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Estimation Method of Natural Water Bodies in the Fracture Cavity Carbonate Reservoir of the Sea

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Abstract
In recent years, the discovery of fractured carbonate reservoirs has made it become a hot spot for the development of such reservoirs. The oil field of south of Bohai is a typical fracture cavity reservoir, which is different from the land oil field. In this oil field, fluid reservoir space is mainly composed of fractures, but caves are not developed, at the same time the reservoir has strong heterogeneity. Oil water relationship and reservoir type are extremely complex and the percolation law is essentially different from the general marine sandstone reservoir. In view of the actual situation of the oil field, the volume of natural water body was studied by reservoir engineering method. By comparative analysis, the results obtained by reservoir engineering method are in agreement with the numerical simulation method. However, reservoir engineering method is simple and rapid, which has a certain reference value for the rapid assessment of water bodies in the same type of oil reservoir at sea.

Key words: Volume of natural water body; Fracture cavity type carbonate reservoir; Strong heterogeneity; Material balance method; Analytic method

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INTRODUCTION
Carbonate reservoir in reservoir occupies an important position in the world, the world has found that more than half of oil and gas reserves from carbonate oil and gas reservoir. In the numerous carbonate reservoir, fractured carbonate reservoir is a special type of reservoir. Fractured-vuggy carbonate reservoir is a multiphase tectonic movement and ancient karst form of interaction, taking karst seam hole as the main control factors, mainly seam hole reservoir of complex reservoir system[1-2]. Southern bohai sea carbonate reservoir of in certain oilfield in a large number of development of crack, and the presence of a small amount of solution pores, so the initial capacity is larger, in contrast, are seriously oilfield produced water and well water breakthrough is fast, early water breakthrough is an important factor of production, reservoir at the beginning of the development and without considering the elastic expansion of rock generally characterized by limited closed reservoir elastic drive[3], but with the development of edge and bottom water invasion, calculation of reserves and dynamic prediction in the process of water influx must be applied to estimate.

1. THE CALCULATION METHOD OF THE WATER BODY
For seam hole type carbonate reservoir fracture medium reservoir, the very low matrix porosity and permeability, cracks and intensive development. So the crack is the main seepage channel and the main reservoir space. Fluid flow in this kind of reservoir and the common sandstone are similar, both follow the darcy's law but has obvious differences in bottom hole pressure changes. Fracture - pore - cave triple media reservoir bottom hole pressure characteristics are divided into three stages:

First stage: Hypothesis is connected, fracture and cave-fracture system of crude oil into the wellbore. Matrix block is still keeping the original state, its pressure Pm stays the same, there is no flow. When the bottom hole pressure reflects a cave system and fracture system features. Its liquidity and homogeneous reservoir basic same, crack-cave system pressure to land is not much, *Pf* + *Pc* and *Pm* difference is small, has not yet established a block matrix to the normal system flows through the cracks. The bottom hole pressure characteristics similar to homogeneous pore reservoir characteristics.

The second stage is the excessive stage. Then (*Pc*+*Pf*)—*Pm* has a certain degree of difference, can set up from the substrate to crack—the flow of the karst cave. The matrix block gap fluid pressure in the *Pm* also gradually reduced. This phase of the pressure change is heterogeneity.

The third stage is the stage of triple medium. This is crude oil from matrix into the crack-cave, crack-cave into the wellbore, *Pm* and (*Pc*+*Pf*) falling at the same time. Bottom hole pressure change reaction is pore-fracture-cave characteristics of the whole system, and show the homogeneous features but this is homogeneous characteristics of pore-fracture-cave overall[4]. Pore fluid flow in the fracture system, called channeling, continuity equation can be written as

$$\frac{\partial(\phi_j\rho_j)}{\partial t}+\nabla(\rho_j v_j)+(-1)^j q_m=0,\ j=1,2\ , \quad (1)$$

$$q_m=\lambda\frac{\rho_o}{\mu}(p_m-p_f)\ .$$

In edge water reservoir, for example, when supply boundary is large enough, the measures will have enough features in cave of equivalent of seepage medium. The fracture network can be regarded as the main flow channel, karst cave, bedrock main storage and the role of fluid exchange. Accordingly, the first to write under the condition of the above, the mathematical model which assumes that the outer boundary for the closed outer boundary, the constant boundary pressure difference inside and outside, formation fluid flow in conformity with the plane radial darcy seepage.

$$\frac{k_f}{\mu}\left(\frac{\partial^2 p_f}{\partial r^2}+\frac{1}{r}\frac{\partial p_f}{\partial r}\right)+\frac{\lambda_{mf}k_m}{\mu r_w^2}(p_m-p_f)-\frac{\lambda_{fc}k_c}{\mu r_w^2}(p_f-p_c)=\varphi_f C_f\frac{\partial p_f}{\partial t}\ , \quad (2)$$

$$\frac{\lambda_{fc}k_c}{\mu r_w^2}(p_f-p_c)-\varphi_c C_c\frac{\partial p_c}{\partial t}=0\ , \quad (3)$$

$$-\frac{\lambda_{mf}k_f}{\mu r_w^2}(p_m-p_f)-\varphi_m C_m\frac{\partial p_m}{\partial t}=0\ . \quad (4)$$

Initial condition:

$$p_m(r,t)|_{t=0}=p_f(r,t)|_{t=0}=p_c(r,t)|_{t=0}=p_i(r_w\le r\le r_e)\ . \quad (5)$$

Internal boundary condition:

$$p_m(r,t)|_{r=r_w}=p_f(r,t)|_{r=r_w}=p_c(r,t)|_{r=r_w}=\text{Const}\ . \quad (6)$$

Outer boundary condition:

$$p_m|_{r\to r_e}=p_f|_{r\to r_e}=p_c|_{r\to r_e}=p_i\ . \quad (7)$$

m.f.c—bedrock, split, limestone cave;
k—permeability, μm2;
μ—viscosity, mPa·s;
λ—channel flow factor;
Cm, *Cf*, *Cc*—coefficient of comressibillity, 1/MPa;
pwf—bottom hole flowing pressure, MPa;
pi—initial formation pressure, MPa;
re—supply radius, m;
rw—wellbore radius , m;
pm, *pf*, *pc*—pressure, MPa.

Introduce dimension: $P_D=\frac{P_i-P}{P_i-P_{wf}}$; $r=\frac{r}{r_w}$; $t_D=\frac{k_f t}{[\varphi_m c_m+\varphi_f c_f+\varphi_c c_c]\mu r_w^2}$.

Tidying:

$$\left(\frac{\partial^2 p_{Df}}{\partial r_D^2}+\frac{1}{r_D}\frac{\partial p_{Df}}{\partial r_D}\right)\cdot\frac{k_f}{r_w^2}+\frac{\lambda_{mf}k_m}{\mu r_w^2}(p_{Dm}-p_{Df})-\frac{\lambda_{fc}k_c}{r_w^2}(p_{Df}-p_{Dc})$$
$$-\frac{k_f}{\mu r_w^2(\varphi_f c_f+\varphi_m c_m+\varphi_c c_c)}\varphi_f c_f\frac{\partial p_{Df}}{\partial t}=0\ . \quad (8)$$

Assume：

$$\omega_f = \frac{\varphi_f c_f}{\varphi_m c_m + \varphi_f c_f + \varphi_c c_c} ;$$

$$\omega_c = \frac{\varphi_c c_c}{\varphi_m c_m + \varphi_f c_f + \varphi_c c_c} ; \quad \omega_m = \frac{\varphi_m c_m}{\varphi_m c_m + \varphi_f c_f + \varphi_c c_c} .$$

The dimensionless results of (2), (3), (4) is:

$$\frac{\partial^2 p_{Df}}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial p_{Df}}{\partial r_D} + \lambda_{mf}\frac{k_m}{k_f}(p_{Dm} - p_{Df}) - \frac{\lambda_{fc}k_c}{k_f}(p_{Df} - p_{Dc}) - \omega_f \frac{\partial p_{Df}}{\partial t_D} = 0 , \tag{9}$$

$$-\lambda_{mf}(p_{Dm} - p_{Df}) - \omega_m \frac{\partial p_{Dm}}{\partial t_D} = 0 , \tag{10}$$

$$\frac{\lambda_{fc}k_c}{k_f}(p_{Df} - p_{Dc}) - \omega_c \frac{\partial p_{Dc}}{\partial t_D} = 0 . \tag{11}$$

The result of Laplace transformation is:

$$\begin{aligned} &\frac{\partial^2}{\partial r_D^2}\int_0^{+\infty} p_{Df}e^{-st}dt + \frac{1}{r_D}\frac{\partial}{\partial r_D}\int_0^{+\infty} p_{Df}e^{-st}\mathrm{d}t + \frac{\lambda_{mf}k_m}{k_f}\int_0^{+\infty}(p_{Dm} - p_{Df})e^{-st}\mathrm{d}t \\ &-\frac{\lambda_{fc}k_c}{k_f}\int_0^{+\infty}(p_{Df} - p_{Dc})e^{-st}\mathrm{d}t - \omega_f\int_0^{+\infty}\frac{\partial p_{Df}}{\partial t_D}e^{-st}\mathrm{d}t = 0 . \end{aligned} \tag{12}$$

$$-\lambda_{mf}\int_0^{+\infty}(p_{Dm} - p_{Df})e^{-st}\mathrm{d}t - \omega_m\int_0^{+\infty}\frac{\partial p_{Dm}}{\partial t_D}e^{-st}\mathrm{d}t = 0 , \tag{13}$$

$$\frac{\lambda_{fc}k_c}{k_f}\int_0^{+\infty}(p_{Df} - p_{Dc})e^{-st}\mathrm{d}t - \omega_c\int_0^{+\infty}\frac{\partial p_{Dc}}{\partial t_D}e^{-st}\mathrm{d}t = 0 . \tag{14}$$

The Laplace transform of the function $f(t)$ is:

$$\frac{\partial^2 \overline{p_{Df}}}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial \overline{p_{Df}}}{\partial r_D} + \frac{\lambda_{mf}k_m}{k_f}(\overline{p_{Dm}} - \overline{p_{Df}}) - \frac{\lambda_{fc}k_c}{k_f}(\overline{p_{Df}} - \overline{p_{Dc}}) - \omega_f(s\overline{p_{Df}} - f(0)) = 0 , \tag{15}$$

$$-\lambda_{mf}(\overline{p_{Dm}} - \overline{p_{Df}}) - \omega_m(s\overline{p_{Dm}} - f(0)) = 0 , \tag{16}$$

$$\frac{\lambda_{fc}k_c}{k_f}(\overline{p_{Df}} - \overline{p_{Dc}}) - \omega_c(s\overline{p_{Dc}} - f(0)) = 0 . \tag{17}$$

Initial condition:

$$\overline{p_{\mathrm{Dm}}}|_{t_D=1} = \overline{p_{Df}}|_{t_D=1} = \overline{p_{Dc}}|_{t_D=1} = 0 . \tag{18}$$

Internal boundary condition:

$$\overline{p_{\mathrm{Dm}}}|_{r_D=1} = \overline{p_{Df}}|_{r_D=1} = \overline{p_{Dc}}|_{r_D=1} = \frac{1}{s} . \tag{19}$$

Outer boundary condition:

$$\overline{p_{\mathrm{Dm}}}|_{r_D\to\infty} = \overline{p_{Df}}|_{r_D\to\infty} = \overline{p_{Dc}}|_{r_D\to\infty} = 0 . \tag{20}$$

Derived from the Formula (16)：

$$\overline{p_{Dm}} = \overline{p_{Df}} \Big/ (1 + s \cdot \frac{\omega_m}{\lambda_{mf}\, k_m / k_f}) \ . \tag{21}$$

Derived from the Formula (17)：

$$\overline{p_{Dc}} = \overline{p_{Df}} \Big/ (1 + s \cdot \frac{\omega_c}{\lambda_{fc} k_c / k_f}) \ . \tag{22}$$

(21) and (22) are substituted into equation (15), At the same time make $\frac{\lambda_{mf} k_m}{k_f} = a \quad \frac{\lambda_{fc} k_c}{k_f} = b$ get:

$$\frac{\partial^2 \overline{p_{Df}}}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial \overline{p_{Df}}}{\partial r_D} - \beta(s)\overline{p_{Df}} = 0 \ . \tag{23}$$

(23) is transformed into a 0-order Bessel equation，among them:

$$\beta(s) = (\frac{a\omega_m}{a + s\omega_m} + \frac{b\omega_c}{b + s\omega_c} + \omega_f) \cdot s \ . \tag{24}$$

The general solution of the 0 - order Bessel function:

$$\overline{p_{Df}} = AI_0(\sqrt{\beta} r_D) + BK_0(\sqrt{\beta} r_D) \, . \tag{25}$$

Substituting boundary conditions:（among them $I_0 = I_1$ $K_0 = -K_1$）

$$A = \frac{I_1(\sqrt{\beta} r_{eD})}{s[K_1(\sqrt{\beta} r_{eD}) I_0(\sqrt{\beta}) + K_0(\sqrt{\beta}) I_1(\sqrt{\beta} r_{eD})]} \ , \tag{26}$$

$$B = \frac{K_1(\sqrt{\beta} r_{eD})}{s[I_1(\sqrt{\beta} r_{eD}) K_0(\sqrt{\beta}) + I_0(\sqrt{\beta}) K_1(\sqrt{\beta} r_{eD})]} \ . \tag{27}$$

When the pressure gradient of the oil-water boundary changes, the oil well will produce water intrusion, it is concluded that:

$$r\frac{\partial p_f}{\partial r}|_{r=r_e} = \frac{q\mu}{2\pi K_f h} \ . \tag{28}$$

According to the Formula (28) to find the calculation formula of water intrusion:

$$q = 2\pi r h \frac{K_f}{\mu}\frac{\partial p_f}{\partial r_w} \ . \tag{29}$$

The formula for calculating the water intrusion is:

$$W_e = \int_0^t q \mathrm{d}t = 2\pi r h \frac{K_f}{\mu}\int_0^t r_w \frac{\partial p_f}{\partial r_w}\mathrm{d}t \ . \tag{30}$$

Substituting dimensionless expression:

$$W_e = 2\pi r_w^2 h(\varphi_m C_m + \varphi_f C_f + \varphi_c C_c)(p_i - p_{wf})\int_0^{t_D} r_D \frac{\partial p_{Df}}{\partial r_D}|_{r_D=1}\mathrm{d}t_D \ . \tag{31}$$

Hypothesis $q_D = r_D \frac{\partial p_{Df}}{\partial r_D}|_{r_D=1}$, dimensionless water influx $Q_D = \int_0^{t_D} q_D \mathrm{d}t_D$

Then:

$$\overline{Q_D} = \frac{1}{s}\overline{q_D} = \frac{1}{s}(r_D \frac{\partial \overline{p_{Df}}}{\partial r_D})|_{r_D=1} . \quad (32)$$

When r_D=1 Formula（25）Simplified as $\overline{p_{Df}} = AI_0(\sqrt{\beta}) + BK_0(\sqrt{\beta})$ Substituting (32) is obtained:

$$\overline{Q_D} = \frac{1}{s}[A\sqrt{\beta}I_1(\sqrt{\beta}) - B\sqrt{\beta}K_1(\sqrt{\beta})] . \quad (33)$$

Stehfest numerical inversion of (33):

$$Q_D(t_D) = \frac{\ln 2}{t_D}\sum_{i=1}^{N} V_i \overline{Q_D}(s) . \quad (34)$$

N is even（General N take 8,10 or 12）， $s = \frac{i \ln 2}{t}$ ， $V_i = (-1)^{\frac{N}{2}+i} \sum_{k=[\frac{i+1}{2}]}^{\min(i,\frac{N}{2})} \frac{k^{\frac{N}{2}+1}(2k)!}{(\frac{N}{2}-k)!k!(k-1)!(i-k)!(2k-i)!}$.

Substituting Equation (34) into Equation (31) yields the water intrusion under single pressure drop:

$$W_e = 2\pi r_w^2 h(\varphi_m C_m + \varphi_f C_f + \varphi_c C_c)(p_i - p_{wf})Q_D . \quad (35)$$

The cumulative water intrusion is:

(36)

According to the assumptions, the main cause of water intrusion is caused by the elastic expansion of rocks and fluids in the aquifer, Water intrusion for unsteady water intrusion. The Equation (36) can be reduced to:

$$W_e = 2\pi r_w^2 h\phi c_t \sum_{0}^{t} \Delta p_k Q(t_D) . \quad (37)$$

Among then

$$\Delta p_k = \frac{p_{k-1} - p_{k+1}}{2} , \quad (38)$$

$$t_D = 3.33\times10^{-1} \frac{kt}{\phi\mu_w c' r_o^2} . \quad (39)$$

W_e—Cumulative water intrusion in constant pressure reduction, m^3;
Δp_k—Stage pressure drop, MPa;
$Q(t_D)$—dimensionless water influx;
t_D—dimensionless time.

The steps to calculate the water body are:

(a) Calculate the cumulative water intrusion by applying the material balance equation，The material balance equation of the fracture system is:

$$\frac{N_p}{\rho_o}[B_o + (R_p - R_s)B_g] = \frac{N}{\rho_o}(R_{si} - R_s)B_g - \frac{W_p B_w}{\rho_w} + \frac{N}{\rho_o}(B_o - B_{oi}) + \frac{W_{ing} B_w}{\rho_w} + \frac{W_e}{\rho_w} + + m\frac{N}{\rho_o}\frac{B_{oi}}{B_{gi}}(B_g - B_{gi}) + \frac{NB_{oi}}{\rho_o}[C_o + mC_g + (1+m)C_c]\Delta p . \quad (40)$$

Where the volume coefficient (B_w) of the formation water and water density (ρ_w) can be approximately equal to one, cumulative water encroachment:

(b) According to Equations (38), (39) to calculate the dimensionless time t_D and stage pressure drop Δp_k.

$$W_e = \frac{N_p}{\rho_o}[B_o + (R_p - R_s)B_g] - \frac{N}{\rho_o}(R_{si} - R_s)B_g + W_p - \frac{N}{\rho_o}(B_o - B_{oi}) - W_{ing} - m\frac{N}{\rho_o}\frac{B_{oi}}{B_{gi}}(B_g - B_{gi}) - \frac{NB_{oi}}{\rho_o}[C_o + mC_g + (1+m)C_c]\Delta p . \quad (41)$$

(c) Calculate dimensionless water influx $Q(t_D)$: Through the previously calculated dimensionless time t_D, give dimensionless radius $r_D = \frac{r_e}{r_w}$, look up the table and find the different corresponding relationship between the $Q(t_D)$ and t_D according to Equation (37) to find aquifer influx W_e.

(d) Adjust the value of the dimensionless radius r_D, the aquifer influx calculated by the material balance method is basically the same as the aquifer influx calculated by the unsteady state method, use r_D to calculate the size of the water.

$$R_{wo} = r_D^2 \frac{H}{h} - 1. \tag{42}$$

2. EXAMPLE ANALYSIS

X oilfield which is development of bottom water reservoir. Design the use of natural energy development then changes into water injection development。Its geological parameters and fluid parameters are shown in Table 1. In order to further determine the reservoir natural energy and way of development. Analytic method, method of reservoir engineering and numerical simulation method are used to calculate the oil field water erosion, history of the field production data is shown in Table 2.

Table 1
X Oilfield Geological Parameters and Fluid Properties

S_{wi} (f)	0.23	C_{eff} (10^{-4}/MPa)	43.79
N ($10^4 m^3 v$)	581	K (mD)	229
μ_w (mPa·s)	0.53	B_o	1.12
φ (f)	0.27	θ (°)	360
ρ_o g/m^3)	0.82	h (m)	97
A_o (km^2)	4.9	μ_o (mPa·s)	0.32

Table 2
Reservoir Development Historical Data

Date (year-month)	N_P ($10^4 m^3$)	W_P ($10^4 m^3$)	P (MPa)	$\triangle P$ (MPa)
2014-03	54.92	2.51	27.4	3.3
2014-09	56.79	4.37	27.2	3.5
2014-12	57.84	4.66	26.9	3.8
2015-03	58.13	5.31	26.6	4.1
2015-06	58.80	6.05	26.3	4.4
2015-09	59.46	6.78	25.9	4.8
2015-12	59.94	7.54	25.6	5.1

According to the unsteady method to calculate water bodies, the simplified formula for material balance Equation (41): Due to the block does not have gas cap so the Formula (41) m=0; $B_o \approx B_{oi}$; $B_g \approx 1$ Formula (41) can be simplified：

$$W_e = \frac{N_p B_o}{\rho_o} + \frac{W_p}{\rho_w} - \frac{NB_{oi}}{\rho_o} C_t \Delta p\,. \tag{43}$$

According to the formula (43) and the cumulative water influx is 719,966.7 m^3.

According to the formula (39) to calculate the dimensionless water influx, then by Formula (38) and phase pressure drop, the calculation results as shown in Table 3.

Table 3
Unsteady Water Influx Calculation Results

Phase	Date	t	t_D	Δp_D	r_D=6.0		r_D=7.0	
					$Q(t_D)$	$\Delta p_D Q(t_D)$	$Q(t_D)$	$\Delta p_D Q(t_D)$
1	2014-03	3287	500.00	1.65	19.1	31.515	22.91	37.8015
2	2014-09	184	499.41	1.75	16.47	28.8225	22.68	39.69
3	2014-12	91	246.99	1.9	16.12	30.628	20.41	38.779
4	2015-03	90	244.27	2.05	15.65	32.0825	20.25	41.5125
5	2015-06	92	249.70	2.2	15.52	34.144	20.33	44.726
6	2015-09	92	249.70	2.4	15.45	37.08	20.21	48.504
7	2015-12	91	246.99	2.55	15.22	38.811	20.21	51.5355

When r_D=6.0 use Formula (3) to calculate water influx is 681,985 m^3. Through the calculation show that when r_D=6.0 the calculations of unsteady water influx are greater than the material balance method to calculate numerical values, reset the value of r_D. When r_D=7.0 to calculate the unsteady water influx is 773,536 m^3.

According to the calculated results using the interpolation method to calculate r_D=6.66, calculation of water multiple are 84 from Formula (42).

Based on fitting better by means of reservoir numerical simulation calculation of water and oil volume is 95, basic and reservoir engineering method to calculate the results are consistent, however, the numerical simulation method to fitting the production performance of reservoir, the process is relatively complex, so reservoir engineering method for this kind of oilfield water scale computing has a certain advantage.

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