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Research on Evaluation Method of Natural Gas Hydrate Resources Based on Probability Distribution Model

Zhetong Zhao[#, *], Yiwei Huang[#], Haoyu Wang[#]

School of Big Data, Qingdao Huanghai University, Qingdao, 266420, China
[*]Corresponding author: limlinker@163.com
[#]These authors contributed equally.

Abstract: Natural gas hydrate, as a highly efficient and clean energy source, has garnered significant attention from both developed and energy-deficient nations. However, to achieve industrial application, several technical challenges must be addressed, including resource exploration, spatial positioning, resource assessment, economic production evaluation, and climate change impact assessment. Currently, our exploration and evaluation system for gas hydrate resources remains immature. This study aims to determine the probability distribution of effective thickness, porosity, and saturation of natural gas hydrate resource parameters in the study area and their variations. Utilizing probability statistics theory, we calculated specific values for all gas hydrate resource parameters from open-source data of 14 exploration well locations, determined their probability distributions, and conducted distribution detection to identify specific distributions. Data analysis was performed using linear graphs and bar charts to summarize patterns. Subsequently, by applying the mathematical formula $Q = A \times Z \times \varnothing \times S \times E$, we categorized natural gas hydrate resource parameters, calculated gas hydrate resources at each effective depth, determined the probability distribution of each obtained data point, and ultimately solved for the total natural gas hydrate resources, yielding a final solution of 31875763695.08.

Keywords: Natural Gas Hydrate, Probability Distribution, Kernel Density Function.

1. Introduction

Natural gas hydrate, also known as "combustible ice" [1-2], is an ice-like crystalline substance formed by natural gas and water under high pressure and low temperature, widely distributed in deep-sea or terrestrial permafrost. As a potential clean energy, it has received much attention from the international community because of its huge reserves and low combustion pollution.

Liu Changling [3] believes that to accurately evaluate the amount of gas hydrate resources, it is necessary to understand the reservoir characteristics, which are mainly affected by the hydrate content and occurrence form, and the latter is controlled by the nature of Marine sediments. In view of the shortage of existing methods, a new method of "detailed evaluation of resources" and "detailed evaluation of resources" is proposed.

The scholars' model adopts a multidisciplinary approach to improve the accuracy of gas hydrate resource evaluation. However, few mathematical resource assessment methods have been proposed to calculate the probability distribution of gas hydrate resources in each layer by calculating the effective thickness and the probability distribution of gas hydrate saturation and porosity in each layer, using the volume method to calculate the gas hydrate resources in each layer, and then adding the resources in all layers to obtain the probability distribution of gas hydrate resources.

Based on this, this paper proposes a method model of resource reserve evaluation based on probability distribution model and reservoir forming method. This innovation is mainly reflected in the following aspects: First, the probability distribution model is innovatively applied to the assessment of natural gas hydrate resources, which improves the accuracy and reliability of resource calculation; Secondly, by considering the effective thickness, saturation, porosity and other factors of natural gas hydrate, the comprehensive evaluation of resources is realized. Finally, this study is expected to establish a more perfect and scientific evaluation method system for gas hydrate resources, which will provide theoretical support and guidance for the future evaluation of gas hydrate resources.

2. Variation of Natural Gas Hydrate Resource Parameters

2.1. Source and processing of data

The data in this paper are from: The 9th Mathematical Modeling Challenge for College Students in 2024 - Mathematical Modeling for Mathematical Cups (nmmcm.org.cn)

The data contains:

Table 1. Drilling Survey Data (Part)

Well name	Depth	Porosity	Hydrate saturation
W01	1814.9316	-9999	-9999
W01	1824.0756	0.7486	-9999
W01	1832.3052	0.5196	0
W01	1832.0004	0.5236	0.0237
W01	1834.134	0.506	0.0049
W01	1834.2864	0.5021	0.0116
W01	1834.4388	0.4834	0.0228
W02	1839.9252	0.4843	0.0083
......	......	......	......
W14	2021.8908	0.4069	0.0316

Table 2. Well Location Information (part)

Well name	*X*	*Y*
W01	34500	45000
W02	36000	45050
W03	37050	45020
W04	37880	46000
......	......	......
W14	35800	49900

Table 1 shows the values of porosity and hydrate saturation corresponding to the different depths of each exploration well location, and Table 2 shows the coordinates of each exploration well location. Due to the existence of abnormal values in the data, the data with partial anomaly of porosity and partial anomaly of hydrate saturation were removed in this paper, and the characteristics of the data were extracted.

2.2. Establishment of model

As it involves determining the effective thickness of gas hydrate resources in the region, data processing is required. In this paper, the hydrate saturation data of each exploration well location is selected as a reference, and the depth difference corresponding to the hydrate saturation data of each section is taken as the effective thickness. Since the resulting values can be regarded as discrete, the empirical probability[5] method can be used to calculate the probability distribution by counting the number of different values in the array and then dividing by the total length of the array.

$$P(X = xi) = \frac{\text{count}(xi)}{N} \tag{1}$$

For calculating the probability distribution of formation porosity and saturation, this paper regards the relevant open source values given on the website as continuous, so the kernel density estimation (KDE) method can be used for processing[6]. KDE is a nonparametric method for estimating the probability density function of a random variable. It does this by placing a kernel function (such as a Gaussian kernel) on each data point, and then adding and normalizing these kernel functions to get a density estimate for the entire data set.

$$\hat{f}(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right) \tag{2}$$

Among them:

1. $\hat{f}(x)$ is the estimated probability density function.

2.*n* is the number of data points in the sample data.

3.*h* is the smoothing bandwidth (also known as core bandwidth or window width), which controls the amount of smoothing. The larger the value of h, the smoother the data.

4.*k* () is a kernel function, usually a non-negative function with an integral of 1 and a mean of 0, such as a Gaussian kernel.

5.*xi* is a data point in the sample data.

For the second problem, to determine the variation law of the effective thickness, formation porosity and saturation of natural gas hydrate resource parameters in the study area in the exploration area, this paper directly adopts the method of data visualization and intuitively obtains the law from the visual images.

Solution process:

1. The probability distribution of effective thickness Z is solved, and effective thickness is screened from the cleaned data. The main idea is to take a continuous non-zero part of the saturation of aqueous compounds in each exploration well location as an effective depth, subtract the initial depth of this section from the last depth of this section, and then obtain the effective thickness contained in each wellhead. After the effective thickness of each exploration well location is obtained, the probability distribution of this data is solved and visualized in Python software.

2. Solve the probability distribution of hydrate saturation S. In the data after data cleaning, calculate the hydrate saturation of each exploration well location, and use Python software to solve and visualize the probability distribution.

3. Solve the probability distribution of the porosity∅. After data cleaning, calculate the porosity of each exploration well location and use Python software to solve and visualize the probability distribution.

4. Carry out distribution detection on the probability distribution obtained above to test whether it is accepted with a certain distribution.

5. At last, the paper discusses the parameters of natural gas hydrate resources and their changes in the exploration area from both horizontal and vertical aspects. In the horizontal aspect, the relationship between the coordinates (*x,y*) of each exploration well location and each resource parameter is obtained by using a linear three-dimensional table. In the vertical aspect, the linear relationship between depth and each resource parameter is obtained by two-dimensional line chart and point chart, and expounded.

2.3. Result of Model

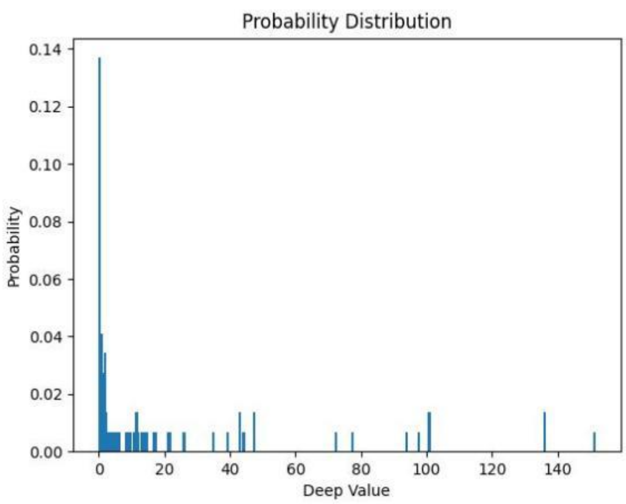


Figure 1. Probability distribution of effective thickness of natural gas hydrate resources

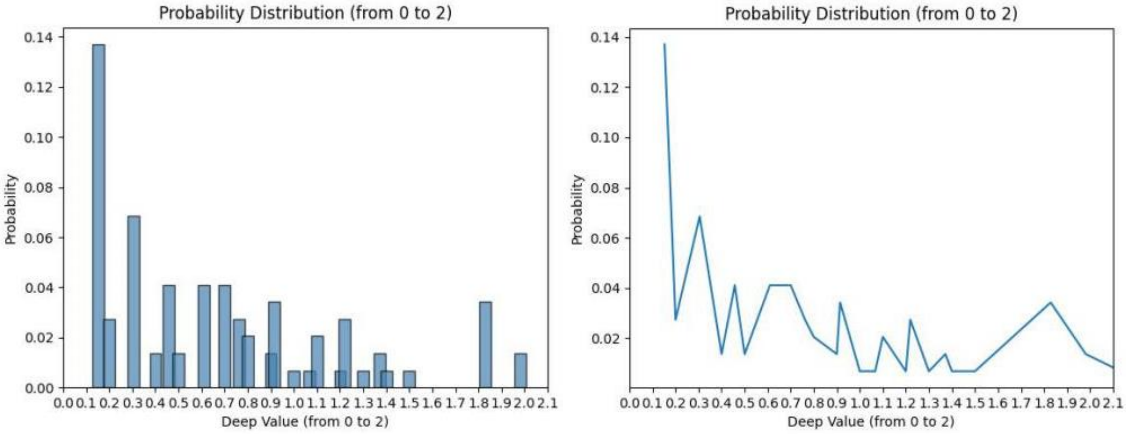


Figure 2. Probability distribution of effective thickness of natural gas hydrate resources (part 0-2)

Figure 1 is the probability distribution of the effective thickness of natural gas hydrate resources, due to this figure is more sparse does not have the research and significance, so only intercept the deep value of the more intensive part of the resulting Figure2, from the figure it can be seen that the probability distribution of the effective thickness of natural gas hydrate resources basically obeys the power law distribution.

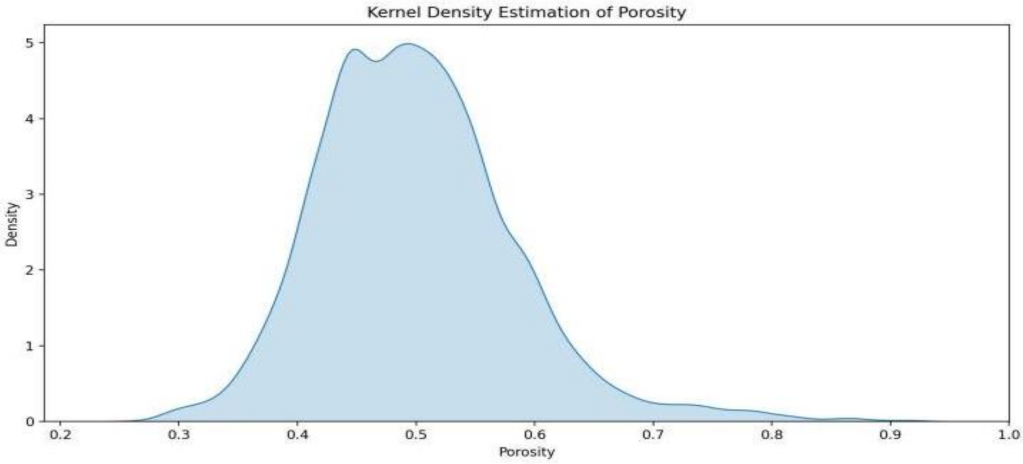


Figure 3. Probability distribution of formation porosity

Table 3. Detection of normal distribution of formation porosity

Name	Sample size	Mean value	Standard deviation	Skewness	Kurtosis
Interpolated Porosity	13415	0.500	0.083	0.766	1.625

As shown in Figure 3 and Table 3, the normal distribution of formation porosity is tested and it can be concluded that the sample has a partial peak, but the peak value and skewness are less than 10 and 3 respectively, which can basically be regarded as accepting the normal distribution.

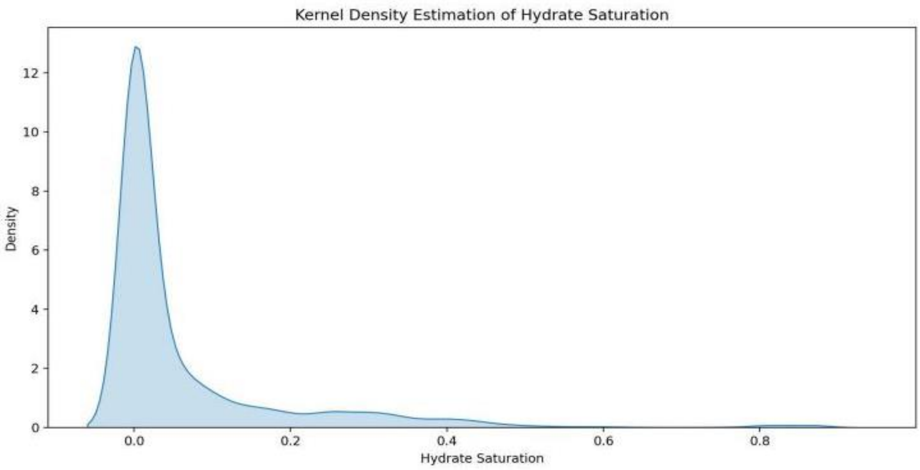
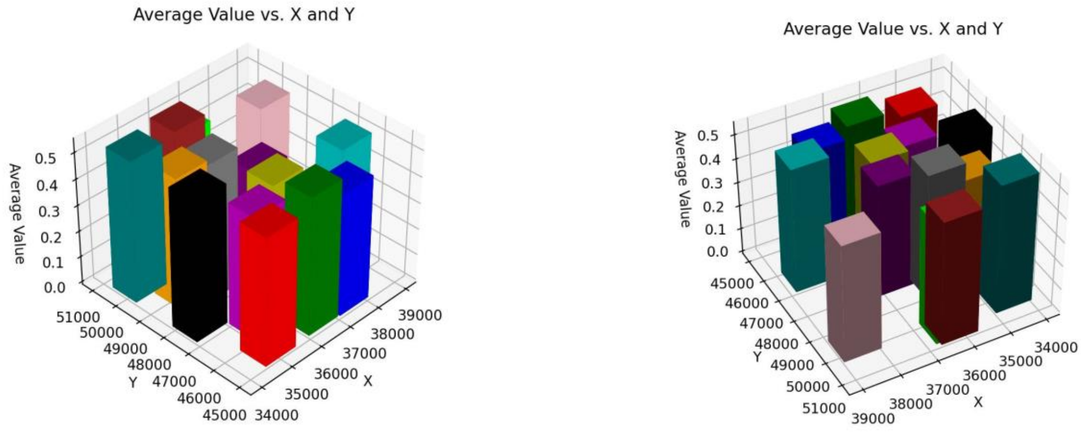


Figure 4. Probability distribution of gas hydrate saturation

As shown in Figure 4 and Table 3, the normal distribution of the saturation of aqueous compounds was tested.

The kurtosis and skewness of the samples are slightly greater than 3 and 10 respectively, so the normal distribution is not accepted.

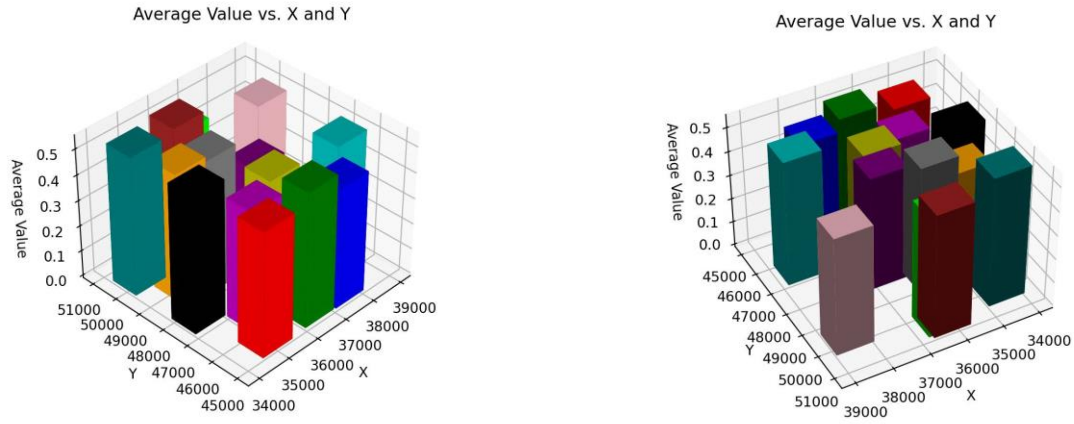
The law of effective thickness value: As shown in Figure 5, the effective thickness value changes with the change of location. Different coordinate points have different effective thickness values. The height of the bar chart represents the value of the average effective thickness, and it can be seen that the average effective thickness values of different coordinate points differ greatly. Based on the color mapping, it can be observed that there is no obvious linear relationship between the average effective thickness value and the position coordinates.



(a) (b)

Figure 5. The variation of effective thickness and its exploration area

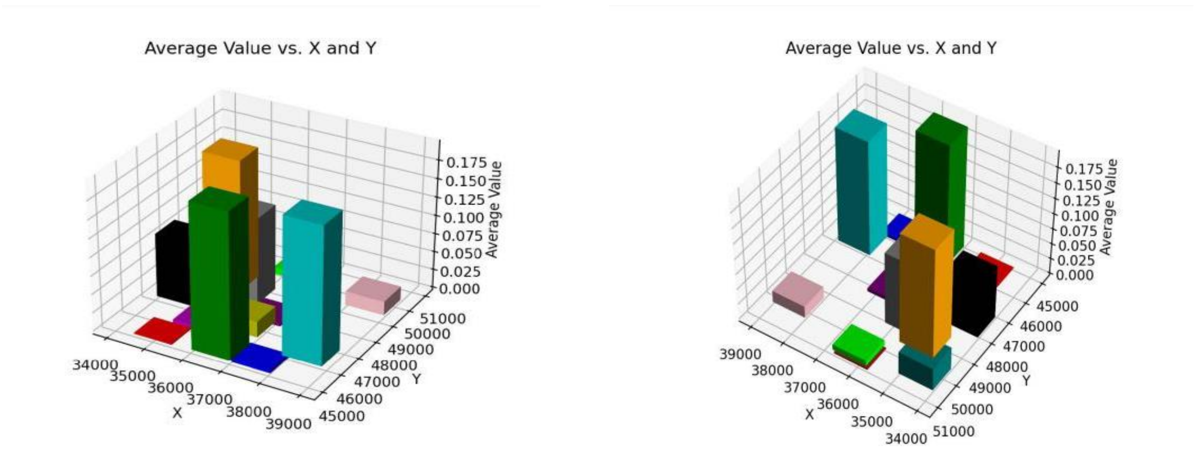
The law of porosity: As shown in Figure 6, (1) porosity changes with the change of x and y. There may be significant differences in porosity values at different locations. (2) There may be some spatial aggregation effect. That is, coordinate points that are adjacent or close to each other tend to have similar porosity values. (3) Some regions have higher porosity values, while others have lower porosity values. This may indicate that there are certain geological differences within the analyzed area or other factors that cause changes in porosity.



(a) (b)

Figure 6. The variation of porosity and its exploration area

The relationship between average hydrate saturation and depth is as follows: As shown in Figure 7, hydrate saturation is generally low, but peaks appear at some depth points, indicating that there may be hydrate enrichment layers at these depths. Uneven distribution: The uneven distribution of hydrate saturation indicates the complexity and localization characteristics of gas hydrate distribution.



(a) (b)

Figure 7. Average aqueous compound saturation and its variation in the exploration area

The law of effective thickness and depth: As shown in Figure 8, the relationship between the saturation of aqueous compounds and the depth is as follows: hydrate saturation is low on the whole, but peaks appear at some depth points, indicating that there may be hydrate enrichment layers at these depths. Uneven distribution: The uneven distribution of hydrate saturation indicates the complexity and localization characteristics of gas hydrate distribution.

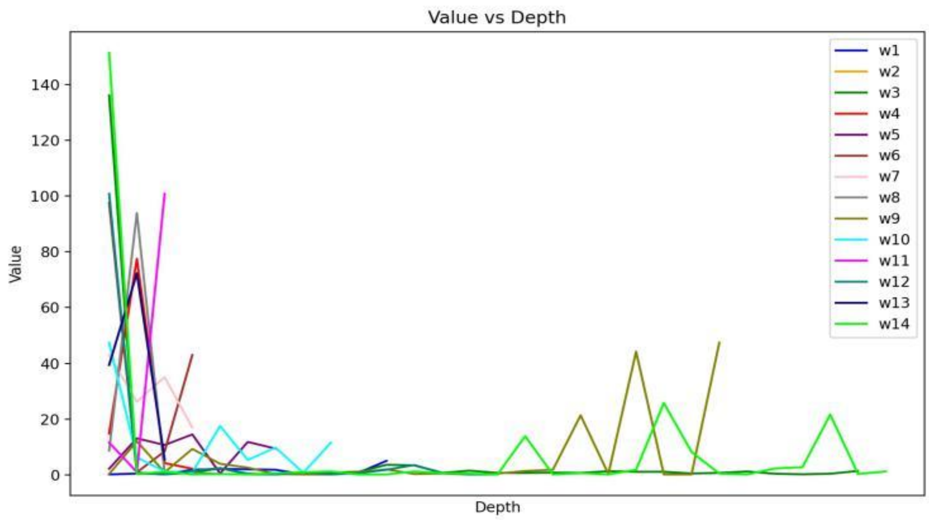


Figure 8. Relationship between porosity and depth

The law of hydrate saturation and depth: As shown in Figure 9, hydrate saturation is low on the whole, but peaks appear at some depth points, indicating that there may be hydrate enrichment layers at these depths. Uneven distribution: The uneven distribution of hydrate saturation indicates the complexity and localization characteristics of gas hydrate distribution.

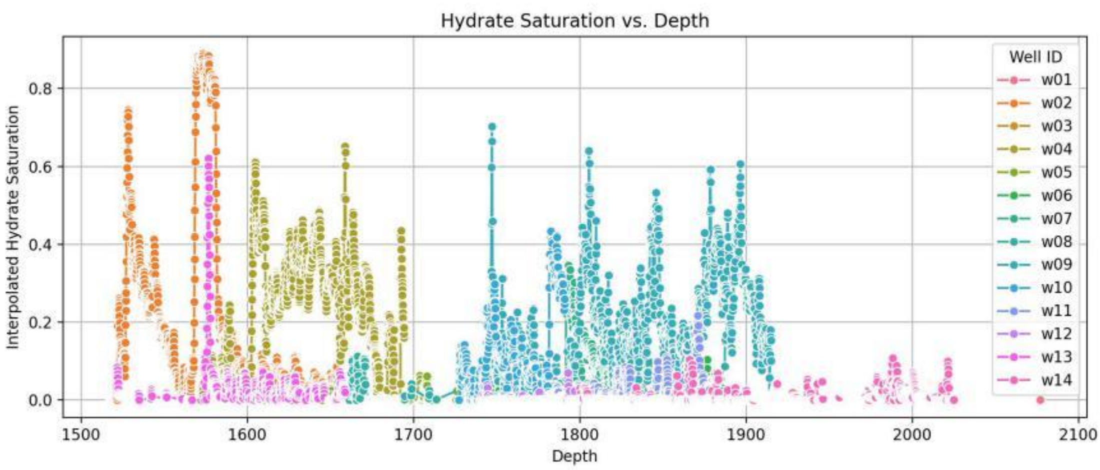


Figure 9. Relationship between aqueous compound saturation and depth

3. Probability Distribution and Estimation of Natural Gas Hydrate

3.1. Establishment of model

This part is similar to the idea in the previous part, both of which are probabilistic and statistical problems. Combined with the mathematical model $Q = A \times Z \times \varnothing \times S \times E$, the probability distribution of natural gas hydrate resources is obtained and the amount of natural gas hydrate resources Q is estimated:

1. A is the effective area. In this problem, the paper directly assumes that the effective area of each exploration well location is equal，then $A=S_A/N$.

2. Z is the effective thickness, and the effective thickness of each exploration well location can be obtained from the upper part.

3. $\varnothing$ is a degree. In this problem, since the required probability distribution of gas hydrate resources requires the porosity corresponding to the effective thickness of each section, but the value of the porosity changes according to the depth, the average porosity within the effective thickness interval is obtained as a parameter for calculation.

4. S is the hydrate saturation, which is similar to the principle of the porosity$\varnothing$, and can be solved in the same way.

5. E indicates a fixed gas production factor (value: 155).

After calculating these parameters, the amount of gas hydrate resources in each effective thickness interval can be calculated. The probability distribution of these values is solved and visualized. Finally, the accumulative sum of natural gas hydrate resources in each effective thickness interval is the required natural gas hydrate resources Q.

3.2. Results of the model

For the solution of the total natural gas hydrate resource Q, the final solution Q is 31875763695.08.As shown in Figure 10,11:

1. Most of the natural gas hydrate resources are concentrated in the range of 0-1e^9. It can be seen from the figure that most of the columnar bars are located in the small range of natural gas hydrate resource quantity, and the probability decreases with the increase of natural gas hydrate resource quantity.

2. The distribution of probability values of natural gas hydrate resources is not uniform: the probability height of natural gas hydrate resources is not uniform, and there are some fluctuations and differences. This indicates that the distribution of gas hydrate resources is not completely uniform, and there may be some specific patterns or trends.

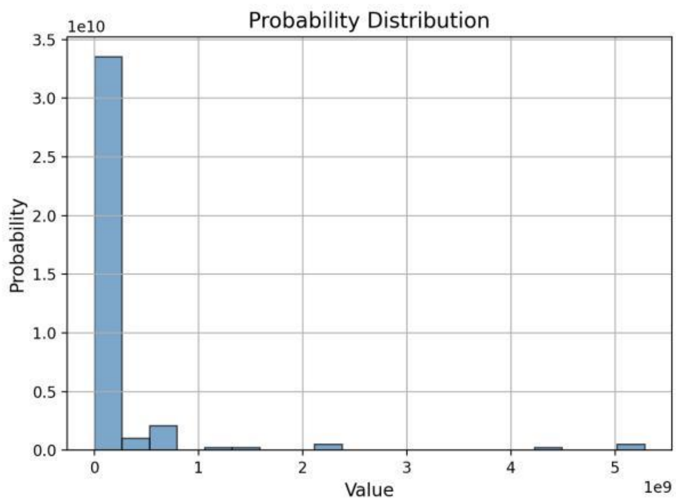


Figure 10. Probability distribution trend of total natural gas hydrate resources.

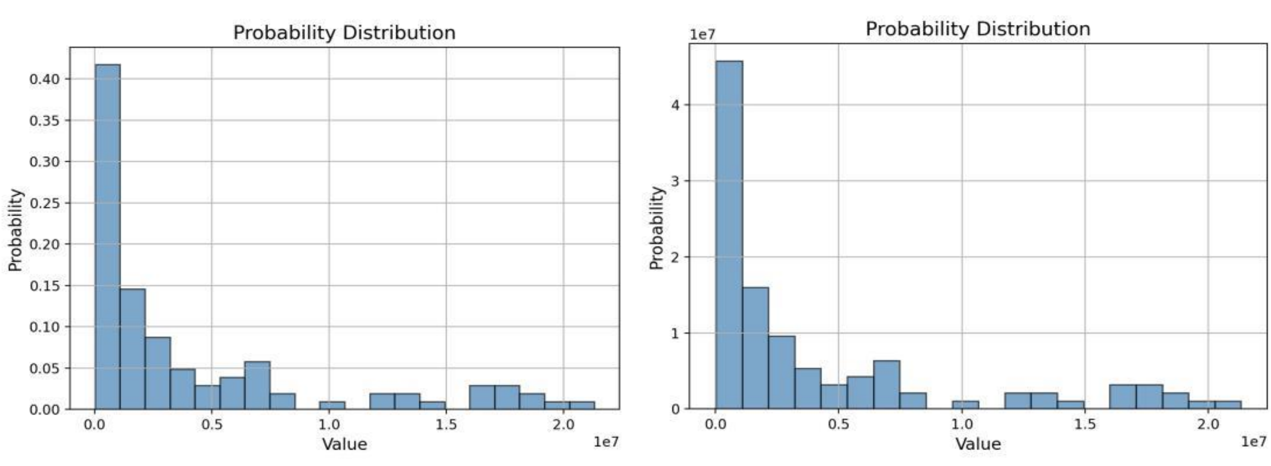


Figure 11. Probability distribution of gas hydrate resources in the interval 0-1e^9

4. Conclusion

This paper estimates the total natural gas hydrate resources Q to be 318,75763695.08 and draws two core conclusions: First, the resources are mainly concentrated in the range of 0 to 1 billion tons, with the probability of occurrence decreasing as resource quantity increases. Second, the probability distribution of resource quantity exhibits non-uniformity, indicating a potential specific distribution pattern or trend. However, there are errors in this paper mainly due to precision loss from rounding to four decimal places in data processing, potential deviations in kernel density estimation (KDE) when dealing with discontinuous distributions, outliers, or noise, and errors introduced during the discretization of empirical probability distributions. To enhance accuracy and reliability, it is recommended to use the quartile method to identify and process outliers, eliminate or correct abnormal data based on IQR, and divide quartiles before data discretization and KDE application to more accurately reflect data distribution characteristics and reduce errors. Furthermore, adjusting the empirical probability distribution using quartiles can optimize accuracy, especially in sparse data regions. Future directions may involve further refining these methods and exploring additional approaches to improve the accuracy and reliability of natural gas hydrate resource estimations.

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