STUDY ON VERTICAL DISTRIBUTION MODEL OF BACKSCATTER COEFFICIENT IN PETROLEUM-POLLUTED WATER BODIES

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ABSTRACT: In the field of water color remote sensing, the change of backscatter coefficient with water depth is one of the basic input parameters for the study of water optical properties. In-situ observational data measured in Dalian Port, Liaoning Province between August 25 and 27, 2018 are used. The data were measured at 3 observation stations, named site A, B, and C, respectively. A semi-empirical model of vertical variation of backscattering coefficient is established based on the vertical distribution theory of suspended load and the separation algorithm of backscattering coefficients. The empirical relationships between backscattering coefficient and suspended matter and between backscattering coefficient and the concentration of petroleum are also used in the derivation of the semi-empirical model. The vertical changing rate of backscattering coefficient is calculated from the model, and the variation characteristics of backscattering coefficient with depth are analyzed. The model is finally validated by analyzing the mean relative error and mean absolute error. The analysis shows the following results: (1) the relationship between backscattering coefficient and water depth is not an elementary function, but it is the sum of a natural exponential function and a complex natural exponential function. (2) In the surface layer, the vertical variation rates of backscattering coefficient at stations A and B are similar, indicating that in the surface layer the variation tendencies of suspended matter and petroleum concentration at the two stations are similar. The vertical changing rate of backscattering coefficient at station C is smaller than at the other two stations in the whole water column and stays stable at values slightly lower than 0.0005. This indicates that overall backscattering coefficient at station C varies uniformly. (3) The mean relative errors of the semi-empirical model for the 3 stations are 1.984, 0.282, and 0.349, respectively, and the mean absolute errors are 0.025, 0.006, and 0.005, respectively. This shows that the model has different accuracy at different locations. For station A, which is the closest to the coast, the accuracy is the lowest, the accuracy for station C is in the middle place, and the accuracy for station B is the best. This model, to some extent, lays the basis for studying the vertical heterogeneity of water bodies.

1. INTRODUCTION

As a non-renewable strategic resource, oil plays an important role in national economy and international relations. A certain scale of petrochemical bases has been formed in coastal, riverside and river regions all over the world. With oil leakage caused by oil tanker accidents and illegal discharge of ship waste oil or oily sewage, many watersheds in the world are facing severe oil pollution problems. When a large number of oil-containing pollutants enter the water body, they will change the original radiation transfer characteristics of the natural water body, thus affecting the ecological environment of the water body. The research on radiation transfer characteristics of petroleum contaminated water bodies has important application prospects for the construction of ecological civilization and environmental protection in watershed.

In the field of ocean color remote sensing, the study of water optical properties mainly includes two aspects: Inherent Optical Properties (IOPs) and Apparent Optical Properties (AOPs). Among them, the study of IOPs mainly involves absorption and scattering characteristics. In the scattering characteristics, the part whose scattering angle is greater than 90 degrees is called backscattering, which is one of the significant factors affecting the radiation transfer characteristics of water body. Previous studies have shown that suspended sediment, chlorophyll and CDOM (colored dissolved organic matter), also known as three key elements of ocean color, are the main factors affecting backscattering characteristics of water bodies. Throughout the research reports on the influence of three key factors of ocean color on backscattering coefficient, it can be seen that scholars have always considered suspended matter as an important factor affecting backscatter coefficient (Gallie et al. ,1992; Stramski et al. , 2004 ;Song,et al.,2006; Le, et al., 2009)

For petroleum contaminated water bodies, the petroleum substances in the water body without obvious oil film forming are regarded as a new ocean color factor. A series of studies have been carried out on the apparent and inherent optical properties of petroleum contaminated water bodies. The results obtained lay a solid foundation for the study of radiation transfer characteristics of petroleum contaminated water bodies. Huang et al. (2009) conducted a study on the backscattering coefficient characteristics of petroleum-contaminated water bodies using the rivers in Panjin City, Liaoning Province, China, as examples and the results show that the backscattering coefficient and suspended particles concentration are close to linear in waters containing petroleum pollution (Huang, et al., 2009). Song et al. (2010) studied the influence of petroleum concentration on the backscattering coefficient spectrum and found that the backscattering coefficient decreased with the increase of petroleum concentration. Huang et al. (2017) used quartz sand as a suspended particles and Oily water as petroleum to carry out oil sand mixing test. The results showed that petroleum adsorbed on the surface of suspended particles, increasing the particle size of the particles, resulting in an increase in the backscattering coefficient. Finally, a classification algorithm of backscattering coefficients is proposed. The backscattering coefficients of suspended matters and petroleum substances are separated from the backscattering coefficients of mixed water with petroleum and sands.

There are two stages in the study of vertical heterogeneity of water bodies. In the first stage, scholars mainly study the vertical distribution of water body components (Orton, et al.,2001. Zhang, et al., 2004 ;Pang, et al., 2009 ; Qiang, et al.,1983). Based on the study of the vertical optical characteristics of water body, scholars applied the vertical variation laws of optical characteristics such as absorption and scattering to the radiation transfer mode HydroLight, which made the underwater optical field simulation closer to the actual situation of water body, and then estimated the optical characteristics of water body from the model. At the same time, considering the scattering characteristics with wavelength and depth is the key part of studying the optical characteristics of petroleum-contaminated water by using the radiation transfer equation. The research on the vertical distribution characteristics of suspended matters (or suspended sediment) and chlorophyll in water components has been made. The progress is mainly focused on the use of turbulent diffusion theory to analyze the concentration of suspended matters and the vertical distribution characteristics of chlorophyll (He, 2014; Mobely.et al.2013). Some scholars have studied the effect of vertical distribution of water body composition on the inversion accuracy of remote sensing inversion algorithm and on the optical properties of water body, and established a related description model (Xiu, et al., 2008; Ma, et al., 2016; Stramska, et al.,2005; Liang, et al.,2017). There are also relevant studies on oil droplet composition in water, focusing mainly on the diffusion process of oil droplets under turbulence and the establishment of turbulent diffusion equation of oil particles based on turbulent diffusion theory (Murray, 1972; Zhao & Jiang, 1990).

A complete study has been conducted on the numerical simulation of the radiation characteristics of natural water body, and Hydrolight, a numerical simulation model of radiation transfer, has been developed. This numerical simulation model has been widely used in many aspects of the international ocean color remote sensing research field(Martin, et al., 2017; John et al.,2016), and has become an effective model for the research of the radiation transfer characteristics of petroleum contaminated water bodies. From the point of view and system of using radiation transfer equation to study the radiation transfer characteristics of petroleum contaminated water bodies, there are still some scientific problems to be solved for the apparent and inherent optical characteristics of petroleum contaminated water bodies. Water scattering characteristics vary with wavelength and depth. Considering the scattering characteristics varying with wavelength and depth is the key link in studying the optical characteristics of petroleum contaminated water bodies by using radiation transfer equation. The existing research results at home and abroad show that the absorption and scattering characteristics of petroleum contaminated water bodies mainly consider the change of wavelength, but not the change of depth. At present, the related research has not been carried out at home and abroad (Huang, et al., 2009 & 2017; Sun, et al., 2007; Snyder, et al., 2008).

This study is based on data from 3 observation stations, 30 observation times, and 5 observation depths in Dalian Port, Dalian, Liaoning Province from August 25-27, 2018. Combining the vertical distribution theory of suspended load, the separation algorithm of backscattering coefficient and the backward scattering coefficient with the empirical relationship between suspended matters and concentration of petroleum, the backscattering coefficient of petroleum water body is studied, its vertical variation law is discussed, and a parametric model is established. The research on the field of underwater light of petroleum water body lays the foundation and expands the research field of ocean color remote sensing.

2. METHOD

2.1 Study area and site distribution

The sea area of Dalian port in Liaoning province is selected as the research area. Three sites were selected, which is represented by A, B and C respectively. There was residual crude oil at site A because of oil pipeline explosions. Site B is located to the east of the crude oil berth, which is located in the shipping channel. Site C is on the edge of the island, and ships pass through it less often than the last two stations. The water depths of the three stations are 21.5 m, 24.8 m and 33.0 m respectively. And the corresponding observation dates are from 7:00 to 17:00 on August 25, 26 and 27, 2018. The samples were numbered according to the station number and time, so the sample number was composed of the station number and time number. The time number was recorded as 1 to 11 from 7:00 to 17:00, for example, the sample of 7:00 at station A was recorded as A1.

2.2 Measurement of backscattering coefficient

The backscatter coefficient measurement instrument is Hydroscat-6 (HS-6) of HOBI labs, USA (6 bands are 420, 442, 470, 510, 590 and 700nm respectively), and the measurement method is in accordance with The Technical Specification for Marine Optical Survey. Meanwhile, the placement depth of the instrument is adjusted according to the water depth of the station on the same day to avoid the instrument hitting the bottom. When placing the instrument, in order to balance the temperature between the instrument and the water body, reducing the influence of bubbles as much as possible, we soak the instrument in water first, and then let it stand for about 2 minutes before place it.

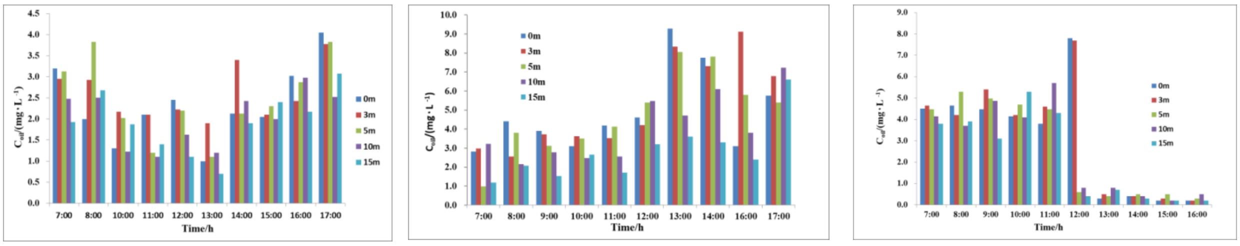
2.3 Measurement of petroleum concentration

The TD-500D Fluorescence Oil Meter (made by Turner Designs Hydrocarbon Instruments, Inc, USA), was used to determine petroleum concentration in water, the measuring principle of which is the molecular fluorescence spectrometric method, meeting The Specification For Marine Monitoring-Part 4: Seawater Analysis(GB 17378.4-2007) and The Water Quality Determination Of Petroleum Oil-Molecular Fluorescence Spectrometric Method(SL 366-2006).

3. RESULTS AND DISCUSSION

3.1 Temporal and spatial variation characteristics of oil concentration

Figure 1 shows the observed oil content for three days from August 25-27. It can be seen from the figure: (1) from the change of concentration, the oil content of site A is between 0.7-4.1 mg/L, the oil content of site B is between 1.0-9.3 mg/L, and the oil content of site C is between 0.2-7.8 mg/L. Among the three observation sites, the oil content of the B site is at a high value throughout the day. This shows that the sea area is a typical petroleum contaminated water bodies; (2) from the perspective of time change, the A site exhibits U-shaped variation characteristics; the change of the B site at different depths during the high tide was relatively stable. After the 11:00 ebb, the oil content at the depth of 0, 3, 5, and 10 m increased sharply, and the depth of 15 m did not change much. The oil content began to decrease after the tide stopped at 16:00; The C site changes smoothly from 7:00 to 11:00, and after a steep drop from 11:00 to 13:00, the oil content changes steadily from 13:00 to 16:00.



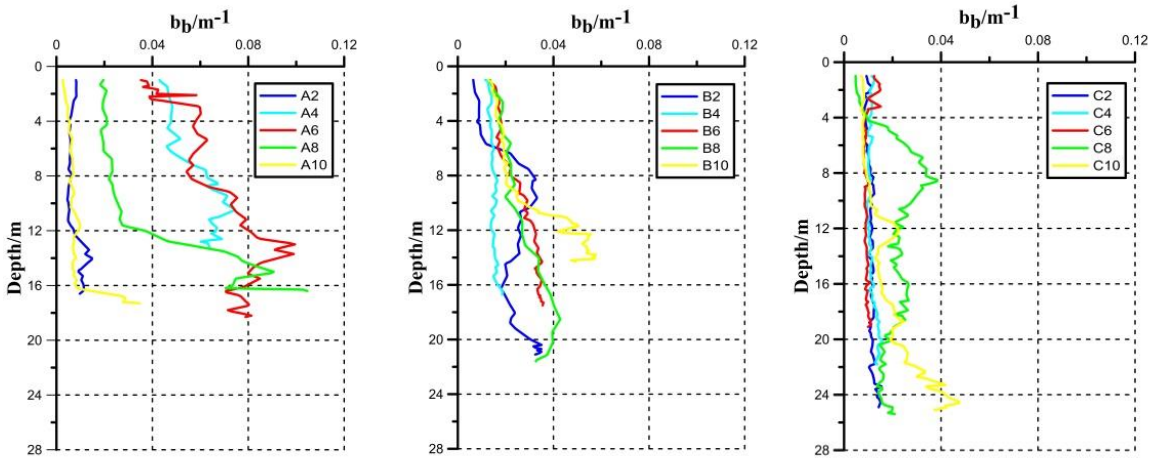
(a) Site A (b) Site B (c) Site C

Fig. 1 the time variation of petroleum concentration at different depths

3.2 Analysis of Vertical Variation Characteristics of Backscattering Coefficient

Previous studies have shown that the influence of petroleum substances on the scattering coefficient of water is mainly reflected by inorganic suspended matters. In the water with petroleum pollution, the backscattering coefficient and suspended matters concentration show a linear relationship model. The logarithmic model can be used to analyze the variation of backscattering coefficients with depth in oil-free water by changing the concentration of suspended matters.

Fig. 2 shows the curves of backscattering coefficients varying with depth at three stations. As can be seen from Figure 2, the curve of backscattering coefficient varying with depth has the following characteristics: (1) In most cases, the backscattering coefficient increases with the increase of depth, which indicates that the settling velocity of suspended matters is faster than the upward transport speed of hydrodynamic forces. (2) The depth at which the backscattering coefficient rises rapidly is mostly greater than 10 m, which indicates that suspended matters are mainly distributed in the water below 10 m. (3) Stations A4, B2, C8 and C10 have peaks at about 10 m, 8 m, 8-10 m and 12 m, respectively, and the difference between backscattering coefficients and mean values at depths of about 7 m, 6 m, 6 m and 10 m is almost greater than zero, indicating that there are more suspended matters in the water layer where the peak value appears, although it has decreased in the deeper layer, it is still higher than that in the shallower layer. There are more suspended solids in the aquifer, showing an upward trend as a whole. (4) The larger backscattering coefficients of stations A2, C4 and C6 are mainly in the water layers less than 5 m and larger than 12 m, but the magnitude of the three sets of data is small, the average value is only about 1 * 10-2, which indicates that the total suspended matter in the water body is less, and the suspended matter mainly distributes in shallow and bottom layers. The backscattering coefficient of station A2 increases rapidly after 12m. Even though the bottom suspended matter increases at this time, the bottom suspended matter concentration of station A2 is lower than other data. (5) Station A4 and A6 are higher than other data of station A. It shows that the concentration of suspended matters increases first and then decreases with time. The situation of C8 is the same, but the backscattering coefficient is not as high as that of A4 and A6. It shows that although the concentration of suspended matters of C8 reaches the maximum level observed on that day, it is not as high as that of A4 and A6. (6) On the whole, the backscattering coefficient of station A is the largest, station B is the second, and station C is the smallest, and the change range is also the largest, station B is the second, and station C is the smallest. This shows that the concentration of suspended matters in station A is high, and the degree of change is greater due to the environmental impact.



(a) Site A (b) Site B (c) Site C

Fig.2 Changing of backscatter coefficient with depth

3.3 Establishment of Vertical Variation Model of Backscattering Coefficient

3.3.1 Vertical Distribution Model of Suspended Load Concentration: In diffusion theory, the three-dimensional diffusion equation of suspended load motion is as follows:

$$\frac{\partial S}{\partial t}+\frac{\partial(uS)}{\partial x}+\frac{\partial(vS)}{\partial y}+\frac{\partial(wS)}{\partial z}=\frac{\partial(\omega S)}{\partial z}+\frac{\partial}{\partial x}\left(\varepsilon_{sx}\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_{sy}\frac{\partial S}{\partial y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_{sz}\frac{\partial S}{\partial z}\right) \quad (1)$$

where, *S* is suspended load concentration (mg/L), u, v and w are flow velocity (m/s) in three directions of x, y and z, and turbulent diffusion coefficients in three directions of ε_{sx}、 ε_{sy} and ε_{sz} are turbulent diffusion coefficients (m^2/s) in *x*, *y* and *z*, respectively, and ω is settling velocity of suspended load (m/s).

Because the diffusion of suspended load in horizontal direction is much smaller than that in vertical direction, the equation (1) is simplified under the assumption of two-dimensional constant uniform flow, and the following equation is obtained:

$$\frac{\partial}{\partial z}\left(\omega S+\varepsilon_{sz}\frac{\partial S}{\partial z}\right)=0 \quad (2)$$

After taking the integral, we get:

$$\omega S + \varepsilon_{sz}\frac{\partial S}{\partial z} = A \qquad (3)$$

Where, *A* is a constant. After reaching equilibrium, the amount of suspended sediment that rises due to the turbulent diffusion of water should be equal to the amount of suspended sediment that settles due to weight, so A should be zero. Then the vertical distribution model of suspended load concentration is obtained by solving the equation.

$$S（z） = S_a \times e^{-\frac{\omega}{\varepsilon_{sz}}(z-a)} \qquad (4)$$

In formula (4), S (z) is suspended load concentration (mg/L) at depth z, A is reference depth (m), Sa is suspended load concentration (mg/L) at depth a, and Z is depth (m).

By taking logarithm of the vertical distribution model of diffusion theory, the following forms are obtained:

$$ln\left(\frac{S(z)}{S_a}\right) = -\frac{\omega}{\varepsilon_{sz}}(z - a) \qquad (5)$$

Linear transformation was carried out to obtain the vertical distribution model of suspended matters concentration.

$$ln(S(z)) = m_0 + m_1 \times z \qquad (6)$$

In formula (6), h is depth (m), m0 and m1 are undetermined coefficients of vertical variation model of suspended solids concentration.

3.3.2 Vertical Distribution Model of Petroleum Concentration:

Without considering the adsorption of oil and suspended matters, Zhao et al. (1990) studied the diffusion of oil droplets based on turbulent diffusion theory, and obtained the vertical distribution model of oil droplets.

$$C(z,d) = C_a \times e^{-\frac{V}{D_z}(z-a)} \qquad (7)$$

In the formula, *a* is the reference depth (m), C_a is the oil concentration (mg/L) at the reference depth, D_z is the diffusion coefficient of oil droplets, *V* is the floating speed of oil droplets, and is a function of particle size. The relationship is as follows:

$$V = \frac{(\rho_w - \rho_o)gd^2}{18\eta_w} \qquad (8)$$

In the formula, ρ_w is the density of water (kg/m^3), ρ_o is the density of oil (kg/m^3), *d* is the diameter of oil droplets (m), and η_w is the viscosity coefficient of water (Pa • s).

The results are very similar to the vertical distribution model of suspended particles concentration based on turbulent diffusion theory, except that oil droplets are upward in diffusion direction. In this study, it is assumed that (1) the number of oil droplets with different particle sizes is the same in different water depths, (2) the effect of adsorption between oil droplets and suspended matters on the floating velocity of oil droplets can be neglected. Thus, the vertical distribution model of oil droplets is simplified by linear transformation, and the same form as the vertical distribution model of suspended solids concentration is obtained.

$$ln(C(z)) = n_0 + n_1 \times z \qquad （9）$$

In formula (7), n_0 and n_1 are the undetermined coefficients of the vertical variation model of petroleum concentration.

3.3.3 Relation Model of Total Backscattering Coefficient with Suspended Matters Concentration and Petroleum Concentration: the data obtained by backscattering coefficient measuring instrument HS-6 are the total backscatter coefficients of all particles. In petroleum water, the total backscattering coefficients include the contributions of suspended matters and petroleum substances. In the research of Huang et al. (2017), a backscattering coefficient separation algorithm is proposed. The empirical relationship between total backscattering coefficient and suspended sediment backscattering coefficient and oil backscattering coefficient is obtained:

$$b_{bs} = j_{bs}\, b_{bos} + k_{bs} \qquad (10)$$

$$b_{bo} = j_{bo}\, ln(b_{bos}) + k_{bo} \qquad (11)$$

In formula (10) and (11), b_{bos} is the total backscattering coefficient (m^{-1}), b_{bs} and b_{bo} are the backscatter coefficient (m^{-1}) of suspended sediment and petroleum substances, j_{bs} and k_{bs} are the undetermined coefficients of b_{bos} and b_{bs}

model, j_{bo} and k_{bo} are the undetermined coefficients of b_{bos} and b_{bo} model.

After sorting out the two formulas, the forms of total backscattering coefficients varying with suspended sediment backscattering coefficients and petroleum backscattering coefficients are obtained:

$$b_{bos} = a_0 b_{bs} + a_1 \tag{12}$$

$$b_{bos} = a_2 e^{a_3 b_{bo}} \tag{13}$$

Formulas (12) and (13) are added and sorted out to obtain the following forms:

$$b_{bos} = \frac{1}{2}\left(a_0 b_{bs} + a_2 e^{a_3 b_{bo}}\right) + \frac{a_1}{2} \tag{14}$$

Therefore, after obtaining the backscattering coefficients of suspended matters and petroleum substances respectively, the total backscattering coefficients can be calculated by formula (14), where a_0, a_1, a_2 and a_3 are the undetermined coefficients.

Many scholars at home and abroad have studied the relationship between backscattering coefficient and suspended matters concentration [28-29]. Huang et al. (2009) found that in petroleum contaminated water bodies, the relationship between backscattering coefficient and suspended matters concentration is nearly linear[26]. Therefore, the relationship between backscattering coefficient and suspended matters concentration is as follows:

$$b_{bs} = j_0 \times S + j_1 \tag{15}$$

In the formula, S is the concentration of suspended matters (mg/L) and $j_{0,1}$ is the undetermined coefficient.

Song et al. (2010) found that, the relationship between the backscattering coefficient per unit of petroleum (i.e. the ratio of backscattering coefficient to petroleum concentration) and the concentration of petroleum satisfies the following relationships:

$$b_{bp}^{*} = k_0 \times C^{k'} \tag{16}$$

In formula (14), $b_{bp}*$ is the unit backscattering coefficient (m^{-1}), C is the concentration of petroleum (mg/L), k_0 and k' are the undetermined coefficients. According to the concept of unit backscattering coefficient of petroleum, the form of backscattering coefficient with respect to petroleum concentration can be achieved.

$$b_{bo} = k_0 \times C^{k_1} \tag{17}$$

After sorting out, the undetermined coefficient k_0 remains unchanged, and the relationship between k' and k_1 is $k_1 = k' + 1$.

3.3.4 Establishment of Vertical Variation Model of Backscattering Coefficient of Petroleum Water: By substituting formulas (15) and (16) into formulas (14), we obtain:

$$b_{bos}(\mathrm{z}) = \frac{1}{2}\left(a_0 j_0 S(z) + a_2 e^{a_3 k_0 C(z)^{k_1}} + a_0 j_1 + a_1\right) \tag{18}$$

Formulas (6) and (9) are transformed into exponential forms:

$$S(z) = e^{m_0} e^{m_1 z} \tag{19}$$

$$C(z) = e^{n_o} e^{n_1 z} \tag{20}$$

Formulas (19) and (20) are substituted into Formula (18) and sorted out:

$$b_{bos}(\mathrm{z}) = \frac{1}{2}\left(a_0 j_0 e^{m_0} e^{m_1 z} + a_2 e^{a_3 k_0 e^{k_1} e^{n_1 k_1 z}} + a_0 j_1 + a_1\right) \tag{21}$$

In order to simplify the model, the undetermined coefficients are integrated to obtain:

$$b_{bos}(\mathrm{z}) = A_0 e^{A_1 h} + A_2 e^{A_3 e^{A_4 h}} + A_5 \tag{22}$$

In the formula, A0, A1, A2, A3, A4 and A5 are integrated undetermined coefficients:

$$\begin{cases} A_0 = \frac{1}{2}a_0 j_0 e^{m_0} \\ A_1 = m_1 \\ A_2 = \frac{a_2}{2} \\ A_3 = a_3 k_0 e^{k_1} \\ A_4 = n_1 k_1 \\ A_5 = \frac{1}{2}(a_0 j_1 + a_1) \end{cases} \tag{23}$$

According to equation (23), the variation of backscattering coefficient with water depth follows the relationship between the sum of e index and composite e index in petroleum contaminated water bodies.

3.3.5 Determination of the undetermined coefficient range of the vertical change model of backscatter coefficient: after the determination of the model, in order to make the results of the model more reasonable, it is necessary to determine the range of the undetermined coefficients according to the deduction process and the actual situation. The specific analysis is as follows:(1) In the study of backscattering coefficient separation algorithm, it can be found that the backscattering coefficient increases with the increase of backscattering coefficient of suspended matters and petroleum, i.e. $a_0 > 0$, $a_2 > 0$ and $a_3 > 0$;(2)In the study of backscattering characteristics of petroleum, it can be found that the backscattering coefficient of suspended matters increases with the increase of suspended matters concentration, and the backscattering coefficient is not less than zero, i.e. $j_0 > 0$ and $j_1 > 0$;(3)In the study of the influence of petroleum content in water on backscattering coefficient, it can be found that the backscattering coefficient of petroleum decreases with the increase of petroleum concentration, that is, k0 > 0 and $k_1 < 0$;(4)In the study of vertical distribution of suspended matters based on diffusion theory, it can be found that the concentration of suspended matters increases with depth, i.e. $m_1 > 0$;(5)In the study of vertical distribution of petroleum based on diffusion theory, it can be found that the concentration of petroleum decreases with the increase of depth, that is, $n_1 < 0$. By synthesizing the above points, combining formula (18), we can get that A_0, A_1, A_2, A_3 and A_4 are all greater than 0.

3.3.6 Regression results of vertical variation model of backscattering coefficient: because there is a regional difference in the proportion of water components, there is also a regional difference in the relationship between the backscatter coefficient and the concentration of the scattering particles[3, 30], so the regression is performed on the three stations, regardless of the time. In the case, the regional regression model is finally obtained, as shown in Table 1.

Table 1 regression model results of back scattering coefficient variation in vertical direction

Station	regression model
A	$b_{bos} = 0.1675e^{0.002343h} + 0.278e^{0.02548e^{0.0882h}} - 0.431$
B	$b_{bos} = 0.02221e^{0.04276h} + 0.1625e^{0.03558e^{0.02146h}} - 0.1793$
C	$b_{bos} = 0.3042e^{0.001322h} + 0.1895e^{0.01016e^{0.02875h}} - 0.4862$

The derivative of the regression model was used to obtain the vertical change rate curve of the backscattering coefficient, as shown in figure 3. From the vertical change rate curve of backscattering coefficient, the following points can be found: (1) the regression models all show a rising trend with the increase of depth, which is consistent with the measured data; (2) the backscattering coefficient of station A is the largest, followed by station B, while that of station C is the smallest, which is consistent with the measured backscattering coefficient and suspension concentration. (3) the vertical change rate of backscattering coefficient of site A and site B increases with depth, and the change slope is increasing, indicating that backscattering coefficient of site A and site B increases with depth at an increasingly fast speed; (4) on the surface layer, the vertical change rate of backscattering coefficient of site A is close to that of site B, indicating that the change trend of backscattering coefficient of site A and site B is similar; (5) the vertical change rate of backscattering coefficient of site C is almost unchanged, slightly less than 0.0005, indicating that the vertical change of backscattering coefficient of site C is close to a linear relationship to some extent.

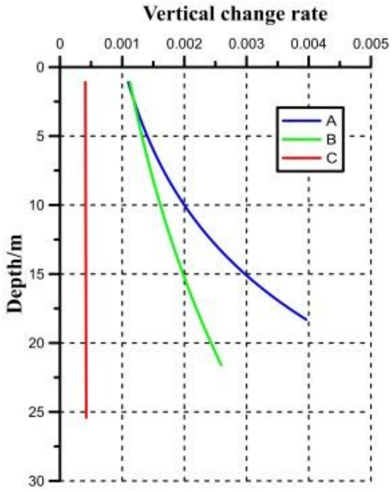


Fig. 3 vertical change rate of backscatter coefficient regression model

3.3.7 Effectiveness analysis of the backscattering coefficient vertical variation model: The backscattering coefficients from one meter to the maximum depth are calculated using the regression model presented in this paper. Combined with the corresponding measured data of backscattering coefficient, the mean relative error and mean absolute error of the regression model are calculated to discuss the effectiveness of the regression model. The calculation formulas of the mean relative error and mean absolute error are as follows:

$$r = \frac{\sum_{i=1}^{n}\left(\frac{\left|x_i^{obs} - x_i\right|}{x_i^{obs}}\right)}{n} \tag{24}$$

$$d = \frac{\sum_{i=1}^{n}\left|x_i^{obs} - x_i\right|}{n} \tag{25}$$

In equations (24) and (25), *r* is the average relative error, *d* is the average absolute error, X_i^{obs} is the observed value, X_i is the calculated value of the model corresponding to the measured value. Where r and d are both greater than 0, the smaller the value is, the smaller the model error is, that is, the more accurate the model is. The average relative errors and average absolute errors of the three sites are shown in table 2.

Table 2 average relative error and mean absolute error

Sites	average relative error	mean absolute error
A	1.984	0.025
B	0.282	0.006
C	0.349	0.005

From the calculation results of average relative error and average absolute error, the following points can be obtained: (1) station A has the largest error, which is because the backscattering coefficient of station A changes the most with time, and the influence of time change is not considered in the model establishment process. (2) C station error is bigger than B station, from the suspended material concentration and backscattering coefficient of the measured data can be found that the measurements of the C8 is larger, and the backscattering coefficient changing with depth has an obvious peak, this could be due to the suspended matters under certain conditions, distribution increased significantly in the middle, while this is not taken into account in the modeling process. (3) for the regression models of the three stations, the accuracy of station B is the highest, the accuracy of station C is similar to that of station B, and the accuracy of station A is the lowest and the accuracy is greatly different from that of station B and C, indicating that the accuracy of the model in open water is better.

Based on the analysis of the model establishment process, the possible error factors include the following :(1) ignoring the influence of oil droplet size on oil droplet diffusion velocity. From equations (5) and (6), it can be found that with the increase of oil droplet size, the rising speed of oil droplet increases, and the decreasing speed of oil droplet concentration from the sea surface to the sea bottom also increases. When the oil droplet size is not the same in each water layer, the vertical distribution of oil droplet concentration changes to some extent; (2) the adsorption between oil droplets and suspended particles is ignored. According to previous studies, the adsorption of suspended substances on oil droplets in seawater saturated with oil droplets is close to a linear relationship. In other words, as the concentration of suspended matters increases, the suspended matters will absorb more oil droplets and spread to the seabed together, leading to a change in the vertical distribution of petroleum concentration. (3) ignoring the influence of ocean currents on the vertical distribution of suspended matters and petroleum substances.

It can be found from the current profile and the measured backscattering coefficient that the backscattering coefficient changes with the tide to some extent, especially in station A. (4) ignore the influence of algae. Algae present a variety of vertical distribution structures in water bodies, and different algae have different scattering characteristics. Therefore, the influence of algae is very complex, which has different degrees of influence on the backscattering coefficient.

4. CONCLUSIONS

In this paper, a vertical variation model of backscattering coefficient of petroleum contaminated water bodies is established, which lays a foundation for studying the law of vertical variation of optical properties of water. It is mentioned in the conclusion that errors are caused by ignoring some influencing factors in the process of establishing the vertical variation model of backscatter coefficient. Therefore, further studies can be conducted in the following aspects in the future to improve the accuracy of the model: (1) vertical distribution law of oil droplet size. By studying this law, the vertical distribution law of oil concentration can be better determined, so as to improve the accuracy of the model; (2) the adsorption effect of oil droplets on suspended particles. Considering the adsorption effect, we can know what proportion of oil droplets are absorbed by suspended matters and spread downward, so as to improve the study on the upward diffusion rate of oil droplets, better determine the vertical distribution rule of oil droplets, and improve the accuracy of the model; (3) the relationship between algae and total backscattering coefficient. As the composition of class II water is complex, the relationship model between algae and total backscattering is established and integrated into the model of this study, so as to consider the influence of water composition more comprehensively and improve the accuracy of the model.

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