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Research on the design of multibeam bathymetric survey line based on geometric derivation

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Abstract. Based on the working principle of multibeam bathymetric system, this paper establishes a multibeam line design optimization model and coverage width geometric model by establishing a spatial right-angled coordinate system, dichotomy method, moving surface method and other methods. A two-dimensional geometric model of the coverage width and the overlap rate of adjacent strips is established in the two-dimensional plane. Then, based on the geometric model, the relationship equations of seawater depth at the centre of different lines are obtained by triangulation, and then the sine equations of seawater depth at the centre of the line, coverage width and coverage rate are obtained by the sine theorem. Then the equations of the line plane, the multibeam plane and the seabed slope are solved in 3D space, and finally the geometric model of the line perpendicular to the gradient and the optimisation model of the line parallel to the gradient are established respectively. Finally, comparing the total lengths of the lines in the two directions, it is determined that the line direction is east-west, the total number of lines is 34, the total length of the lines is 125936m, and the interval between the lines decreases with the increase of gradient.

Keywords: Geometric models; optimisation models; iterative algorithms; plane equation relationships.

1. Introduction

Measuring the topography and bathymetry of the seabed is a crucial task in the development of marine resources and environmental monitoring. With the continuous development of technology, multibeam bathymetry has gradually become one of the main means of measuring the ocean bottom. However, in practice, the accurate calculation of parameters such as the coverage width and seawater depth of multibeam bathymetry is of great significance in guaranteeing the accuracy and reliability of the measurement results. Therefore, this paper addresses the key issues in multibeam bathymetry technology, aiming to establish accurate models and calculation methods to improve the practicality and reliability of multibeam bathymetry technology.

In the plane, the focus is on the calculation of the coverage width and overlap rate in multibeam bathymetry, and the relationship equations of the coverage width, seawater depth and overlap rate are derived through the establishment of a geometric model and mathematical derivation, which provide the basis for the analysis of the measurement results. In the three-dimensional space, it focuses on the determination of the coverage intersection line and line direction in multibeam bathymetry, and through the establishment of a spatial coordinate system and the derivation of equations, key parameters such as the angle of the line direction and the width of the coverage are determined, which provides theoretical support for the practical operation. Finally, the problem of line placement in multibeam bathymetry is considered, and the optimal line placement scheme is finally determined by analyzing different placement schemes and line intervals, which provides guidance for the planning and implementation of oceanographic surveying work [1].

By studying and analyzing these key issues, this paper aims to provide useful theoretical support and practical methods for the further application and development of multibeam bathymetry.

2. Modelling and solving

In this paper, a two-dimensional geometric model of the plane and seabed slope profile perpendicular to the direction of the survey line is constructed based on the given survey lines at different distances from the centre point, with an interval of 200 m between adjacent survey lines (see Fig.1).

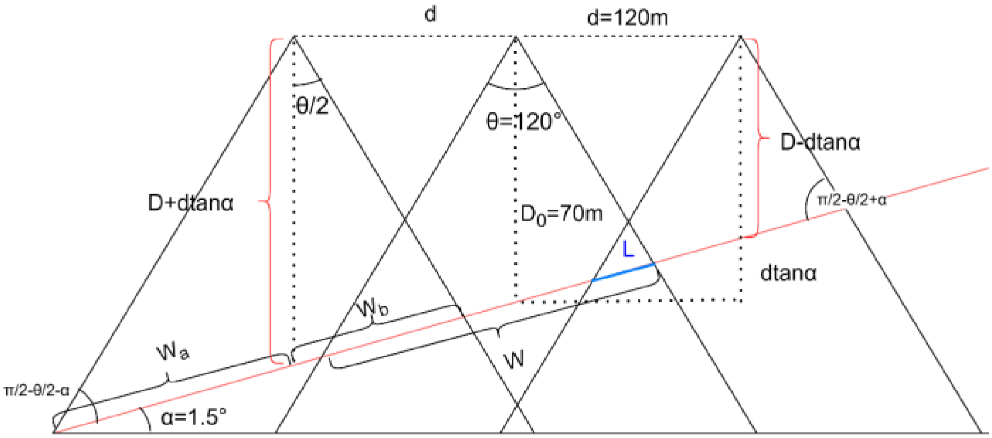

Figure 1. Multibeam 2D geometric model

Defined as the strip coverage width, and, respectively, the distance from the intersection of the centre line and the seabed slope to the left and right edges of the strip, the depth of the sea water at the centre of the sea area is the depth of the sea water, and the overlapping width of the adjacent strips is the width of the strips [2-3].

The multibeam coverage width and adjacent strip coverage problem can be normalized to solve the triangular equation problem. Firstly, according to the triangular relationship, the depths of the centres of different survey lines from the seabed slope have the following relationship equation:

$$D_i = D_0 - idtan\alpha, i \in [-4,4] \tag{1}$$

In a multibeam planar triangle, according to the sine theorem, the following equation can be derived:

$$\begin{cases} \frac{D_i}{\sin\left(\frac{\pi}{2}-\frac{\theta}{2}-\alpha\right)} = \frac{W_{a,i}}{sin\frac{\theta}{2}} \\ \frac{D_i}{\sin\left(\frac{\pi}{2}-\frac{\theta}{2}+\alpha\right)} = \frac{W_{b,i}}{sin\frac{\theta}{2}} \\ \frac{W_i-L_i}{\sin\left(\frac{\pi}{2}+\frac{\theta}{2}\right)} = \frac{d}{\sin\left(\frac{\pi}{2}-\frac{\theta}{2}-\alpha\right)} \\ W_i = W_{a,i} + W_{b,i} \\ \eta_i = \frac{L_i}{W_i} \end{cases} \tag{2}$$

2.1. Solving the model

Equations (1) and (2) can be solved to obtain the mathematical model of the coverage width and the overlap rate between adjacent strips for multibeam bathymetry as:

$$\begin{cases} D_i = D_0 - idtan\alpha, i \in [-4,4] \\ W_i = \frac{D_i sin\frac{\theta}{2}}{\cos\left(\frac{\theta}{2}+\alpha\right)} + \frac{D_i sin\frac{\theta}{2}}{\cos\left(\frac{\theta}{2}-\alpha\right)} \\ \eta_i = 1 - \frac{dcos\frac{\theta}{2}}{W_i \cos\left(\frac{\theta}{2}+\alpha\right)} \end{cases} \quad (3)$$

2.1.1. D modelling.

To solve the multibeam coverage width of different measurement line directions in a rectangular sea. The key to solving the problem is the angle between the direction of the survey line and the horizontal plane and the depth of the sea water at the position of the survey ship, and the mathematical model of the multibeam coverage width can be obtained by substituting the expressions of the two into the model of the problem [4].

2.1.2. Coordinate system-based modelling of line planes, multibeam planes and seabed slopes.

The intersection line of the survey line plane and the multibeam plane is the axis, the projection of the slope normal to the horizontal plane is the axis, and the perpendicular of the axis in the horizontal plane is the axis, and the centre of the horizontal plane is the origin of the spatial right-angled coordinate system. Define the survey line slope, multibeam plane, the seabed slope, respectively, the position of the measurement vessel for the position of the measurement vessel at the depth of the sea water, as shown in Fig. 2. next, we analyse the direction of the survey line as a survey line,

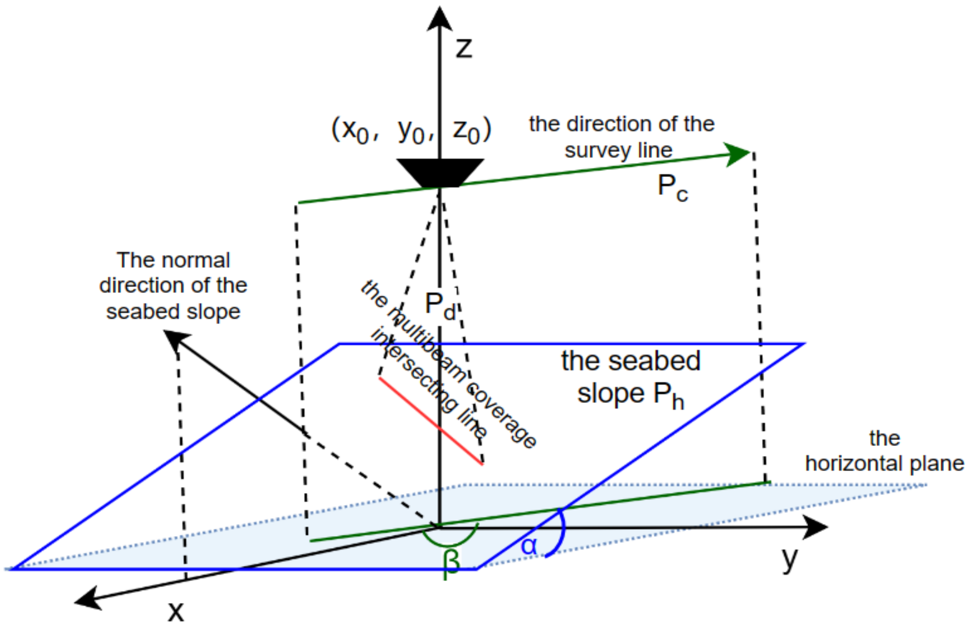

Figure 2. 3D geometrical model of multibeam

$$P_c: \ sin\beta x - cos\beta y = 0 \quad (4)$$

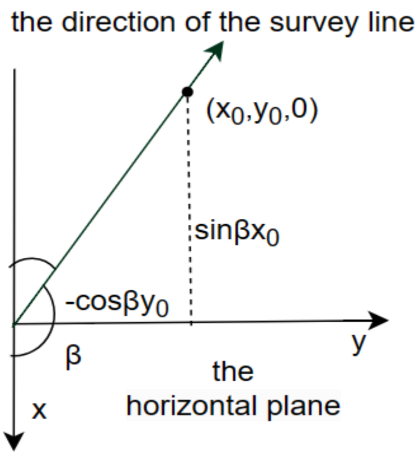

Figure 3. Schematic diagram of the direction of the measuring line in the horizontal plane

Let the multibeam plane equation be $A_2x + B_2y + C_2z + D_2 = 0$, Since the multibeam plane is perpendicular to the line plane, the dot product of the normal vector of the multibeam plane and the normal vector of the line plane is zero, and we get $A_2 = \cos\beta, B_2 = \sin\beta, C_1 = D_1 = 0$, Again, as a result of going through (x_0, y_0, z_0) point [5-6], Obtain the multibeam plane equation:

$$P_d:\ cos\beta(x - x_0) + \ sin\beta(y - y_0) = 0 \tag{5}$$

Let the submarine slope equation be $A_3x + B_3y + C_3z + D_3 = 0$, point on an inclined plane: $(0,0, z_0 - D'), (0,1, z_0 - D'), (\frac{z_0 - D'}{\tan\alpha}, 0,0)$, Substituting the three points into the equation and solving for the coefficients of the equation yields the slope equation:

$$P_h:\ \frac{tan\alpha}{z_0 - D'}x + \frac{1}{z_0 - D'}z - 1 = 0 \tag{6}$$

Above, three plane equations can be obtained:

$$\begin{cases} P_c:\ sin\beta x - cos\beta y = 0 \\ P_d:\ cos\beta(x - x_0) + \ sin\beta(y - y_0) = 0 \\ P_h:\ \frac{tan\alpha}{z_0 - D'}x + \frac{1}{z_0 - D'}z - 1 = 0 \end{cases} \tag{7}$$

2.1.3. Modelling of multibeam coverage intersection lines and their angles to the horizontal plane.

In order to find the angle between the direction of the measurement line and the horizontal plane, i.e., the angle φ between the multibeam coverage intersection line and the horizontal plane, two plane equations are linked:

Let $x = 0 \Rightarrow y = \frac{\cos\beta x_0 + \sin\beta y_0}{\sin\beta}, z = z_0 - D'$, Let $z = 0 \Rightarrow x = \frac{z_0 - D'}{\tan\alpha}, y = \frac{\tan\alpha(\cos\beta x_0 + \sin\beta y_0) - (z_0 - D')\cos\beta}{\tan\alpha\sin\beta}$

That is, there is a point of intersection on the line of intersection of the two planes [7]:

$(0, \frac{cos\beta x_0 + sin\beta y_0}{sin\beta}, z_0 - D'), (\frac{z_0 - D'}{tan\alpha}, \frac{tan\alpha(cos\beta x_0 + sin\beta y_0) - (z_0 - D')cos\beta}{tan\alpha sin\beta}, 0)$

Then the direction vector of the multibeam coverage intersection line is obtained as:

$\overrightarrow{L_f} = (\frac{1}{tan\alpha}, \frac{1}{tan\alpha tan\beta}, 1)$

Let the angle between the multibeam coverage intersection line and the horizontal plane be φ, as shown in Fig. 4:

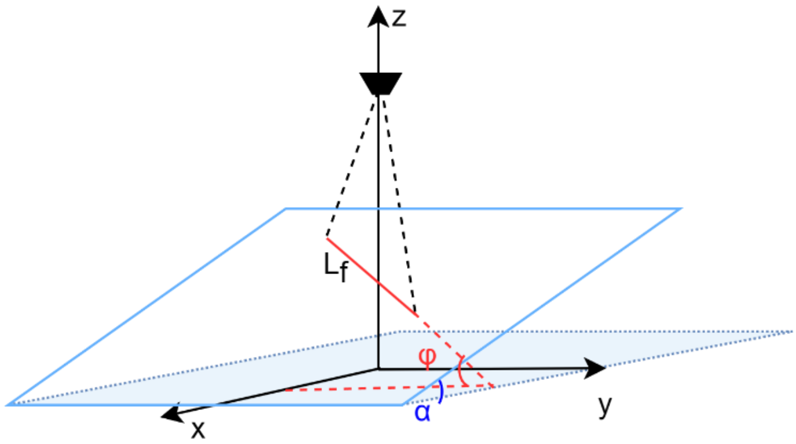

Figure 4. Schematic diagram of intersecting lines with multibeam coverage

Arbitrarily take the normal vector on the horizontal plane and combine it with the direction vector $\overrightarrow{L_f} = (\frac{1}{tan\alpha}, \frac{1}{tan\alpha tan\beta}, 1)$, The expression for the angle φ between the multibeam coverage intersection line and the horizontal plane can be obtained from the space vector relationship:

$$tan\varphi = tan\alpha tan\beta, \varphi = arctan(tan\alpha tan\beta) \quad (8)$$

2.1.4. Modelling of the intersection of the line plane and the slope surface.

In order to find the depth of seawater at the position of the survey vessel, the equation of the plane of the joint line and the slope of the seabed are [9-10]:

Let $x = 0 \Rightarrow y = 0, z = z_0 - D'$, Let $z = 0 \Rightarrow x = \frac{z_0 - D'}{tan\alpha}, z = \frac{(z_0 - D')tan\beta}{tan\alpha}$

i.e., there is a point of intersection on the line of intersection of the two planes:

$(0,0,z_0 - D'), (\frac{z_0 - D'}{tan\alpha}, \frac{(z_0 - D')tan\beta}{tan\alpha}, 0)$

Then we can get the direction vector of the intersection line of the two planes $(\frac{1}{tan\alpha}, \frac{tan\beta}{tan\alpha}, -1)$

Let the intersection of the survey line plane and the seabed slope be L_d, The depth of the sea at the position of the survey vessel is D', As shown in Fig. 5:

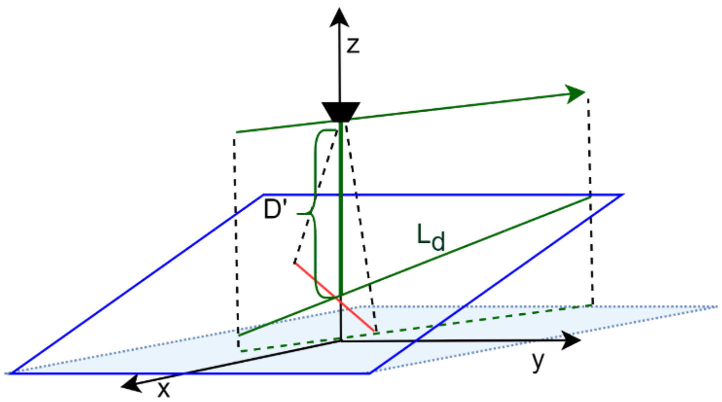

Figure 5. Schematic of the intersection of the survey line plane and the slope surface

Intersecting line L_d equation is $\frac{x-x_0}{A_4}=\frac{y-y_0}{B_4}=\frac{z-z_0}{C_4}$, the intersection obtained from the previous $(0,0,z_0-D')$ and the direction vector of the intersection line ($\frac{1}{\tan\alpha}$, $\frac{\tan\beta}{\tan\alpha}$, -1), Obtain the equation of the intersecting line:

$$\frac{x-x_0}{-\frac{1}{tan\alpha}}=\frac{y-y_0}{-\frac{tan\beta}{tan\alpha}}=\frac{z-(z_0-D\prime)}{1} \tag{9}$$

Consider also the sea level equation as:$z=z_0$, the expression for the depth of the sea water at the position of the survey vessel is obtained by solving the equation for the distance between a line and a surface as [8]:

$$D'=D_0'+x_0 tan\alpha \tag{10}$$

2.1.5. Construction of multibeam coverage width model.

The angle φ between the multibeam coverage intersection line and the horizontal plane and the depth of the sea water at the position of the survey vessel are known, the mathematical model of the multibeam bathymetric coverage width is obtained as follows:

$$\begin{cases} \frac{D'}{\sin\left(\frac{\pi}{2}-\frac{\theta}{2}-\varphi\right)}=\frac{W\prime_a}{sin\frac{\theta}{2}} \\ \frac{D'}{\sin\left(\frac{\pi}{2}-\frac{\theta}{2}+\varphi\right)}=\frac{W\prime_b}{sin\frac{\theta}{2}} \\ W'=W'_a+W'_b \\ \varphi=\arctan(tan\alpha tan\beta) \\ D'=D_0'+x_0 tan\alpha \end{cases} \tag{11}$$

As in Fig. 6, from the triangulation of the projection of the direction of the survey line on the horizontal plane, we get, Position of the survey vessel (x_0,y_0,z_0) is related to the distance S of the survey vessel from the centre of the sea by the equation: $x_0=S\cos\beta$

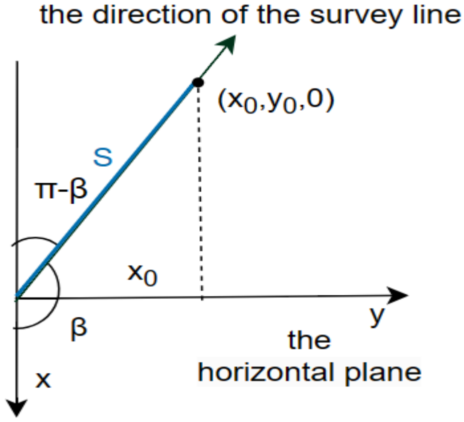

Figure 6. Schematic projection of the direction of the survey line on the horizontal plane

The expression obtained: $D'=D_0'+S\cos\beta\tan\alpha$, the analytical equation for the multibeam coverage width is obtained as:

$$W'=\frac{(D\prime_0+Scos\beta tan\alpha)sin\frac{\theta}{2}}{\cos\left(\frac{\theta}{2}+\arctan(tan\alpha tan\beta)\right)}+\frac{(D\prime_0+Scos\beta tan\alpha)sin\frac{\theta}{2}}{\cos\left(\frac{\theta}{2}-\arctan(tan\alpha tan\beta)\right)} \tag{12}$$

2.2. Modelling of survey lines

Design a set of survey lines on a rectangular sea area that meet the shortest length and coverage within a certain range. Laying of survey lines includes two aspects, namely the direction of survey lines and the selection of survey line intervals. After determining the direction of survey lines by combining the actual situation and analysing the assumptions based on the conditions of the problem, the optimal model of survey line intervals is established with the shortest path as the objective function to find a range of coverage that meets the constraints to complete the layout of the survey lines.

2.2.1. Determination of line orientation based on hypothetical analyses and actual conditions.

In order to improve the capability and efficiency of seabed geomorphology detection in the actual deployment of sea survey line direction, the selection of survey line direction should meet the following principles: In order to represent the seabed geomorphology most effectively, the direction of the bathymetric line is generally perpendicular or parallel to the general direction of the isobath; To facilitate the work of the system and avoid excessive steering in order to improve the detection efficiency. Avoid laying too many short lines on the map.

Combining the above principles, considering that the course is in the shape of a "bow", and assuming that the normal direction of the survey line direction of the seabed slope is projected on the horizontal plane at the angle of β.

Cohorting $\beta \neq \frac{k\pi}{2}, k = 1,2,3,4$(as shown in figure 7), The coverage zone of the survey line has more omissions at the boundary of the sea area and cannot cover the whole sea area. Moreover, the width and coverage of the same line along the direction of the line varies over a large span on the seabed slope, which makes it difficult to meet the requirements for the overlap rate, and therefore the direction of the line is not considered.

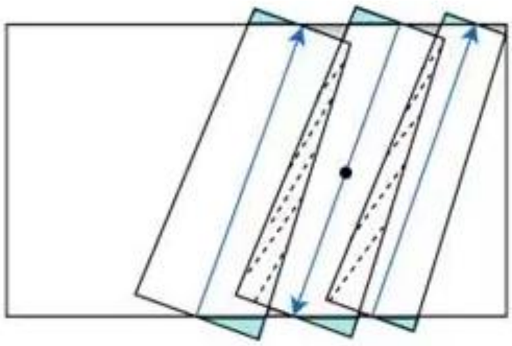

Figure 7. $\beta \neq \frac{k\pi}{2}$, k=1, 2, 3, 4 layout of the time line direction

When $\beta = \frac{k\pi}{2}, k = 1,2,3,4$ (Fig. 8), the direction of the line is perpendicular or parallel to the general direction of the isobath, and the system is easy to work with and fulfils the principle of line laying., make certain $\beta = \frac{k\pi}{2}$ is the direction of the line of sight.

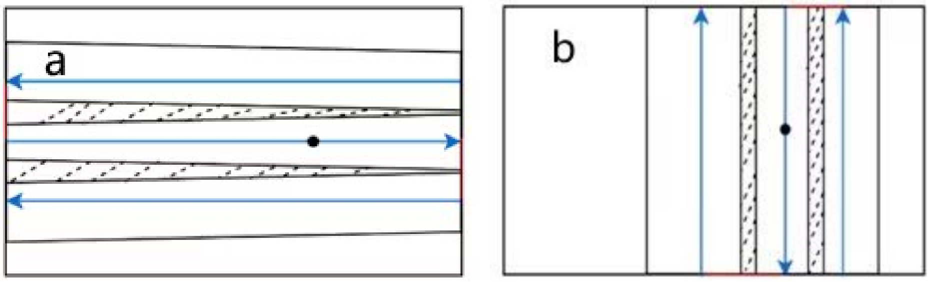

Figure 8. $\beta = \frac{k\pi}{2}$, k=1,2,3,4

2.2.2. Modelling and solving the east-west direction of the survey line.

Based on the direction of the measurement line of $\beta = \pi$ or 2π, it can be seen from the previous assumptions that the interval d between each group of measurement lines is fixed. From the requirements of the topic can establish the optimisation model of the measurement line interval as follows:

First of all, assume that there are a total of n groups of measuring line, measuring length L.

Measuring line interval and the number of groups of measuring lines have a relationship: $n = \frac{2*1852}{d}$.

In order to make the measurement length L is the shortest, the number of measurement line group n should be as small as possible, by n and d of the relationship between the formula can be obtained: $\max \quad f = d$

Next, the title requires the overlap rate to satisfy $10\% \leq \eta \leq 20\%, w = 2D\tan\frac{\theta}{2}$

When at the top of a submarine slope, conditions are to be met: $\eta \geq 10\%, \eta = 1 - \frac{d_1}{w_1} \geq 10\%$, Let the top cover width be w_1, The depth of the sea is $D_1, w_1 = 2D_1\tan\frac{\theta}{2}$.

From the trigonometric relationship, $D_1 = 110 - 3704\tan\alpha$, As shown in Fig. 9. Then there are constraints at the top of the submarine slope (1):

$$\begin{cases} 1 - \frac{d_1}{w_1} \geq 10\% \\ w_1 = 2D_1\tan\frac{\theta}{2} \\ D_1 = 110 - 3704\tan\alpha \end{cases} \tag{13}$$

When at the bottom of a submarine slope, conditions are to be met: $\eta \leq 20\%, 1 - \frac{d_2}{w_2} \leq 20\%$, Let the bottom cover width be w_2, The depth of the sea is $D_2, w_2 = 2D_2\tan\frac{\theta}{2}$.

From the trigonometric relationship $D_2 = 110 + 3704\tan\alpha$, As shown in Fig. 10. Then there are constraints at the bottom of the submarine slope (2):

$$\begin{cases} 1 - \frac{d_2}{w_2} \leq 20\% \\ w_2 = 2D_2\tan\frac{\theta}{2} \\ D_2 = 110 + 3704\tan\alpha \end{cases} \tag{14}$$

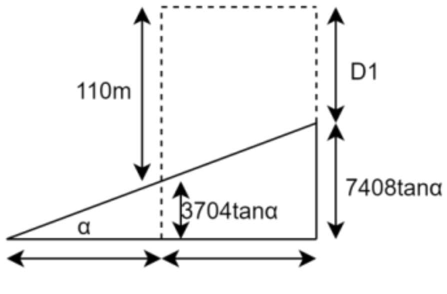

Figure 9. Schematic representation of the top of the seafloor slope

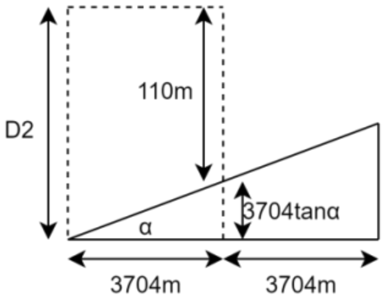

Figure 10. Schematic of the bottom of the seabed slope

In summary, the optimisation model for line spacing is obtained as follows:

$$max \quad f = d \tag{15}$$

$$s.t.\begin{cases}\begin{cases}1-\frac{d_1}{w_1} \geq 10\% \\ w_1 = 2D_1 \tan\frac{\theta}{2} \\ D_1 = 110-3704_{\tan}\alpha\end{cases} \\ \begin{cases}1-\frac{d_2}{w_2} \leq 20\% \\ w_2 = 2D_2 \tan\frac{\theta}{2} \\ D_2 = 110+3704_{\tan}\alpha\end{cases}\end{cases} \tag{16}$$

Getting the range of d_1 and d_2:

$$\begin{gathered} 36.04704 \leq d_1 \leq 40.55292 \\ 573.63488 \leq d_2 \leq 645.33924 \\ \text{Pick } d=40.5529. \end{gathered} \tag{17}$$

At this time the number of lines n and the total length of the line L:

$$\begin{gathered} n = \left\lceil \frac{2*1852-\frac{w_1}{2}}{40.5529} \right\rceil = 91 \\ L = n * \frac{4*1852}{\cos^{\alpha}} = 674359.09 \end{gathered} \tag{18}$$

2.2.3. Modelling and solving the north-south alignment of the survey line.

Based on the direction of the measurement line of $\beta = \frac{\pi}{2}$ or $\frac{3\pi}{2}$, at this time in the same measurement line each measurement point coverage width w are equal, so the overlap rate between two adjacent measurement lines η, constant, in order to design a set of measurement line with the shortest total length of the measurement, which can completely cover the entire sea to be measured, the control of η as small as possible to make the smallest number of measurement lines, i.e., the design of the line with the shortest length of the measurement.

The first survey line is fixed, as shown in Fig. 11.

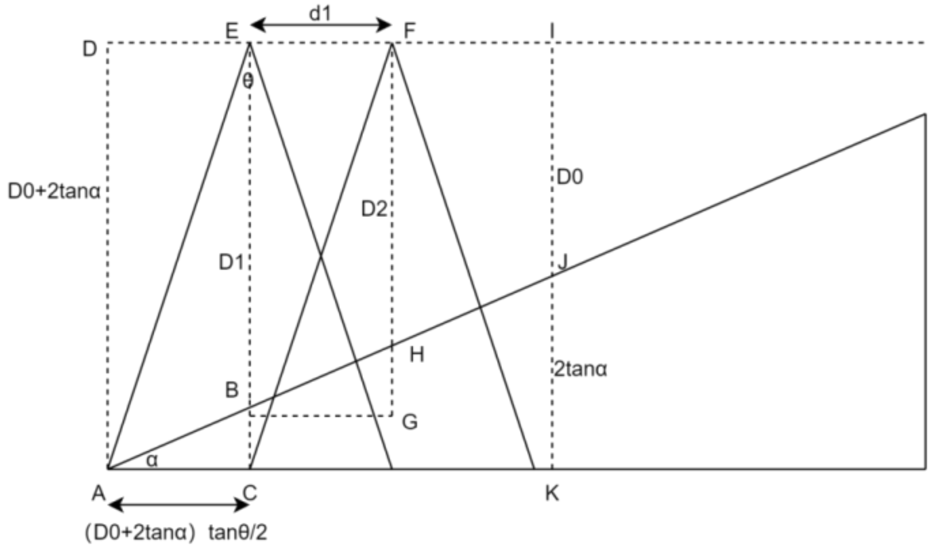

Figure 11. Schematic diagram of the north-south alignment

$$D_1 = (D_0 + 2 * 1852 * \tan\alpha)\left(1 - \tan\frac{\theta}{2}\tan\alpha\right) = 197.604429949$$
$$w_1 = D_1 \sin\frac{\theta}{2}\left(\frac{1}{\cos\left(\frac{\theta}{2}+\alpha\right)} + \frac{1}{\cos\left(\frac{\theta}{2}-\alpha\right)}\right) = 686.167995192 \quad (19)$$
$$d_1 = \frac{(1-\eta)\times w_1 \times \cos\left(\frac{\theta}{2}+\alpha\right)}{\cos\frac{\theta}{2}} = 589.339925848584$$

The result obtained is n=34 and the total length of the measuring line L=n*2*1852=125936m.

2.2.4. Line laying programme.

Comparing the east-west and north-south line direction options, the minimum number of lines in the east-west direction is 91, and the total length of the lines is 674359.09 m; the minimum number of lines in the north-south direction is 34, and the total length of the lines is 125,936 m. Therefore, the north-south direction of the line direction is chosen, i.e., the line direction of $\beta = \frac{\pi}{2}$ or $\frac{3\pi}{2}$.

In order to get the specific survey line layout scheme based on the survey line direction of $\beta = \frac{\pi}{2}$ or $\frac{3\pi}{2}$, considering that the last survey line covering the strip does not fall completely on the slope of the rectangular sea area.

The coverage η is incremented in units, and from Table 1, we can see that when $\eta = 12\%$, the total number of survey lines increases by = 35. From this, we use the dichotomy method in the interval of $\eta \in (10,12)$, so that the coverage between the first n-1 survey lines η_{n-1} takes the interval dichotomy value in turn, and then adjusts the position of the last survey line so that the adjusted survey line is in the rectangular sea area and the coverage of the adjusted last line η_n meets the conditions of $10\% \leq \eta_n \leq 20\%$. If the condition is not met, then by analogy, use the following model to calculate until the condition is met η_n.

$$\begin{cases} d_n = (1-\eta)(D_{n-1} - d_{n-1}\tan\alpha)\tan\frac{\theta}{2}\left(1 + \frac{\cos\left(\alpha+\frac{\theta}{2}\right)}{\cos\left(\frac{\theta}{2}-\alpha\right)}\right) \\ \sum_{i=2}^{n} d_i \leq 4 \times 1852 - \tan\frac{\theta}{2}(D_0 + 2 \times 1852 \times \tan\alpha) \\ \eta_n = 1 - \frac{d_{34} - \sum_{i=1}^{n} d_i - (D_0 + 2\times 1852 \tan\alpha)\tan\frac{\theta}{2} + 4*1852}{\tan\frac{\theta}{2}\frac{\left(1+\cos\left(\alpha+\frac{\theta}{2}\right)\right)}{\cos\left(\frac{\theta}{2}-\alpha\right)}(D_{33} - d_{33}\tan\alpha)} \end{cases} \quad (20)$$

Table 1. Coverage dichotomous adjustment table

η_{n-1}	n	η_n
10	34	0.6133
11	34	0.3110
12	35	/
11.5	35	/
11.25	34	0.2367
11.375	34	0.1998

As shown in Table 1, when adjusted to the last line η_n to meet the overlap rate condition, the overlap rate between the first 33 lines η_{n-1} = 11.375, the overlap rate between the 33rd line and the 34th line η_n = 0.1998, the total length of the line $L = n \times 2 \times 1852$ = 125936m.

3. Conclusion

This study delves deep into the intricacies of multibeam bathymetric surveying, offering a comprehensive approach to tackle critical aspects such as coverage width and overlap rates. By developing intricate mathematical models grounded in triangular relationships and the sine theorem, the research provides a robust framework for solving these complex problems. Through sophisticated 3D modeling techniques, the study elucidates the intricate dynamics between survey lines, multibeam planes, seabed slopes, and the depth of seawater at the survey vessel's position. This detailed modeling not only enhances our understanding of the surveying process but also lays the groundwork for optimizing survey line design. Speaking of which, the research delves into the principles guiding survey line orientations, considering factors like seabed geomorphology, isobaths, and operational efficiency. The result is an optimized model that minimizes the number of survey lines while ensuring comprehensive coverage and meeting overlap rate requirements. This meticulous approach extends to the line laying program, where careful analysis and adjustments lead to an optimal survey line layout that balances coverage needs with operational feasibility. Overall, this study's contributions are poised to significantly advance multibeam bathymetric surveying, offering practical solutions that enhance underwater mapping accuracy and efficiency in environmental monitoring efforts.

References

[1] Xiao Zhen. Research on the deployment of surface GNSS/sonic line and its impact on seabed positioning [D]. Shandong University of Technology, 2023.

[2] Guo Lin. Resonant acoustic detection of deep-sea cold spring water bodies [D]. Harbin Engineering University, 2023.

[3] Chen Yuxue. Simulation method of offshore submarine landslide disaster mechanism and evolution process [D]. Shandong University, 2022.

[4] Wang Vigorous. Research on deep-sea multibeam acoustic substrate classification [D]. China University of Geosciences, 2022.

[5] Xu Ruohao. Research on immersive virtual reality environment in the polymetallic sulphide contract area in the Southwest Indian Ocean [D]. Zhejiang University, 2021.

[6] Xiong Z. Research on key technology of underwater gravity measurement based on multi-sensor fusion [D]. National University of Defence Technology, 2021.

[7] Wu Bo. Research on seabed terrain alignment technology based on 3D point cloud data [D]. Harbin Engineering University, 2021.

[8] Wina Zhao, Xunhua Zhang, Huigang Wang, et al. Data characterization and noise combination suppression for shallow wide-angle sounding of submarine seismometers - An example of the OBS2016 survey line in the South Yellow Sea [J]. Geophysical Journal, 2020, 63 (06): 2415 - 2433.

[9] Lu Yanyang. Research on target localisation and sonar deployment method based on acoustic field characteristics [D]. Northwestern Polytechnical University, 2020.

[10] Yue Xi-he. Hydrothermal activity and control mechanism of the 27 Ridge Section in the Southwest Indian Ocean [D]. China University of Geosciences, 2020.