processes

Article

All-Factor Average Method of Reserve Parameters with Crude Oil Volume and Mass Constraints

Doujuan Zhang [1,2,*], Haimin Guo [1], Yuyan Wu [1], Cunyuan Chen [3], Ao Li [1], Jinyan Zhang [4] and Yonggang Wang [2]

1 College of Geophysics and Petroleum Resources, Yangtze University, Wuhan 430100, China; ghm@yangtzeu.edu.cn (H.G.); 202073021@yangtzeu.edu.cn (Y.W.); 2022730026@yangtzeu.edu.cn (A.L.)
2 Research Institute of Exploration and Development, Sinopec Shengli Oilfield Company, Dongying 257000, China; wangyg212.slyt@sinopec.com
3 Shengli Geologging Company of Sinopec Matrix Corporation, Dongying 257000, China; chency57.osjw@sinopec.com
4 Sinopec Matrix Corporation, Qingdao 266000, China; zhangjy532.osjw@sinopec.com
* Correspondence: 2021730028@yangtzeu.edu.cn

Abstract: In order to make the average value of each reserve parameter of a set of oil reserves more representative, this paper puts forward the all-factor average method of reserve parameters with crude oil volume and mass constraints. In the first step, the two constraint methods of crude oil volume and mass are adopted to calculate the average value of various parameters of the total items. The weight coefficient when the parameter is averaged is, respectively, the partial derivative of the volume or mass reserve calculation formula with respect to the parameter. Compared with the original calculation results, the average of their parameters all show a shift towards values with a significant share of reserves, especially effective porosity, oil saturation, and crude oil volume factor. The all-factor average method considers a more comprehensive set of factors than the original method. Therefore, each new average parameter should also be much more representative. Since the current reserve specification stipulates that each parameter needs to retain a certain number of decimal places, there inevitably is some carry error between the reserve results calculated by the parameters of the total items and the accumulated reserves of each unit. The second step is to select the optimal average value of each reserve parameter by using the full permutation combination selection method to reduce the carry error. A set of parameters that minimizes the sum of squared relative errors of crude oil volume and mass reserves is selected using the full permutation combination selection method, which is the optimal selection of the average value of the total set of items. Compared with the original method, the full permutation combination selection method can effectively reduce the carry error.

Keywords: reserve parameters; all-factor average method; crude oil volume constraint; crude oil mass constraint; full permutation combination selection method; carry error

check for updates

Citation: Zhang, D.; Guo, H.; Wu, Y.; Chen, C.; Li, A.; Zhang, J.; Wang, Y. All-Factor Average Method of Reserve Parameters with Crude Oil Volume and Mass Constraints. *Processes* **2023**, *11*, 2558. https://doi.org/10.3390/pr11092558

Academic Editors: An Su and Kejun Wu

Received: 11 July 2023
Revised: 21 August 2023
Accepted: 24 August 2023
Published: 26 August 2023

1. Introduction

Oil reserves are the results of exploratory work and the basis of development; therefore, oil reserves data and parameters are very important. In reserve calculation, we usually use the volume method to calculate the reserves of each calculation unit in a certain oilfield block, after which we need to calculate the average value of each parameter of a set of total items. Each average parameter represents an important property of the reservoir and the crude oil of its reserves. The reserve parameters between different oil fields or the reserve parameters calculated across different sections of an oil field can be compared and analyzed, which is essential in the evaluation of oil fields. The reserves of an oil field often consist of multiple zones and blocks, and the number of units in large oil fields sometimes reaches hundreds. There is usually a certain error between the reserves calculated by using the average value of each parameter of the total items calculated via the existing average method and the cumulative reserves of each unit. Meanwhile, the factors considered by the existing average value method, where only some factors are taken into account, are not comprehensive enough.

At present, the main average methods for each parameter are as follows: The average net pay thickness is calculated by dividing the volume sum of each unit by the superimposed oil-bearing area. In other words, the average net pay thickness equals the sum of each unit area times the net pay thickness divided by the superimposed oil-bearing area. The average parameter equals the sum of each unit area times net pay thickness times the parameter divided by the sum of each unit area times net pay thickness in the volume trade-off method. The average parameter equals the sum of each unit area times net pay thickness times effective porosity times the parameter divided by the sum of each unit area times net pay thickness times effective porosity in the pore volume trade-off method. The average parameter equals the sum of each unit area times net pay thickness times effective porosity times oil saturation times the parameter divided by the sum of each unit area times net pay thickness times effective porosity times oil saturation in the oil pore volume trade-off method. The average effective porosity is calculated using the volume trade-off method. The average oil saturation is calculated using the pore volume trade-off method and the average crude oil volume factor is calculated using the oil pore volume trade-off method in studies by Yang T. [1], Chen G. [2], Xiong Q. [3], Wang T. [4], and Yan G. [5]. The average parameter equals the sum of each unit net pay thickness times the parameter divided by the sum of net pay thickness of each unit in the net pay thickness trade-off method. The average effective porosity and oil saturation are all calculated using the net pay thickness trade-off method in a study by Lei Q. et al. [6]. The average effective porosity is calculated using the net pay thickness trade-off method in studies by Deng P. [7], Zhang D. [8], Ma Y. [9], and Wang J. [10]. The average net pay thickness, porosity, and oil saturation are all calculated using the contour area trade-off method, and the average net pay thickness is equal to the sum of the net pay thickness multiplied by its specific area divided by the total area in studies by Guo X. [11], Wang J. [10], Wang T. [4], and Yan G. [5]. The average effective porosity is equal to the sum of the effective porosity multiplied by its specific area divided by the total area, while the average oil saturation is equal to the sum of the oil saturation multiplied by its specific area divided by the total area in a study by Guo X. [11]. The average net pay thickness is calculated using the triangulation pattern well point area trade-off method, the average effective porosity is calculated using the triangulation pattern well point rock volume trade-off method, and the average oil saturation is calculated using the triangulation pattern well point porosity volume trade-off method in a study by Jiang W. [12]. The factors taken into account by the above methods in calculating the average parameters of the total items are not comprehensive enough because the differences in the effective porosity, oil saturation, crude oil volume factor, and crude oil density parameters of each unit are not considered when calculating the average net pay thickness; further, the differences in the oil saturation, crude oil volume factor, and crude oil density parameters of each unit are not considered in calculating the average effective porosity. The differences in crude oil volume factor and crude oil density parameter of each unit are not considered in the calculation of average oil saturation, and the differences in the crude oil density parameters of each unit are not considered in the calculation of average crude oil volume factor. The differences in other parameters are all considered in the study of the improved flattening algorithm of reserve parameters by Zhang D. [13]. However, there still are some remaining problems. In practical applications of crude oil mass, volume, and dissolved gas constraints, it was found that the average reserve parameters obtained via the method of dissolved gas volume constraints are quite different from those calculated via the method with crude oil volume and mass constraints, greatly changing the dynamic range of parameters and greatly increasing computation without noticeably improving the final calculation accuracy. Therefore, this paper optimizes the improved flattening algorithm of reserve parameters, removes the method of dissolved gas constraints, and only considers the constraints of crude oil volume and crude oil mass to average the total item parameters; in other words, this paper presents an application of the all-factor average method of reserve parameters with crude oil volume and mass constraints. Meanwhile, the full permutation combination selection method is adopted to reduce the carry error.

There are two main contributions of this paper.

Firstly, the all-factor average method with crude oil volume and mass constraints considers a more comprehensive set of factors than the original method. The weight coefficient when the parameter is averaged is, respectively, the partial derivative of the volume or mass reserve calculation formula with respect to the parameter. The parameter averages all show a shift towards values with a significant share of reserves, especially effective porosity, oil saturation, and crude oil volume factor. The differences in oil-bearing area, effective porosity, oil saturation, crude oil volume factor, and crude oil density parameters of each unit are considered in calculating the average net pay thickness. The differences in oil-bearing area, net pay thickness, oil saturation, crude oil volume factor, and crude oil density parameters of each unit are considered in calculating the average effective porosity. The differences in oil-bearing area, net pay thickness, effective porosity, crude oil volume factor, and crude oil density parameter of each unit are considered in the calculation of average oil saturation. The differences in oil-bearing area, net pay thickness, effective porosity, oil saturation, and crude oil density parameters of each unit are considered in the calculation of average crude oil volume factor. Therefore, each new average parameter should be much more representative.

Secondly, the full permutation combination selection method was adopted to reduce the carry error. A set of parameters was selected via full permutation combination to minimize the sum of squared relative errors of crude oil volume and mass reserves. The relative error of volume reserves and mass reserves calculated using this set of parameters reaches a relatively small and balanced state, thus achieving the purpose of reducing the carry error relatively well. Compared with the original method, the full permutation combination selection method can effectively reduce the carry error.

This paper is structured as follows. In Section 1, we introduce the all-factor average method of reserve parameters, with crude oil volume and mass constraints, and its application. In Section 2, we introduce the full permutation combination selection method and its application. In Section 3, we provide our conclusion. In Section 4, we point out that the all-factor average method of reserve parameters with crude oil volume and mass constraints, and the full permutation combination selection method, are superior to the original method and provide our suggestion for further research.

2. The All-Factor Average Method of Reserve Parameters with Crude Oil Volume and Mass Constraints

2.1. Some Fundamentas

According to the actual production requirements, the purpose of the average reserve parameter is to best represent the accumulative reserves of many calculation units while simultaneously minimizing the error between the volume reserves and mass reserves calculated via the average value and the cumulative reserves of each unit. The core of the all-factor average of the reserve parameters method is to consider the influence of all parameters and ensure that the crude oil reserves calculated using the average parameter of the total items are as equal as possible to the cumulative reserves of each unit.

1. The cumulative volume reserves of each calculation unit in a block are calculated using the following equation [1]:

$$N = \sum_{i=1}^{n} 100 A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} \tag{1}$$

N—the cumulative volume reserves of each calculation unit in a block, $\times 10^4$ m^3;
i—index of the ith calculation unit in a block, an integer;

n—the number of calculation units in a block, an integer;

A_i—the oil-bearing area of the ith calculation unit in a block, km^2, (i = 1, 2, . . ., n);

h_i—the net pay thickness of the ith calculation unit in a block, where the net pay thickness is the thickness of the reservoir that is capable of producing oil and gas in an oil-bearing formation that meets the reserve threshold, m, (i = 1, 2, . . ., n);

$\varnothing_i$—the effective porosity of the ith calculation unit in a block, where the effective porosity is the ratio of the volume of interconnected pores in the rock to the total volume of the rock, f, (i = 1, 2, . . ., n);

S_{oi}—the oil saturation of the ith calculation unit in a block, where the oil saturation is the percentage of the oil volume of the rock to the effective pore volume, f, (i = 1, 2, . . ., n);

B_{oi}—the crude oil volume factor of the ith calculation unit in a block, where the crude oil volume factor is the ratio of the volume of crude oil underground to its volume after degassing at the surface, f, (i = 1, . . ., n).

2. The cumulative mass reserves of each calculation unit in a block are calculated using the following equation [1]:

$$N_z = \sum_{i=1}^{n} 100 A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} \rho_{oi} \tag{2}$$

N_z—the cumulative mass reserves of each calculation unit in a block, $\times 10^4$ t;

ρ_{oi}—the crude oil density of the ith calculation unit in a block, where the crude oil density is per cubic meter of crude oil mass at standard conditions of 20 degrees Celsius and one atmosphere, t/m^3, (i = 1, . . ., n).

3. The cumulative dissolved gas reserves of each calculation unit in a block are calculated using the following equation [1]:

$$G_s = \sum_{i=1}^{n} 10^{-4} A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} R_{si} \tag{3}$$

G_s—the cumulative dissolved gas reserves of each calculation unit in a block, $\times 10^8$ m^3;

R_{si}—the dissolved gas–oil ratio of the ith calculation unit in a block, where the dissolved gas–oil ratio is the amount of gas dissolved in formation crude oil at reservoir temperature and pressure, m^3/m^3.

4. The volume reserves are calculated using the average parameters of the total items:

$$N_a = 100 A \overline{h} \overline{\varnothing} \overline{S_o} \frac{1}{\overline{B_o}} \tag{4}$$

N_a—the volume reserves calculated using the average parameters of the total items, $\times 10^4$ m^3;

A—the oil-bearing area is the maximum projected closed area of the maximum oil-bearing boundary of the reservoir in the horizontal plane, km^2;

h—the average net pay thickness of the total items, m;

$\varnothing$—the average effective porosity of the total items, f;

S_o—the average oil saturation of the total items, f;

B_o—the average crude oil volume factor of the total items, f.

It is required that the volume reserves N_a calculated by the average parameters of the total items should be equal to the cumulative volume reserves N (Figure 1).

5. The mass reserves are calculated using the average parameters of the total items:

$$N_{za} = 100 A \overline{h} \overline{\varnothing} \overline{S_o} \frac{1}{\overline{B_o}} \overline{\rho_o} \tag{5}$$

N_{za}—the mass reserves calculated using the average parameters of the total items, $\times 10^4$ t;

$\overline{\rho_o}$—the average crude oil density of the total items, t/m^3.

It is required that the mass reserves N_{za} calculated using the average parameters of the total items should be equal to the cumulative mass reserves N_z (Figure 1).

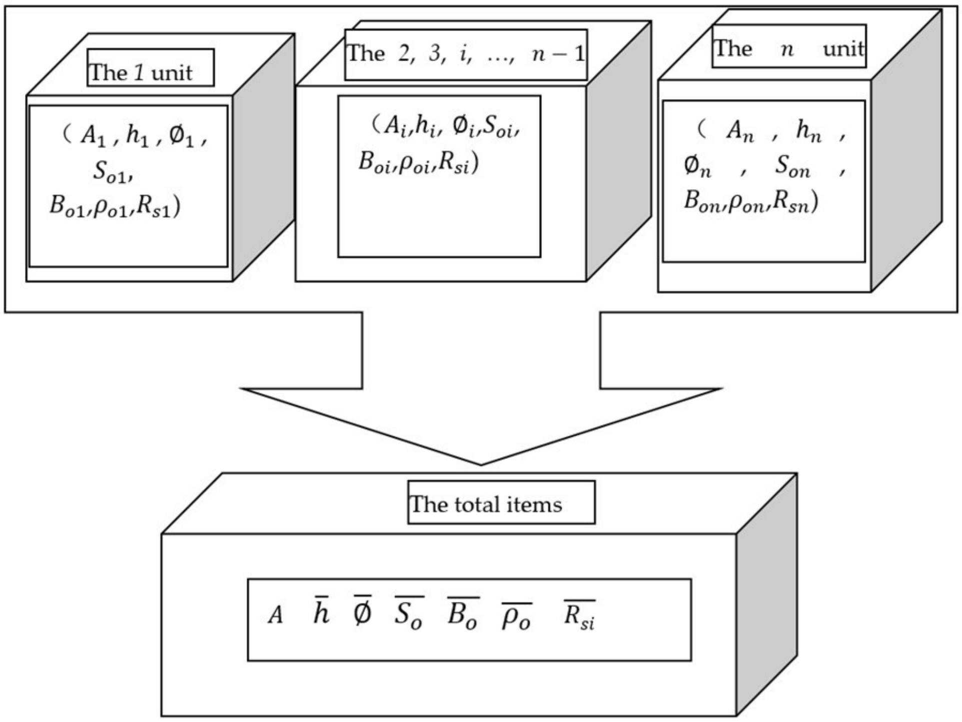

Figure 1. Diagrammatic drawing of the all-factor average method of reserve parameters. (The volume and mass reserves calculated using the average parameters of the total items should be equal to the cumulative volume and mass reserves of each unit, respectively.)

2.2. Calculation Steps of the All-Factor Average Method (Figure 2)

2.2.1. The Oil-Bearing Area A of the Total Items

The oil-bearing area of the total items is the superimposed oil-bearing area A of each unit oil-bearing A_i, among which the vertical oil-bearing area of some units may be superimposed (Figure 2).

2.2.2. The Average Crude Oil Density and the Average Dissolved Gas–Oil Ratio

The average crude oil density (Equation (6)) and the average dissolved gas–oil ratio (Equation (7)) are all calculated using the crude oil volume reserves constraint method [1].

$$\overline{\rho_{oa}} = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} \rho_{oi} / \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} = \sum_{i=1}^{n} N_{\text{zi}} / \sum_{i=1}^{n} N_i \quad (6)$$

$\overline{\rho_{oa}}$—the average crude oil density of the total items, t/m^3.

$$\overline{R_{\text{sia}}} = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} R_{si} / \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} = \sum_{i=1}^{n} G_{\text{si}} / \sum_{i=1}^{n} N_i \quad (7)$$

$\overline{R_{\text{sia}}}$—the average dissolved gas–oil ratio of the total items, m^3/m^3.

Each oil-bearing calculation unit $A_1, A_2 \ldots A_i \ldots A_n$ is firstly superimposed to the total oil-bearing items A.

The average crude oil density and the average dissolved gas-oil ratio are secondly all calculated by the crude oil volume reserves constraint method.

$$\overline{\rho_{oa}} = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} \rho_{oi} / \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} = \sum_{i=1}^{n} N_{\text{zi}} / \sum_{i=1}^{n} N_i$$

$$\overline{R_{\text{sia}}} = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} R_{si} / \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} = \sum_{i=1}^{n} G_{\text{si}} / \sum_{i=1}^{n} N_i$$

After that the average effective porosity, oil saturation and crude oil volume factor are all calculated by the crude oil volume and mass constraints.The subscript 1 indicates crude oil volume constraint method, the subscript 2 indicates crude oil mass constraint method. The same below.

$$\overline{\emptyset}_1 = \sum_{i=1}^{n} A_i h_i \Phi_i S_{oi} \frac{1}{B_{oi}} / \sum_{i=1}^{n} A_i h_i S_{oi} \frac{1}{B_{oi}}$$

$$\overline{\emptyset}_2 = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} \rho_{oi} / \sum_{i=1}^{n} A_i h_i S_{oi} \frac{1}{B_{oi}} \rho_{oi}$$

$$\overline{S_{o1}} = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} / \sum_{i=1}^{n} A_i h_i \emptyset_i \frac{1}{B_{oi}}$$

$$\overline{S_{o2}} = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} \rho_{oi} / \sum_{i=1}^{n} A_i h_i \emptyset_i \frac{1}{B_{oi}} \rho_{oi}$$

$$\overline{B_{o1}} = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} / \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}}$$

$$\overline{B_{o2}} = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \rho_{oi} / \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} \rho_{oi}$$

The average net pay thickness is inversely calculated in the end.

$$\overline{h_1} = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} / (A \overline{\emptyset_1} \overline{S_{o1}}) \overline{B_{o1}}$$

$$\overline{h_2} = \sum_{i=1}^{n} A_i h_i \emptyset_i S_{oi} \frac{1}{B_{oi}} \rho_{oi} / (A \overline{\emptyset_2} \overline{S_{o2}} \overline{\rho_{oa}}) \overline{B_{o2}}$$

Figure 2. Detailed calculation steps of the all-factor average method of reserve parameters.

2.2.3. The Average Effective Porosity, Oil Saturation, and Crude Oil Volume Factor

The average effective porosity, the average oil saturation, and the average crude oil volume factor are all calculated using the crude oil volume and mass constraints.

(1) The average effective porosity is calculated using the crude oil volume and mass constraints.

The weight coefficient when the effective porosity is averaged is, respectively, the partial derivative of the volume or mass reserve calculation formula with respect to the effective porosity ($\frac{\partial N}{\partial \varnothing} = 100AhS_o\frac{1}{B_o}$, $\frac{\partial N_z}{\partial \varnothing} = 100AhS_o\frac{1}{B_o}\rho_o$).

The differences in oil-bearing area, net pay thickness, oil saturation, crude oil volume factor, and crude oil density parameters of each unit are considered in calculating the average effective porosity.

$$\overline{\varnothing}_1 = \sum_{i=1}^{n} A_i h_i \Phi_i S_{oi}\frac{1}{B_{oi}} / \sum_{i=1}^{n} A_i h_i S_{oi}\frac{1}{B_{oi}} \tag{8}$$

$\overline{\varnothing}_1$—the effective porosity $\overline{\varnothing}_1$ of the total items is calculated using the crude oil volume constraint method, %.

$$\overline{\varnothing}_2 = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi}\frac{1}{B_{oi}}\rho_{oi} / \sum_{i=1}^{n} A_i h_i S_{oi}\frac{1}{B_{oi}}\rho_{oi} \tag{9}$$

$\overline{\varnothing}_2$—the effective porosity $\overline{\varnothing}_2$ of the total items is calculated using the crude oil mass constraint method, %.

(2) The oil saturation is calculated using the crude oil volume and mass constraints.

The weight coefficient when the oil saturation is averaged is, respectively, the partial derivative of the volume or mass reserve calculation formula with respect to the oil saturation ($\frac{\partial N}{\partial S_o} = 100Ah\varnothing\frac{1}{B_o}$, $\frac{\partial N_z}{\partial S_o} = 100Ah\varnothing\frac{1}{B_o}\rho_o\Big)$.

The differences in oil-bearing area, net pay thickness, effective porosity, crude oil volume factor, and crude oil density parameters of each unit are considered in the calculation of average oil saturation.

$$\overline{S_{o1}} = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi}\frac{1}{B_{oi}} / \sum_{i=1}^{n} A_i h_i \varnothing_i\frac{1}{B_{oi}} \tag{10}$$

$\overline{S_{o1}}$—the oil saturation $\overline{S_{o1}}$ of the total items is calculated using the crude oil volume constraint method, %.

$$\overline{S_{o2}} = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi}\frac{1}{B_{oi}}\rho_{oi} / \sum_{i=1}^{n} A_i h_i \varnothing_i\frac{1}{B_{oi}}\rho_{oi} \tag{11}$$

$\overline{S_{o2}}$—the oil saturation $\overline{S_{o2}}$ of the total items is calculated using the crude oil mass constraint method, %.

(3) The crude oil volume factor is calculated using the crude oil volume and mass constraints.

The weight coefficient when the crude oil volume factor is averaged is, respectively, the partial derivative of the volume or mass reserve calculation formula with respect to the inverse of the crude oil volume factor ($\frac{\partial N}{\partial (1/B_o)} = 100Ah\varnothing S_o$, $\frac{\partial N_z}{\partial (1/B_o)} = 100Ah\varnothing S_o\rho_o\Big)$.

The differences in oil-bearing area, net pay thickness, effective porosity, oil saturation, and crude oil density parameters of each unit are considered in the calculation of average crude oil volume factor.

$$\overline{B_{o1}} = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} / \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi}\frac{1}{B_{oi}} \tag{12}$$

$\overline{B_{o1}}$—the crude oil volume factor $\overline{B_{o1}}$ of the total items is calculated using the crude oil volume constraint method, f.

$$\overline{B_{o2}} = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} \rho_{oi} / \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} \rho_{oi} \tag{13}$$

$\overline{B_{o2}}$—the crude oil volume factor $\overline{B_{o2}}$ of the total items is calculated using the crude oil mass constraint method, f.

2.2.4. The Net Pay Thickness of the Total Items

The differences in oil-bearing area, effective porosity, oil saturation, crude oil volume factor, and crude oil density parameters of each unit are considered in calculating the average net pay thickness.

Since the oil-bearing area of each calculation unit may overlap vertically, the net pay thickness of the total items may increase, and the carry error has a great influence on the calculation results of reserves because the net pay thickness only retains one decimal place. Therefore, the average net pay thickness is inversely calculated according to the cumulative crude oil volume and mass reserves in the end.

$$\overline{h_1} = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} / \left(A \overline{\varnothing_1} \overline{S_{o1}}\right) \overline{B_{o1}} \tag{14}$$

$\overline{h_1}$—the net pay thickness $\overline{h_1}$ of the total items is inversely calculated using the cumulative crude oil volume reserves, m.

$$\overline{h_2} = \sum_{i=1}^{n} A_i h_i \varnothing_i S_{oi} \frac{1}{B_{oi}} \rho_{oi} / \left(A \overline{\varnothing_2} \overline{S_{o2}} \overline{\rho_{oa}}\right) \overline{B_{o2}} \tag{15}$$

$\overline{h_2}$—the net pay thickness $\overline{h_2}$ of the total items is inversely calculated using the cumulative crude oil mass reserves, m.

Through the comparison of the application of the all-factor average method and the original method in xx1 block (Table 1), when all decimal places are reserved, it can be seen that the results of the all-factor average method are consistent with the original calculation method in terms of the average parameters, and the crude oil mass and volume reserves calculated by the two methods and the accumulative crude oil volume and mass reserves are consistent, without error. Compared with the original calculation results, the average value of each reserve parameter is different from the original calculation results, except for oil-bearing area and crude oil density (Tables 2–5). This can easily be seen in the second example in xx2 block (Table 3), where the parameters differ considerably. The average of their parameters all show a shift towards values with a significant share of reserves, such as effective porosity of three decimal places, oil saturation of three decimal places, and crude oil volume factor of three decimal places. The average effective porosity of the original method is 14.0%, that of the new method with crude oil mass constraint is 17.2%, and that of the new method with crude oil volume constraint is 16.6%; the average oil saturation of the original method is 72.9%, that of the new method with the crude oil mass constraint is 73.4%, and that of the new method with the crude oil volume constraint is 73.2%; the average crude oil volume factor of the original method is 1.023, that of the new method with the crude oil mass constraint is 1.020, and that of the new method with the crude oil volume constraint is 1.021 (Table 5). Since the all-factor average method considers more comprehensive factors in calculation, each new averaging parameter should be much more representative.

At present, the characteristic of each average parameter calculated is that the error between the volume reserves calculated by combination 1 (A, $\overline{h_1}$, $\overline{\varnothing_1}$, $\overline{S_{o1}}$, $\overline{B_{o1}}$, $\overline{\rho_{oa}}$, $\overline{R_{sia}}$) and the volume reserves sum of each unit is zero; the error between the mass reserves calculated using combination 2 (A, $\overline{h_2}$, $\overline{\varnothing_2}$, $\overline{S_{o2}}$, $\overline{B_{o2}}$, $\overline{\rho_{oa}}$, $\overline{R_{sia}}$) and the sum of mass reserves of each unit is zero. It can be seen from Table 2 that the average net pay thickness $\overline{h_1}$ and $\overline{h_2}$, effective porosity $\overline{\varnothing_1}$ and $\overline{\varnothing_2}$, oil saturation $\overline{S_{o1}}$ and $\overline{S_{o2}}$, and crude oil volume factor $\overline{B_{o1}}$ and $\overline{B_{o2}}$ calculated using the all-factor average method are not always the same, since the current reserve calculation specification requires that certain decimal places be reserved for each parameter. For examples, the oil area is two decimal places, the net pay thickness is one decimal place, the effective porosity is three decimal places, the oil saturation is three decimal places, the crude oil volume factor is three decimal places, the crude oil density is three decimal places, and the dissolved gas–oil ratio is rounded [14]. In this way, the average value of reserve parameters after retaining certain decimal places will inevitably lead to more or less carry errors in the final calculation of crude oil volume and mass reserves (Tables 4 and 5).

Table 1. Reserve parameters of xx1 block.

Unit	Oil-Bearing Area km^2	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Density t/m^3	Crude Oil Volume Factor	Crude Oil Reserves in Volume 10^4 m^3	Crude Oil Reserves in Mass 10^4 t
1	1.15	3.0	34.0	55.0	0.848	1.300	49.6269230769231	42.0836307692308
2	1.65	5.0	32.0	60.0	0.848	1.300	121.846153846154	103.325538461538
3	2.25	4.5	25.0	62.0	0.870	1.250	125.55	109.2285
4	3.11	7.0	24.0	65.0	0.874	1.240	273.88064516129	239.371683870968
5	2.80	6.5	22.0	68.0	0.878	1.230	221.359349593496	194.353508943089
Total items	5.00						792.263071677863 (the total)	688.362862044826 (the total)

Table 2. Comparison of the application of the all-factor average method and original average method in xx1 block.

Average Method	Oil-Bearing Area km^2	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Density t/m^3	Crude Oil Volume Factor	Crude Oil Reserves in Volume 10^4 m^3	Crude Oil Reserves in Mass 10^4 t	Absolute Error in Volume 10^4 m^3	Absolute Error in Mass 10^4 t
Original [1]	5.00	12.359	25.2011489602719	63.6828688021935	0.868856427432625	1.25177675882291	792.263071677863	688.362862044826	0	0
All-factor average method (Mass constraint)	5.00	12.4820381877236	24.90108752874	63.7976714236979	0.868856427432625	1.25143771766104	792.263071677863	688.362862044826	0	0
All-factor average method (Volume constraint)	5.00	12.472952135769	24.9431197701869	63.7538278148721	0.868856427432625	1.25177675882291	792.263071677863	688.362862044826	0	0

Table 3. Comparison of the application of the all-factor average method and original average method in xx2 block.

Unit	Oil-Bearing Area km^2	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Density t/m^3	Crude Oil Volume Factor	Crude Oil Reserves in Volume 10^4 m^3	Crude Oil Reserves in Mass 10^4 t
1	5.00	5.0	25.0	75.0	0.900	1.010	464.108910891089	417.69801980198
2	2.50	10.0	3.0	55.0	0.800	1.200	34.375	27.5
Total items	5.00						498.483910891089 (the total)	445.19801980198 (the total)
Original [1]	5.00	10.0	14.0	72.8571428571429	0.893104090373037	1.02310222829123	498.483910891089	445.19801980198
All-factor average method (Mass constraint)	5.00	8.05706813550352	17.2059948979592	73.352365415987	0.893104090373037	1.01997565986699	498.483910891089	445.19801980198
All-factor average method (Volume constraint)	5.00	8.38038009403774	16.6035726554449	73.1653042688465	0.893104090373037	1.02114944428204	498.483910891089	445.19801980198

Table 4. Carry error comparison between the all-factor average method and the original average method in xx1 Block.

Average Method	Oil-Bearing Area km^2	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Density t/m^3	Crude Oil Volume Factor	Crude Oil Reserves in Volume 10^4 m^3	Crude Oil Reserves in Mass 10^4 t	Absolute Error in Volume 10^4 m^3	Absolute Error in Mass 10^4 t
Total items	5.00						792.27 (The total)	688.36 (The total)		
Original [1]	5.00	12.4	25.2	63.7	0.869	1.252	794.93	690.79	2.66	2.43
All-factor average method (Mass constraint)	5.00	12.5	24.9	63.8	0.869	1.251	793.68	689.70	1.41	1.34
All-factor average method (Volume constraint)	5.00	12.5	24.9	63.8	0.869	1.252	793.04	689.15	0.77	0.79

Table 5. Carry error comparison between the all-factor average method and the original average method in xx2 Block.

Average Method	Oil-Bearing Area km^2	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Density t/m^3	Crude Oil Volume Factor	Crude Oil Reserves in Volume 10^4 m^3	Crude Oil Reserves in Mass 10^4 t	Absolute Error in Volume 10^4 m^3	Absolute Error in Mass 10^4 t
Total items	5.00						498.49 (The total)	445.20 (The total)		
Original [1]	5.00	10.0	14.0	72.9	0.893	1.023	498.83	445.45	0.34	0.25
All-factor average method (Mass constraint)	5.00	8.1	17.2	73.4	0.893	1.020	501.28	447.64	2.79	2.44
All-factor average method (Volume constraint)	5.00	8.4	16.6	73.2	0.893	1.021	499.85	446.37	1.36	1.17

3. Method to Reduce Carry Error

3.1. Full Permutation Combination Selection Method (Figure 3)

Here, in order to evaluate the error degree as reasonably as possible, the relative error is chosen. In this paper, a simple method of full permutation combination selection to reduce carry error is adopted. Firstly, these parameters are discretized according to the minimum unit step within their respective variation ranges; then, a set of parameters is selected via full permutation combination to minimize the sum of squared relative errors of crude oil volume and mass reserves. The relative error of volume reserves and mass reserves calculated using this set of parameters reaches a relatively small and balanced state, thus achieving the purpose of reducing the carry error relatively well [13].

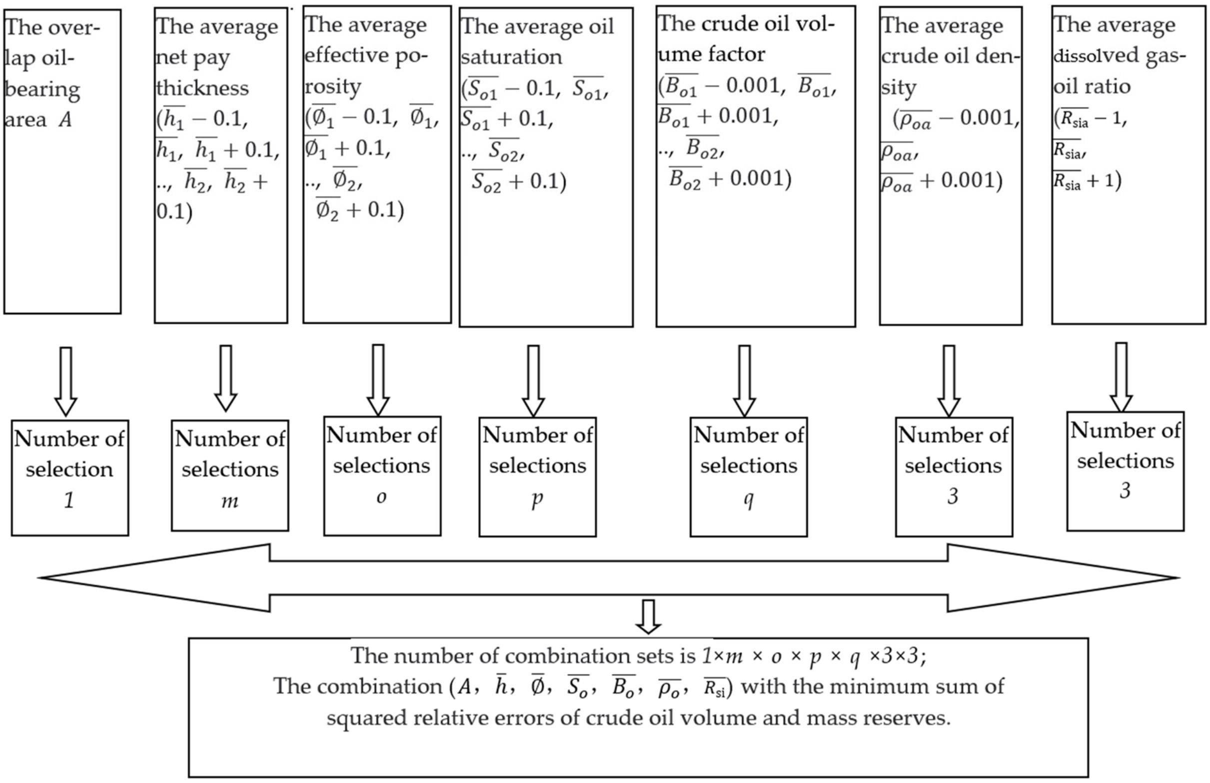

Figure 3. Operation steps of full permutation combination selection method.

3.2. Operation Steps to Reduce Carry Error

1. The oil-bearing area of the total items is the superimposed oil-bearing area A of the area A_i of each calculation unit.

2. The number of selections of the average net pay thickness is m (assuming $\overline{h_2} > \overline{h_1}$)

$m = 10\left[\left(\overline{h_2}+0.1\right)-\left(\overline{h_1}-0.1\right)\right]$ (the constraint condition is $\overline{h} \geq h_{min}$)

m—number of selections for average net pay thickness, an integer;

h_{min}—the minimum net pay thickness of all units, m.

3. The number of selections of average effective porosity is o (assuming $\overline{\varnothing_2} > \overline{\varnothing_1}$)

$o = 10[(\overline{\varnothing_2}+0.1)-(\overline{\varnothing_1}-0.1)]$ (the constraint condition is $\varnothing_{max} \geq \overline{\varnothing} \geq \varnothing_{min}$)

o—number of selections for average effective porosity, an integer;

$\varnothing_{max}$—the maximum effective porosity of all units, %;

$\varnothing_{min}$—the minimum effective porosity of all units, %.

4. The number of selections of average oil saturation is p (assuming $\overline{S_{o2}} > \overline{S_{o1}}$)

$p = 10\left[\left(\overline{S_{o2}}+0.1\right)-\left(\overline{S_{o1}}-0.1\right)\right]$ (the constraint condition is $S_{oimax} \geq \overline{S_o} \geq S_{oimin}$)

p—number of selections for average oil saturation, an integer;

S_{oimax}—the maximum oil saturation of all units, %;

S_{oimin}—the minimum oil saturation of all units, %.

5. The number of selections of crude oil volume factor is q (assuming $\overline{B_{o2}} > \overline{B_{o1}}$)

$q = 1000\left[\left(\overline{B_{o2}} + 0.001\right) - \left(\overline{B_{o1}} - 0.001\right)\right]$ (the constraint condition is $B_{oimax} \geq \overline{B_o} \geq B_{oimin}$)

q—number of selections for average crude oil volume factor, an integer;

B_{oimax}—the maximum crude oil volume factor of all units, f;

B_{oimin}—the minimum crude oil volume factor of all units, f.

6. There are 3 selections for average crude oil density.

$\overline{\rho_{oa}} - 0.001$, $\overline{\rho_{oa}}$, $\overline{\rho_{oa}} + 0.001$ (the constraint condition is $\rho_{oimax} \geq \overline{\rho_o} \geq \rho_{oimin}$)

ρ_{oimax}—the maximum crude oil density of all units, t/m^3;

ρ_{oimin}—the minimum crude oil density of all units, t/m^3.

7. There are 3 selections for the average dissolved gas–oil ratio.

$\overline{R_{\text{sia}}} - 1$, $\overline{R_{\text{sia}}}$, $\overline{R_{\text{sia}}} + 1$ (the constraint condition is $R_{simax} \geq \overline{R_{\text{si}}} \geq R_{simin}$) R_{simax}—the maximum dissolved gas–oil ratio of all units, m^3/m^3, an integer;

R_{simin}—the minimum dissolved gas–oil ratio of all units, m^3/m^3, an integer.

All parameters are combined with full permutation. The number of combination sets is $1 \times m \times o \times p \times q \times 3 \times 3$ (Figure 3). The optimal parameter combination (A, $\overline{h}$, $\overline{\varnothing}$, $\overline{S_o}$, $\overline{B_o}$, $\overline{\rho_o}$, $\overline{R_{\text{si}}}$) is finally selected as the parameter combination with the minimum sum of squared relative errors of crude oil volume and mass reserves.

One example, xx1 Block, shows that the new method can effectively reduce the carry error compared with the original method [1]. The volume relative error of the original method is 0.34% and that of the new one is reduced to 0.01%. The relative mass error of the original method is 0.35% and that of the new one is reduced to 0.03% (Table 6). The other example, xx2 Block, shows that the new method can also effectively reduce the carry error compared with the original method. The volume relative error of the original method is 0.07% and that of the new one is reduced to −0.01%. The relative mass error of the original method is 0.06% and that of the new one is reduced to −0.03% (Table 7)

Table 6. Comparison of the application results of the all-factor average method and the original average method in xx1 Block.

Average Method	Oil-Bearing Area km^2	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Volume Factor	Crude Oil Density t/m^3	Oil Reserves		Absolute Error in Volume 10^4 m^3	Absolute Error in Mass 10^4 t	Relative Error in Volume %	Relative Error in Mass %
							In Volume 10^4 m^3	In Mass 10^4 t				
Total items	5.00						792.27 (the total)	688.36 (the total)				
The Original average method [1]	5.00	12.4	25.2	63.7	1.252	0.869	794.93	690.79	2.66	2.43	0.34	0.35
All-factor average method	5.00	12.5	24.8	63.9	1.250	0.869	792.36	688.56	0.09	0.20	0.01	0.03

Table 7. Comparison of the application results of the all-factor average method and the original average method in xx2 Block.

Average Method	Oil-Bearing Area km²	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Volume Factor	Crude Oil Density t/m³	Oil Reserves		Absolute Error in Volume 10^4 m³	Absolute Error in Mass 10^4t	Relative Error in Volume %	Relative Error in Mass %
							In Volume 10^4 m³	In Mass 10^4 t				
Total items	5.00						498.49 (The total)	445.20 (The total)				
The Original average method [1]	5.00	10.0	14.0	72.9	1.023	0.893	498.83	445.45	0.34	0.25	0.07	0.06
All-factor average method	5.00	8.3	16.7	73.5	1.022	0.893	498.43	445.09	−0.06	−0.11	−0.01	−0.03

4. Discussion

Compared with the original method [1], the all-factor average method considers more comprehensive factors to calculate the average parameters of the total items. The calculation results should be relatively more representative. The full permutation combination selection method can also more effectively reduce the carry error. Both the all-factor average method of reserve parameters with crude oil volume and mass constraints and the full permutation combination selection method have certain popularization and application value.

Some suggestions are given for further research. The new all-factor average method of parameters with crude oil volume and mass constraints can be further optimized and improved in the subsequent actual reserve estimation. Some experiments can also be carried out to test the applicability of the new method.

5. Conclusions

5.1. The All-Factor Parameter Average Method

The all-factor parameter average method of reserve parameters proposed in this paper adopts the two constraint methods of crude oil volume and mass to calculate the parameters of the total items. The weight coefficient when the parameter is averaged is, respectively, the partial derivative of the volume or mass reserve calculation formula with respect to the parameter. Compared with the original calculation results, the average value of each reserve parameter is different from the original calculation [1] results, except for oil-bearing area and crude oil density. The average of their parameters all show a shift towards values with a significant share of reserves, such as effective porosity, oil saturation, and crude oil volume factor in the second example. This can easily be seen in the second example, where the parameters differ considerably. The average effective porosity of the original method is 14.0%, that of the new method with the crude oil mass constraint is 17.2%, and that of the new method with the crude oil volume constraint is 16.6%; the average oil saturation of the original method is 72.9%, that of the new method with the crude oil mass constraint is 73.4%, and that of the new method with the crude oil volume constraint is 73.2%; the average crude oil volume factor of the original method is 1.023, that of the new method with the crude oil mass constraint is 1.020, and that of the new method with the crude oil volume constraint is 1.021 (Table 5). Since the all-factor average method considers more comprehensive factors to calculate the average parameters of the total items, the calculation results should be relatively more representative.

5.2. The Full Permutation Combination Selection Method

In order to reduce the carry error, the average parameter values are firstly discretized according to the minimum unit step within their variation range; then, a set of parameters that minimizes the sum of squared relative errors of crude oil volume and crude oil mass reserves is selected by the full permutation combination selection method [13]. This set of parameters is the selection of the optimal reserve parameter average term (Tables 8 and 9). Two tests show that this method can effectively reduce the carry error. One example, xx1 Block, shows that the volume relative error of the original method is 0.34% and that of the new one is reduced to 0.01%; the relative mass error of the original method is 0.35% and that of the new one is reduced to 0.03% (Table 6). The other example, xx2 Block, shows that the volume relative error of the original method is 0.07% and that of the new one is reduced to −0.01%; the relative mass error of the original method is 0.06% and that of the new one is reduced to −0.03% (Table 7).

Table 8. The final results table of reserve parameters of xx1 block.

Unit	Oil-Bearing Area km^2	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Density t/m^3	Crude Oil Volume Factor	Crude Oil Reserves in Volume 10^4 m^3	Crude Oil Reserves in Mass 10^4 t
1	1.15	3.0	34.0	55.0	0.848	1.300	49.63	42.08
2	1.65	5.0	32.0	60.0	0.848	1.300	121.85	103.33
3	2.25	4.5	25.0	62.0	0.870	1.250	125.55	109.23
4	3.11	7.0	24.0	65.0	0.874	1.240	273.88	239.37
5	2.80	6.5	22.0	68.0	0.878	1.230	221.36	194.35
Total items	5.00	12.5	24.8	63.9	0.869	1.250	792.27	688.36

Table 9. The final results table of reserve parameters of xx2 block.

Unit	Oil-Bearing Area km^2	Net Pay Thickness m	Effective Porosity %	Oil Saturation %	Crude Oil Density t/m^3	Crude Oil Volume Factor	Crude Oil Reserves in Volume 10^4 m^3	Crude Oil Reserves in Mass 10^4 t
1	5.00	5.0	25.0	75.0	0.900	1.010	464.11	417.70
2	2.50	10.0	3.0	55.0	0.800	1.200	34.38	27.50
Total items	5.00	8.3	16.7	73.5	0.893	1.022	498.49	445.20

Author Contributions: Methodology, D.Z.; Software, C.C.; Writing—original draft, D.Z.; Writing—Review & Editing, H.G., Y.W. (Yuyan Wu), A.L., J.Z. and Y.W. (Yonggang Wang). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Where data is unavailable due to privacy or ethical restrictions.

Acknowledgments: During the completion of this paper, Rui Deng and Cuiqiong Guan put forward reasonable suggestions and I would like to hereby express my special thanks. I also thank the anonymous reviewers for their valuable comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yang, T.; Fan, S.; Chen, Y.; Hu, Y.; Wu, Q. *Calculation Method of Petroleum and Natural Gas Reserves*, 2nd ed.; Petroleum Industry Press: Beijing, China, 1998; pp. 109–114.
2. Chen, G. Logging reserve calculation method for carbonate gas reservoir. *Well Logging Technol.* **1987**, *11*, 1–12. [CrossRef]
3. Xiong, Q.; Wang, Z.; Cai, Y.; Wang, H.; Zhao, Y. Methods and Techniques of Petroleum Reserves Calculation for Heterogeneous Oil Field. *Geol. Rev.* **1996**, *42*, 296–301. [CrossRef]
4. Wang, T. The Determination of Reserves Parameters of Jurassic and Triassic in Baihe Oil Region in the Ordos Basin. Master's Thesis, Xi'an Shiyou University, Xi'an, China, 6 June 2014; pp. 61–64. [CrossRef]

5. Yan, G.; Liu, Z.; Song, H.; Han, X.; Wang, X. Effect of Vertical Subdivision of Computing Units on Reserve Parameters and Results of Multilayer Structural Reservoir. *Geol. Resour.* **2020**, *29*, 342–350. [CrossRef]
6. Lei, Q.; Song, Z.; Tang, C.; Li, N. On Reserve Estimate of Heterogeneous Reservoir in the Lower Es_3 of Block Shen-84. *Well Logging Technol.* **2000**, *24*, 47–51. [CrossRef]
7. Deng, P. *Research and Application "SEC Estimation Approach for Oil&Gas Reserves" in China*; China University of Geosciences: Beijing, China, 2006; pp. 95–103.
8. Zhang, D.; Chen, C. Application of Excel Subroutine in Statistics of Reserves Parameters. *Well Logging Technol.* **2006**, *30*, 541–543. [CrossRef]
9. Ma, Y. Study on OOIP Calculation of Heterogeneous Reservoirs Using Volumetric Method. *Sci. Technol. Eng.* **2011**, *11*, 3540–3542. [CrossRef]
10. Wang, J. A Study on Evaluation of the Oil Reserves in Anding Zichang. Master's Thesis, Xi'an Shiyou University, Xi'an, China, 20 May 2012; pp. 27–30. [CrossRef]
11. Guo, X. Study on calculation method of lithologic reservoir reserve parameters of Chang 2 Member of Yanchang Formation in Xigou Oilfield. *Inn. Mong. Petrochem. Ind.* **2009**, *4*, 178–190.
12. Jiang, W.; Mo, R.; Zhang, Y.; Fu, C. Improved Voronoi diagram for optimizing the calculation of oil and gas reserves parameter. *Complex Hydrocarb. Reserv.* **2013**, *6*, 7–9. [CrossRef]
13. Zhang, D.; Chen, C.; Geng, B.; Su, C.; Song, X.; Wang, Y.; Li, Y.; Fang, L.; Qin, D.; Zhai, X.; et al. Study on modified averaging method of reserves parameters. *J. Yangtze Univ. Nat. Sci. Ed. Sci. Eng.* **2012**, *9*, 61–64.
14. *DZ/T 0217-2020*; Regulation of Petroleum Reserves Estimation. Geological and Mineral Industry Standards of the People's Republic of China; Ministry of Natural Resources of the People's Republic of China: Beijing, China, 2020.