Research On Multi-Beam Line Measurement Design Based on Genetic Algorithm

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Abstract. This paper aims to measure the seabed depth using a multibeam survey line scheme and analyze its performance in a real sea area. The multibeam depth measurement system can send and receive multiple sound waves in a plane perpendicular to the survey line, achieving high accuracy, resolution and efficiency. This paper builds a mathematical model, using geometric analysis, vector algebra, iteration, traversal and other methods, to determine the multibeam depth measurement coverage width model, and find the variable relationship of survey line length, spacing, overlap rate, slope, etc. Using a rectangular seabed slope as an example1, this paper first covers the sea area with parallel survey lines, and then applies the genetic algorithm to calculate the coverage width of different survey line positions, and derive the shortest, full-coverage, overlap rate 10%~20% survey line combination.

Keywords: Multi-beam sounding, vector conversion, line spacing, genetic algorithm.

1. Introduction

The multibeam depth measurement system calculates the depth of seawater by measuring the time difference between the transmitted and received signals of sound waves in seawater [1]. In the sea area where the seabed is relatively flat, it can measure a full-coverage depth strip with a certain width along the survey line of the measurement ship, but the real seabed terrain fluctuates greatly, which may cause missing measurement and excessive overlap rate. The Naval Research Laboratory (NRL) of the United States has developed a seabed target detection technology based on the multibeam depth measurement system, which uses the intensity and phase information of the sound echo signal to realize the automatic detection, identification and localization of the seabed target. This paper involves the mathematical model of multibeam depth measurement under various conditions, and calculates the seawater depth, the seabed width covered by the multibeam transducer and the overlap rate between adjacent strips by using various calculation methods, to determine the seawater depth under the real complex situation.The data in the article comes from this website: In this paper, the data mainly comes from the website: http://www.mcm.edu.cn/html_cn/block/f104f25e0431f7882cb1ddd5be2d8a14.html and the software simulation and software simulation.

2. Establishment and solution of various line models:

2.1. Establishment and solution of sounding model for simple inclined plane

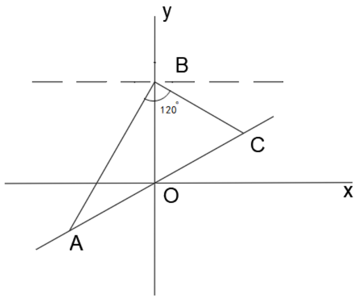

Figure 1 Schematic diagram of problem 1

As shown in the figure 1, a plane rectangular coordinate system is established, O point is the projection of the survey ship on the slope, X is the horizontal direction, AC is the slope, the water depth at the known center point is 70m, the Angle of the transducer is $\theta = 120°$, the slope is $\alpha = 1.5°$, x is the distance from the center, and the depth of the sea water is D[2].

Because the slope is α, so

$$D = 70 - x\tan\alpha \tag{1}$$

In △ABC, $\angle BAC = \frac{\pi}{2} - \frac{\theta}{2} - \alpha$, $\angle AOB = \frac{\pi}{2} + \alpha$, by the sine theorem

$$\frac{AB}{\sin\left(\frac{\pi}{2} + \alpha\right)} = \frac{D}{\sin\left(\frac{\pi}{2} - \frac{\theta}{2} - \alpha\right)} \tag{2}$$

So

$$AB = \frac{D\cos\alpha}{\cos\left(\frac{\theta}{2} + \alpha\right)} \tag{3}$$

In △ABC, $\angle ACB = \frac{\pi}{2} - \frac{\theta}{2} + \alpha$, $\angle ABC = \theta$ by the sine theorem

$$\frac{AB}{\sin\left(\frac{\pi}{2} - \frac{\theta}{2} + \alpha\right)} = \frac{AC}{\sin\theta} \tag{4}$$

So

$$AC = \frac{AB\sin\theta}{\cos\left(\alpha - \frac{\theta}{2}\right)} \tag{5}$$

$$AC = \frac{D\cos\alpha\sin\theta}{\cos\left(\alpha - \frac{\theta}{2}\right)\cos\left(\alpha + \frac{\theta}{2}\right)} \tag{6}$$

As shown in Figure 1, AC is the coverage width.

Therefore

$$W = \frac{D\cos\alpha\sin\theta}{\cos\left(\alpha - \frac{\theta}{2}\right)\cos\left(\alpha + \frac{\theta}{2}\right)} \tag{7}$$

As shown in Figure 2, the coverage width of different X values is schematic diagram:

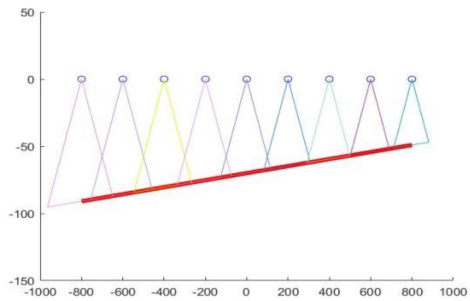

Figure 2. Coverage widths for different X values

According to the meaning of the question, the distance between two adjacent measurement lines $d = 200m$, W is set as the coverage width of the measured point, W_1 is set as the coverage width of the previous point of the measured point, so the coverage η is.

$$\eta = \frac{2d}{W_1 + W} \tag{8}$$

Fill in the results in Table 1 according to the above formula:

Table.1 Result of the above calculation.

Distance of the line from the center point/m	−800	−600	−400	−200	0	200	400	600	800
Sea depth/m	90.94873726	85.71155294	80.47436863	75.23718431	70	64.76281569	59.52563137	54.28844706	49.05126274
Covering width/m	314.9477059	296.8117841	278.6758623	260.5399406	242.4040188	224.268097	206.1321752	187.9962534	169.8603317
The overlap rate with the previous line/%	——	34.61482715	30.49372954	25.81819786	20.46827632	14.28671513	7.063255806	-1.489760931	-11.77662133

2.2. Establishment and solution of sounding model of rectangular bevel to be measured

As shown in Figure 3, a space rectangular coordinate system is established, taking the center of the sea area as the origin, and the projection of the normal direction of the slope surface on the horizontal plane is the positive direction of the x axis, and the vertical horizontal side is the positive direction of the z axis.

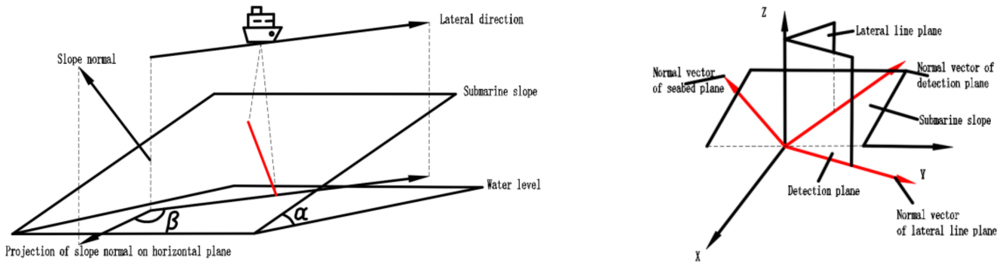

Figure. 3 Two-coordinate diagrams of the problem

It is easy to know that the submarine slope is perpendicular to the plane XOY, and the plane determined by the projection of the survey line on the horizontal plane is the survey line plane, and the plane where the ship emits the wave is called the detection plane[3]. It can be seen that both the measurement line plane and the detection plane are perpendicular to the plane XOY.

$$\vec{n}_{\text{Slopenormal vector}} = (\sin\alpha, 0, \cos\beta) \to \text{Submarine slope} \tag{9}$$

$$\vec{n}_{\text{Measurenormal vector}} = (\sin\beta, -\cos\beta, 0) \to \text{Line plane} \tag{10}$$

$$\vec{n}_{\text{Probenormal vector}} = (\cos\beta, \sin\beta, 0) \to \text{Detection plane} \tag{11}$$

As shown in Figure 4, it can be seen from the plane YOZ

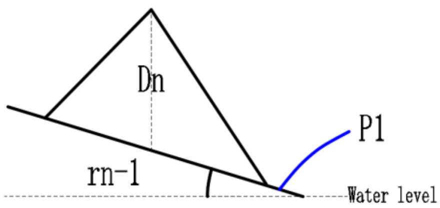

Figure.4 Plane YOZ

To obtain r_1, we need to know the direction vector of the intersection line between the detection plane and the submarine slope[4].Then let the direction vector of the intersection line be $\vec{n}_1 = (a, b, c)$

Since the normal vector is perpendicular, so

$$\vec{n}_1 \cdot \vec{n}_{\text{Slopenormal vector}} = 0 \tag{12}$$

$$\vec{n}_1 \cdot \vec{n}_{\text{Probenormal vector}} = 0 \tag{13}$$

mean:

$$a \cdot \sin\alpha + c \cdot \cos\alpha = 0 \tag{14}$$

$$a \cdot \cos\beta + b\sin\beta = 0 \tag{15}$$

$$\vec{n}_1 = (-\cos\alpha, \frac{\cos\alpha}{\tan\beta}, \sin\alpha) \tag{16}$$

If $a = -\cos\alpha$, we get a direction vector: Let the Angle between n and the horizontal plane be r_{n-1}.

So, we know that:

$$\sin(r_{n-1}) = \frac{\sin\alpha}{\sqrt{1 + \frac{\cos^2\alpha}{\tan^2\beta}}} \tag{17}$$

$$\cos(r_{n-1}) = \sqrt{\frac{\cos^2\alpha + \frac{\cos^2\alpha}{\tan^2\beta}}{1+\frac{\cos^2\alpha}{\tan^2\beta}}} \tag{18}$$

As shown in Figure 5, viewed from the plane of the measurement line

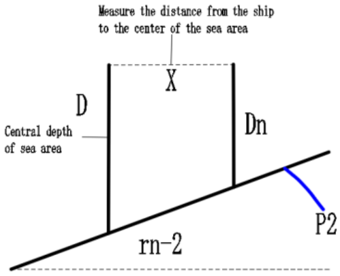

Figure 5 Viewed from the line plane.

It can be seen from the above formula that if D_n is required, r_{n-2} needs to be obtained first, and the intersection line between the survey line plane and the submarine slope needs to be obtained[5]. Let the normal vector of this intersection be $\vec{n}_2 = (a', b', c')$

Since the normal vector is perpendicular, so

$$\vec{n}_2 \cdot \vec{n}_{\text{Slopenormal vector}} = 0 \tag{19}$$

$$\vec{n}_2 \cdot \vec{n}_{\text{Measurenormal vector}} = 0 \tag{20}$$

mean:

$$a' \cdot \sin\alpha + c' \cdot \cos\alpha = 0 \tag{21}$$

$$a' \cdot \cos\beta - b' \cdot \sin\beta = 0 \tag{22}$$

Similarly, if $\alpha' = \cos\beta$, the direction vector of the intersection line is $(\cos\beta, \sin\beta, -\cos\beta\tan\alpha)$

So:

$$\tan(r_{n-2}) = -\cos\beta \cdot \tan\alpha \tag{23}$$

$$D_n = D - X_n \cdot \tan r_{n-2} \tag{24}$$

Replacing the model obtained in problem 1, the coverage width is:

$$W_n = D_n \cdot \sin\frac{\theta}{2} \cdot \left(\frac{1}{\cos(r_{n-1} - \frac{\theta}{2})} + \frac{1}{\cos(r_{n-1} + \frac{\theta}{2})}\right) \cdot \cos r_{n-1} \tag{25}$$

mean:

Fill in the results in Table 2 according to the above formula.

$$W_n = (D - X_n \cdot \tan r_{n-2}) \cdot \sin\frac{\theta}{2} \cdot \left(\frac{1}{\cos(r_{n-1} - \frac{\theta}{2})} + \frac{1}{\cos(r_{n-1} + \frac{\theta}{2})}\right) \cdot \cos r_{n-1} \tag{26}$$

Table. 2 The calculation result of the above formula.

Covering width/m		Measure the distance of the ship from the center of the sea							
		0	0.3	0.6	0.9	1.2	1.5	1.8	2.1
Measuring line direction Included Angle	0	415.692	466.091	516.489	566.888	617.287	667.686	718.085	768.484
	45	416.120	451.794	487.468	523.142	558.816	594.490	630.164	665.838
	90	416.549	416.549	416.549	416.549	416.549	416.549	416.549	416.549
	135	416.120	380.446	344.772	309.097	273.423	237.749	202.075	166.401
	180	415.692	365.293	314.894	264.495	214.096	163.697	113.299	62.9001
	225	416.120	380.446	344.772	309.097	273.423	237.749	202.075	166.401
	270	416.549	416.549	416.549	416.549	416.549	416.549	416.549	416.549
	315	416.120	451.794	487.468	523.142	558.816	594.490	630.164	665.838

2.3. Establishment and solution of arbitrary slope rectangular sea line model

2.3.1 Model parameter setting

(1) Sea depth D: the fluctuation and change of the seabed topography will affect the design of the survey line. Because of the flat topography of the sea floor, we can assume that the depth of the water does not change much throughout the ocean.

(2) The opening Angle of the transducer θ: The opening Angle of the multi-beam transducer will affect the coverage width W of the measuring line. As the opening Angle increases, the coverage width also increases.

(3) Cover width of the strip W: the cover width of the strip changes with the change of the opening Angle of the transducer and the depth of the sea water.

2.3.2 Factors affecting survey line coverage

When the first line defined by random initialization is extended to both sides, the following conditions may occur at the edge:

(1) The predicted position of the next line at the edge is beyond the edge of the sea area.

(2) When adding the position of the next survey line at the edge, the slope is too shallow or too deep, and side leakage or excessive overlap will affect the coverage of the entire sea area[6].

2.3.3 Preliminary prediction of line coverage model

Assuming that a survey line passes through the center point of the sea area, where the water depth is known to be 110m, the water depths of other survey lines are solved by using the survey line spacing and slope. Due to the west-low and east-high slope, the same survey line forms a trapezoid with a wide west side and a narrow east side, as shown in Figure 6. Moreover, the coverage width changes with the variation of the angle [2].

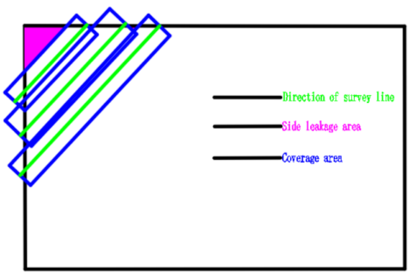

Figure. 6. Schematic diagram of covered area

Since the measuring lines are parallel to each other, in the case of the same measuring line spacing, the included Angle will also affect the measuring length. As can be seen from Figure 7, when β is closer to 90°, its single measuring line length will be shorter, thus reducing the total length of the measuring line[7].

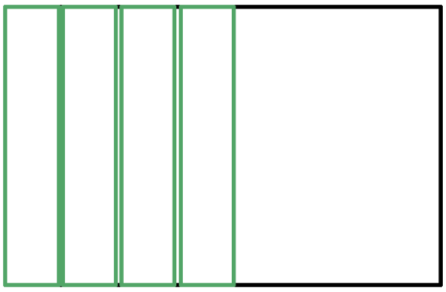

Figure.7. Optimum Angle diagram

Therefore, the larger the spacing of the lines, the more sparse the lines, the shorter the measuring length. However, in order to meet the requirement of overlap rate, the overlap rate of the width of the line in the easternmost part of each line should be the minimum required value, and other methods should be used to solve the measurement line spacing.

2.3.4 Optimizing the algorithm to solve the line position list

To solve the problem of survey line spacing, we use a genetic algorithm to find the optimal survey line position list, and search for the best survey line position through continuous iteration and optimization, so that the survey line can cover the entire sea area and meet the overlap rate requirement between adjacent strips.

The specific algorithm solving process is as follows. First, define the initial situation of the problem, that is: the sea area is 2 nautical miles long from north to south, 4 nautical miles wide from east to west, rectangular in shape, the water depth at the center of the sea area is 110 m, deeper in the west and shallower in the east, the slope is 1.5, the opening angle of the multibeam transducer is 120 ◦, and the overlap rate between adjacent strips is 10%-20%[8]. Then, according to the minimum and maximum distance, generate a population of size 100, representing the position sequence of the survey line. The population has 500 generations, a scale of 10, and a mutation rate of 0.1.

Calculate the fitness value of each chromosome (survey line position list), that is, the length of the survey line, according to the fitness function. Select the chromosomes with higher fitness as the parents, to produce the next generation population. Perform crossover operation with a certain probability, and generate new chromosomes[9]. The crossover operation produces offspring by combining gene segments of parental chromosomes. Perform mutation operation with a certain probability, and change the position value in the chromosome. The mutation operation increases the diversity of the population by randomly changing the position value in the chromosome. Sort the population according to the fitness value, and select the chromosomes with higher fitness as the next generation population, for the next selection. Repeat the above steps until the preset stop condition is reached.

Through the above algorithm solving process, the optimal survey line position list can be obtained, so that the survey line can cover the entire sea area and meet the overlap rate requirement between adjacent strips[10]. In the solving process, factors such as water depth, transducer opening angle and seabed terrain fluctuation, as well as the overlap rate requirement, are considered, thus ensuring the cost-effectiveness, data integrity and measurement efficiency of the measurement.

The solution results are as follows: List of best line positions (north-south direction, in meters) :

[231.73493497, 555.52852639, 877.75975392, 1003.01738257,
1330.42955417, 1655.18630546, 1978.70469522, 2296.37720124,
2624.47978975, 2941.21978639, 3273.09412047, 3794.35406802,
4115.67889509, 4447.65171789, 4767.67700196, 5088.37131656,
5216.8831328 , 5539.48840968, 6063.75343982, 6388.43877984,
6513.23794651, 6838.33219966])

3. Conclusions

To simulate the real situation as much as possible, we consider the slope angle, different inclinations, different orientations of the ship and the sea area, and obtain the above model, and solve a widely applicable multibeam survey line model.

Using this model, people can monitor and predict the changes of the ocean, such as sea level rise, ocean acidification, ocean pollution, etc., and reduce the impact on human response.The problem of this model is that it does not consider the non-uniformity of multi-beam and the phase noise of multi-beam, which needs to be eliminated 0or reduced by the corresponding compensation and correction methods.

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