressure in encrypted horizontal wells. Research has shown that the heterogeneity of ultra-low permeability reservoirs is significant, and the anisotropy of permeability has a controlling effect on pressure distribution. By fitting and predicting differentiated zones such as oil-water interface, reserves, relative permeability, and measures, the prediction error is reduced compared to traditional reservoir engineering methods; Based on the pressure prediction results and combined with the pilot well field test, the shut in pressure of the water wells around the encrypted horizontal well in the ultra-low permeability reservoir was optimized, and the pressure limit was raised by 3MPa; After optimization, the drilling time is shortened, the block pressure is maintained at a good level, the drilling effect of the block is better than expected, and the production loss of old wells is reduced. The overflow flow caused by drilling is also reduced, and the overall operating cost is lowered. The technical research results provide reference for the encryption adjustment of similar oil fields.

Keywords: Water drive ultra-low permeability reservoir, encrypted horizontal well, formation pressure prediction method, drilling fluid density design

1. Introduction

Horizontal well densification adjustment is an effective means to improve the development effect of thin layer ultra-low permeability Aonan oilfield [1]. Due to the unclear pressure distribution characteristics of encrypted horizontal wells and the more complex drilling technology of horizontal

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wells, which require higher safety pressure requirements, it is necessary to study the pressure distribution in the horizontal section of horizontal wells in Aonan Oilfield, further explore the drilling pressure limit suitable for ultra-low permeability reservoirs, reduce the impact of drilling production, maintain formation energy, improve encrypted well productivity, and enhance development effectiveness [2]. The Aonan Oilfield is located at the junction of three secondary structural zones, Daqing Changyuan, Gulong Depression, and Sanzhao Depression, in the central depression area of the northern Songliao Basin [3]. It is a long-term developed inherited nose shaped structure. The Putaohua oil reservoir in the oilfield is mainly controlled by the sedimentary system of the northern delta. The reservoirs are mainly composed of underwater distributary channel sand, river mouth bars, delta outer front sheet sand, and shore shallow lake sand ridges, with an average effective thickness of 2.6m and an average of 2.9 oil layers encountered during single well drilling. The physical properties of the encrypted block reservoir are poor, with an average effective porosity of 16.7% and an average air permeability of 3.8×10-3μ m^2.

Traditional methods for predicting well pressure, such as the plane radial flow formula under the assumption of homogeneity and the potential superposition principle, ignore reservoir heterogeneity [4-8]. Numerical simulation methods, based on black oil models and component models, are widely used in commercial software for oilfield development, but there are limitations in simulating non Darcy flow in ultra-low permeability reservoirs. Ultra low permeability reservoirs need to consider factors such as start-up pressure gradient and pressure sensitivity effect. Existing research has mostly focused on vertical wells, with less research on horizontal wells [9]. This article is based on previous research on drilling standards for vertical wells in low-permeability reservoirs [10]. Multiple methods are used to comprehensively predict the pressure distribution in the horizontal section of horizontal wells, propose reasonable drilling pressure limits, and effectively guide the design of horizontal well drilling engineering to improve development efficiency [11].

2. Fine modeling of encrypted well area and numerical modeling prediction of segmented pressure in horizontal wells

2.1. Fine geological modeling based on precise quality control of the target area

Strictly following the geological modeling principle of closely combining deterministic modeling and stochastic modeling, adopting a multi parameter collaborative modeling method with phased characteristics to establish a detailed geological model of the block, reducing or eliminating the inconsistency of spatial distribution of different reservoir parameters that do not conform to actual geological understanding [12-15].

On the basis of fault combination, the fault model is used to reposition the fault, control the fracture surface of the well breakpoint, fine tune the fracture surface of the well stratification, and establish the fault model [16]. By using the sand body trend in the sedimentary facies model to constrain the porosity model and controlling it with facies control parameters, the heterogeneous planar distribution of porosity, permeability, and oil saturation can be obtained. The cross-sectional model of the grid-based filling blocks in Aonan Oilfield is shown in Figure 1.

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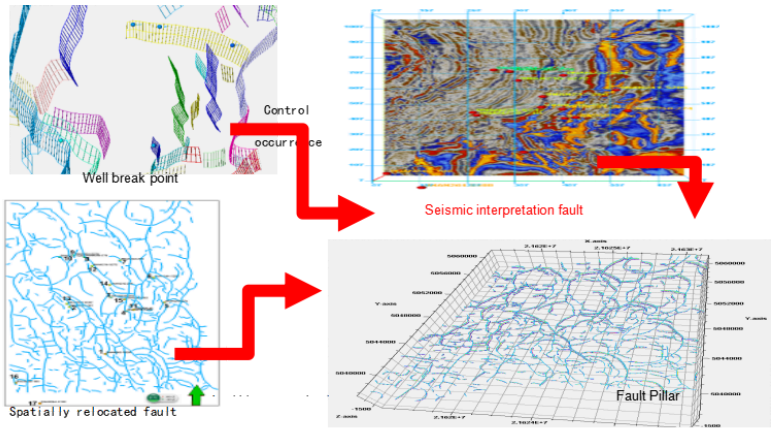


Figure 1. The cross-sectional model of the gridded infill block in Aonan Oilfield

Through repeated calculations, the calculation method and parameter selection of the attribute model were determined to improve the accuracy of reservoir plane attribute prediction, and a high-precision integrated geological model was constructed. The porosity and permeability models of the gridded infill block in Aonan Oilfield is shown in Figure 2.

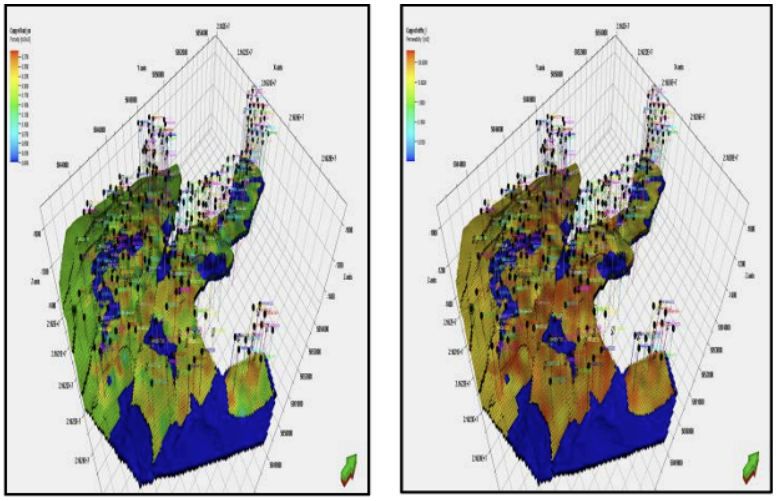


Figure 2. The porosity and permeability models of the gridded infill block in Aonan Oilfield

2.2. Fine numerical simulation based on differentiated partitioning of key parameters

Establish a numerical model for the encrypted area of the oilfield, carry out multi parameter partitioning and step-by-step fine historical fitting of the model, improve the fitting accuracy, and lay the foundation for predicting the formation pressure at the encrypted well in a layered and segmented manner [17-20].

Fine numerical simulation of key parameter differentiation zoning, with a total simulated area of 65.87 km2 in the encrypted block of Aonan Oilfield, including 11 horizontal wells and 310 vertical and inclined wells [21]. Combine three-dimensional geological models, fluid models, and production dynamic models to establish a high-precision four-dimensional reservoir model required for numerical simulation. Establish a numerical model for the encrypted area of the oilfield, carry out multi parameter partitioning and step-by-step fine historical fitting of the model, improve the

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fitting accuracy, and lay the foundation for predicting the formation pressure at the encrypted well in a layered and segmented manner [22].

On the basis of differentiated zoning such as oil-water interface, reserves, relative permeability, and measures, and based on the actual development of each block in the oilfield, historical fitting and dynamic prediction were carried out step by step for each block, well group, and single well. The error between the calculated value and the actual value was within 2%, and the fitting effect was good. The reserves, oil - water interface, relative permeability, and measure partitioning of the infill block in Aonan Oilfield is shown in in Figure 3.

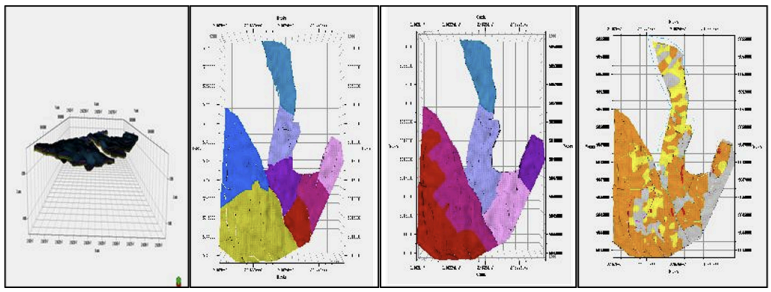


Figure 3. The reserves, oil - water interface, relative permeability, and measure partitioning of the infill block in Aonan Oilfield

According to the numerical simulation results, the formation pressure at the encrypted well location is predicted by extracting the formation pressure values of the grid. Based on the numerical simulation results, the average formation pressure is predicted to be 20.00MPa, with a formation pressure coefficient of 1.49. Based on numerical simulation, predict the pressure distribution of various parts and sedimentary units of the encrypted well, with a pressure range between 18-22MPa.

3. Engineering methods for reservoir pressure prediction in encrypted well areas

In order to better predict formation pressure, based on the theory of seepage, a plane radial flow under single-phase liquid stable seepage, considering oil-water viscosity plane radial flow, and predicting the pressure of encrypted wells based on a simple production system [1-12] are adopted for better comparative analysis. Statistical table of pressure prediction for each part of horizontal well numerical simulation is shown in Table 1.

Table 1. Statistical table of pressure prediction for each part of horizontal well numerical simulation

Serial number	Hash sign	Root pressure (MPa)	Central pressure (MPa)	Toe end pressure (MPa)
1	NAN	20.23	20.33	20.46
2	NAN	20	20.02	20.05
3	NAN	19.21	19.27	19.3
4	NAN	18.24	18.3	18.36
5	NAN	18.15	18.14	18.15
6	NAN	18.62	18.67	18.72
7	NAN	18.59	18.6	18.65
8	NAN	21.71	21.78	21.92
9	NAN	21.59	21.69	21.85

DOI: 10.54254/2755-2721/2025.28006

Table 1. (continued)

10	NAN	20.3	20.42	20.59

The comparison between the average formation pressure calculated by reservoir engineering and the measured value shows that the formation pressure value at the adjustment well point calculated by the bottomhole pressure of the water well is higher. The main reason is that the actual reservoir is highly heterogeneous and anisotropic, resulting in different pressure transmission velocities in various directions of the water well. The pore throat changes dramatically in various directions, and the capillary force and Jamin effect are significant, requiring overcoming multiple and multi-stage resistances. Therefore, the pressure values calculated using the planar radial flow formula are corrected to obtain the final predicted formation pressure. Using the single-phase stable plane radial flow pressure prediction formula for encrypted well pressure prediction, the average formation pressure predicted for encrypted block adjustment wells is 20.33MPa, with a formation pressure coefficient of 1.51; Apply the formula for predicting the radial flow pressure of oil-water viscosity plane to predict the pressure of encrypted wells. The average formation pressure predicted for the adjustment well in the encrypted block is 20.39 MPa, with a formation pressure coefficient of 1.52; Applying the simple production system pressure prediction formula for encrypted well pressure prediction, the average formation pressure predicted for encrypted block adjustment wells is 20.29 MPa, with a formation pressure coefficient of 1.51.

From the predicted results, it can be seen that the formation pressure coefficient predicted by reservoir engineering methods is slightly higher than that predicted by numerical simulations. The pressure coefficient of the formation at the encrypted well predicted by the two methods of planar radial flow is basically the same, which is higher than the result predicted by the simple production system pressure. Statistical comparison table of pressure prediction for infill wells is shown in Table 2.

Table 2. Statistical comparison table of pressure prediction for infill wells

Project	Oil reservoir engineering methods								Numerical simulation		
	Single phase stable planar radial flow			Consider oil-water viscosity plane radial flow			Based on a simple production system				
	Maximum formation pressure (MPa)	Average formation pressure (MPa)	pressure coefficient	Maximum formation pressure (MPa)	Average formation pressure (MPa)	Pressure coefficient average formation pressure (MPa)	pressure	Maximum coefficient grid pressure (MPa)	Average grid pressure (MPa)	pressure coefficient	Maximum formation pressure (MPa)
Ave	21.78	20.33	1.51	21.86	20.39	1.52	20.26	1.51	20.17	20	1.49

4. Comparative analysis of predicted pressure and actual drilling pressure

According to the predicted pressure, the 26 wells are divided into 5 batches, and drilling is gradually carried out from low to high, gradually exploring the pressure limit value.

The influence of the relationship between formation coefficient and pressure difference coefficient, starting pressure gradient, and annular pressure loss on drilling fluid density design. Optimize pressure difference, reduce drilling fluid density, and minimize the occurrence of complex well leakage without serious oil and gas invasion. The design of drilling fluid density should take into account the formation pressure coefficient and safety negative pressure difference, as well as the formation fracture pressure. The predicted drilling fluid density is 1.60 ± 0.05g/cm3.

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Comparing the actual drilling data to calculate the actual formation pressure, and comparing the drilling formation pressure with the predicted formation pressure, the overall error is between 2.17% and 2.64%. The prediction accuracy is high and can meet the on-site drilling requirements. Comparison table of predicted pressures in the infill well area of Aonan Oilfield is shown in Table 3.

Table 3. Comparison table of predicted pressures in the infill well area of Aonan Oilfield

Hash sign	Complete drilling pressure		Prediction of planar radial flow				Considering oil-water viscosity ratio for predicting radial flow in a plane			
	Formation pressure MPa	pressure coefficient	Formation pressure MPa	pressure coefficient	Pressure difference (MPa)	Error %	Formation pressure MPa	pressure coefficient	Formation pressure MPa	pressure coefficient
NAN6	20.85	1.46	21.48	1.59	0.63	3.02	20.36	1.5	-0.49	-2.35
NAN	20.3	1.46	19.93	1.54	-0.37	-1.82	19.79	1.53	-0.51	-2.51
NAN	19.1	1.45	19.26	1.58	0.16	0.84	19.8	1.63	0.7	3.66
NAN	17.6	1.43	18.49	1.47	0.89	5.06	18.28	1.45	0.68	3.86
NAN	18.05	1.46	17.99	1.39	-0.06	-0.33	18.49	1.42	0.44	2.44
NAN	18.05	1.46	18.12	1.44	0.07	0.39	18.82	1.5	0.77	4.27
NAN	18.3	1.48	18.6	1.42	0.3	1.64	18.38	1.4	0.08	0.44
NAN	20.95	1.48	21.11	1.4	0.16	0.76	21.43	1.42	0.48	2.29
NAN	21.4	1.61	22.01	1.6	0.67	3.13	22.04	1.63	0.43	2.01
NAN	19.85	1.56	19.22	1.4	-0.63	-3.17	20.57	1.49	0.72	3.63

Simple Production Pressure System Prediction				Numerical simulation prediction			
Pressure difference (MPa)	Error %	Formation pressure MPa	pressure coefficient	Formation pressure MPa	pressure coefficient	Formation pressure MPa	pressure coefficient
				20.34	1.5	-0.51	-2.45
				20.03	1.55	-0.27	-1.33
19.24	1.58	0.14	0.75	19.26	1.58	0.16	0.84
17.58	1.4	-0.02	-0.1	18.3	1.45	0.7	3.98
18.62	1.43	0.57	3.16	18.15	1.4	0.1	0.55
18.89	1.5	0.84	4.63	18.68	1.49	0.63	3.49
18.48	1.41	0.18	0.98	18.61	1.42	0.31	1.69
20.91	1.38	-0.04	-0.18	21.8	1.44	0.85	4.06
21.96	1.59	0.56	2.63	22	1.6	0.31	1.45
20.06	1.46	0.21	1.04	20.44	1.48	0.59	2.97

5. Determination and effectiveness of drilling pressure for encrypted blocks

The pressure prediction results have completed drilling tests and water injection adjustments in the encrypted block of Aonan Oilfield, and effectively guided the control pressure limit of drilling

DOI: 10.54254/2755-2721/2025.28006

attention wells, thereby reducing drilling downtime, improving development efficiency, accelerating production speed, and generating good social and economic benefits.

According to the predicted pressure, drilling will be gradually carried out from low to high, and the pressure limit of the surrounding water injection wells will be gradually set. By combining the water drive direction, pressure, and well spacing, priority will be given to implementing well positions with low pressure and far distance from the water wells. 28 horizontal wells will be drilled, including 10 wells with a pressure of 4-6 MPa, 7 wells with a pressure of 6-8 MPa, 6 wells with a pressure of 8-10 MPa, and 3 wells with a pressure greater than 10 MPa.

The Nan well is a horizontal well located in the middle of the nose shaped structure in the area. The predicted pressure using the radial flow prediction method is 1.60, considering the oil-water viscosity, the predicted pressure is 1.63, and the predicted pressure using numerical simulation method is 1.60. Based on the pressure prediction results and taking into account factors such as surrounding water injection well pressure, start-up pressure gradient, annular pressure loss, and tolerable overflow rate, the drilling fluid density is designed to be 1.53-1.58g/cm3, with a maximum safe negative pressure difference of -0.05MPa.

During on-site construction, the well was drilled to a depth of 1960 meters, and oil, gas, and water invasion occurred. In order to avoid leaking the formation and expanding the complexity, the method of weighting, drilling, and maintaining the drilling fluid performance was adopted to maintain the drilling fluid density between 1.58-1.60g/cm3, achieving safe completion of drilling in the event of oil and gas invasion. The logging curve shows that the well exhibits high pressure characteristics at 1920-1950 meters, with an explanatory pressure coefficient of 1.60. To ensure the safety of well cementing, the drilling fluid density of the well was increased to 1.65g/cm3 after drilling, and there was slight wellbore leakage. 5 tons of composite plugging agent were added, and the well was successfully completed.

The drilling fluid density of the well is 1.65g/cm3, indicating a leakage display, indicating that the density has reached the upper limit of the block density. At this time, the formation pressure is 22.70MPa, and the injection well pressure is 8.9MPa, which is the critical upper limit of pressure in the area.

Based on the predicted results, combined with different well areas, permeability levels, and drilling distances, determine the drilling limit values for water injection wells. When drilling encrypted horizontal wells, the permeability is less than 5mD, and the pressure limit of the water well at a distance of 300-400m is 6MPa. The drilling pressure drops by 3MPa, and the drilling time is reduced by 6 months. Statistical table of drilling shut-in pressure boundaries for water wells around infill wells is shown in Table 3.

Table 4. Statistical table of drilling shut-in pressure boundaries for water wells around infill wells

Well area	Number of encrypted wells (mouth)	Penetration level (mD)	Crypto block water well pressure limit (MPa)				
			＜250m	250-300m	300-400m	400-500m	500-600m
Mao	5	1-5	4.0		6.0	8.0	10.0
Ao	2	5-10	3.0	4.0		6.0	8.0
Ao	3	＞10			4.0	6.0	

A total of 26 wells have been drilled in the block, with an average drilling fluid density of 1.59g/cm3, an average mechanical drilling speed of 32.78m/h, an average drilling cycle of 5.61d, an

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average well construction cycle of 9.85d, a zero occurrence rate of stuck drilling, a 100% wellbore qualification rate, a 100% cementing qualification rate, and an 86.7% cementing quality rate.

Due to the shortened drilling time and better pressure maintenance, after production, the average daily oil production per horizontal well was 6.7 tons, with a comprehensive water content of 23.1%, significantly better than expected. At the same time, reducing the loss of production from drilling and closing old wells, minimizing the amount of overflow caused by drilling and closing, and lowering overall operating costs.

6. Conclusion

(1) Based on precise quality control of the target area, fine geological modeling is carried out to reposition faults, control well breakpoints and fine tune well layering sections. The sand body trend in the sedimentary facies model is used to constrain the porosity model, and phase control parameters are used to reduce or eliminate the inconsistency of spatial distribution of different reservoir parameters that do not conform to actual geological understanding.

(2) Based on precise numerical simulation of key parameter differentiation zoning, differential zoning fitting prediction is carried out for oil-water interface, reserves, relative permeability, measures, etc. According to the actual development of each block in Aonan Oilfield, the error between calculated values and actual values is within 2%; And achieved accurate segmented pressure prediction for horizontal wells, displaying the formation pressure at the finger, root, and middle positions of the horizontal well.

(3) Multiple reservoir engineering methods are used to predict and analyze the pressure through numerical simulation, and compared with the measured pressure for correction. The final predicted formation pressure is compared with the actual drilling pressure, and the error in comparison meets the drilling requirements.

(4) Based on the pressure prediction results and combined with the pilot well field test, the shut in pressure of the water wells around the encrypted horizontal well in the ultra-low permeability reservoir was optimized, and the pressure limit was raised by 3MPa.

(5) Due to the shortened drilling time and better pressure maintenance level,

The drilling effect of the block was better than expected, and the loss of production from drilling old wells was reduced, the overflow flow caused by drilling was reduced, and the overall operating cost was lowered.

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