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DETERMINATION OF THE OPTIMAL DENSITY CONTRAST IN THE SEAFLOOR DEPTH INVERSION FROM GRAVITY ANOMALIES USING THE GRAVITY-GEOLOGIC METHOD ON THE CENTRAL EAST SEA

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ABSTRACT

In the seafloor depth inversion from gravity anomalies using the Gravity-Geologic Method, the density contrast between the seawater and the ocean bottom topographic mass needs to be determined. In this study, the iteration method was applied to determine the optimal density contrast. Firstly, a density contrast is given. Then, the seafloor depths are calculated and compared with the shipborne depths. In the next step, change the density contrast and repeat the calculation. Finally, the optimal density contrast is determined corresponding to the smallest deviation between the gravity anomaly-derived depths and the shipborne depths. The experiment calculations were carried out on the central East Sea with eight density contrast values, which varied from 1.10 g/cm^3 to 3.0 g/cm^3. The results show that the optimal density contrast in the study area is 1.40 g/cm^3.

1. INTRODUCTION

The world's oceans cover 71 % of the Earth's surface. Despite many attempts to measure, to date, only about 18 % of the ocean's area has been measured using echosounders (Wölfl, 2019). Measuring the entire ocean by direct depth measurement method is very difficult and expensive in terms of money and time.

Vietnam is a country with a coastline of up to 3260 km, a territorial sea area of over 64000 km^2 and an exclusive economic zone of nearly 1 million km^2. Seas and islands play an important role in the economic development of the country, security and defense work and international exchanges (Dang, 2008). Up to now, Vietnam has only established charts of 1:200,000 scale with about 53 % of the area of Vietnam's seas; completed seabed topographic surveys of about 24.5 % of Vietnam's sea area at the scales from 1:500,000 to 1:50,000 (Ministry of Natural Resources and Environment, 2019). Thus, there is still a large area of the East Sea that has not been measured and mapped. Measuring depth over the entire East Sea by direct measurement method is very difficult and expensive, especially not possible for the sea areas that are not directly accessible. In that context, indirect methods of depth determination need to be studied and applied. The Gravity Geologic Method (GGM) is one such indirect method.

In the GGM, it is very important to determine the optimal density contrast (DC) between the seafloor matter and seawater. Different seas have different density contrast. Globally, there are some studies to determine the optimal density contrast: In the study (Yeon et al., 2018), the determined optimal contrast density over Korean waters is 5.0 g/cm^3. In the reference (Yu et al., 2011), the Downward Continuation Method (DWC) was used to determine density contrast in two study areas in southern Greenland. The results of this study show that the optimal density contrast in the first experimental area is 1.47 g/cm^3 and in the second area is 1.30 g/cm^3.

In this study, the iterative method will be studied and applied to determine the optimal density contrast for the area in the center of the East Sea.

2. STUDY AREA AND DATA

2.1 Study area

The study area is located in the center of the East Sea, between latitudes 8ºN and 14ºN and longitudes 110ºE and 115ºE (Figure 1), covering an area of about 363,000 km^2. This is an area located on the margin of the sea with diverse and complex architecture that has undergone a special geological development process, attracting the attention of many geophysicists and geologists in the world and abroad. The seafloor topography of the study area is diverse and complex. The Southeast of the study area is the sea of the Spratly Islands, with many submerged and floating islands. The Northeast of the study area is a deep depression of the East Sea, with the greatest depth is nearly 5,000 m. The Western side of the study area is the continental slope, with a depth of about 1,000 m to 2,000 m, a steep slope (Bui et al., 2005).

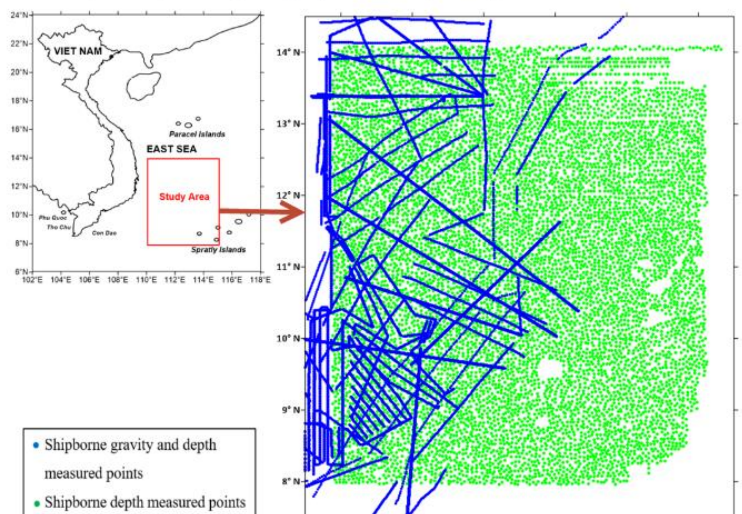

Figure 1. Study area and data.

2.2 Data used

2.2.1 Satellite-derived gravity anomaly data

In this study, the DTU17GRAV model is used. This is a model of the global marine gravity field, determined from satellite altimeter data and provided by the Technical University of Denmark (DTU) (Andersen et al., 2020). The gravity anomalies of this model are in the form of a square grid with a mesh size is 1 inch x 1 inch. The coordinates of this model are in the World Geodetic System WGS84. Over the study area, a total of 151,200 gravity anomalous values of this model were used. The maximum gravity value is 135.40 mGal; the smallest is -53.70 mGal; and the average of 9.98 mGal.

2.2.2 Shipborne gravity and depth data

In this study, the 19,226 points, measured simultaneous gravity and depth, were used (blue points in Figure 1). These data were measured in 1987, 1990 and 1992 in cooperation projects between Vietnam and Russia and Vietnam and France in the East Sea, specifically as follows: the geophysical surveying project was implemented in 1987; the survey project of the Gagarinsky ship carried out in 1990-1992; the survey project of the Atalante ship carried out in 1993. These data have high reliability, the parameters are very clear and the gravimetric accuracy is ± 1mGal (Bui et al., 2008). The coordinates of the measured points are in the World Geodetic System WGS-84. These data cover more than 0.5° study area.

2.2.3 Shipborne depth data

The shipborne depth data consists of 9,403 points (green points in Figure 1), measured by the Vietnamese Navy using a single-beam echosounder in 2009 and a multi-beam echosounder from 2010 to 2016. The measurement and process were carried out according to the standards of the International Hydrographic Organization (IHO). The coordinates of the measured points are in the WGS-84 (Khuong, 2018). The depths have been converted to the mean sea level of Vietnam based on the data of the tidal stations. It is important to note that the 9,403 points have the depth value only. Therefore, the gravity anomaly value for these points was further determined using the DTU17GRAV model.

The summary of the data used in this study is presented in (Table 1).

Table 1. Summary of the data used in this research.

No.	Data	Coverage (φ: latitude, λ: longitude	Number of points
1	DTU17GRAV model	$7.5^{o} \leq \varphi \leq 14.5^{o}$; $109.5^{o} \leq \lambda \leq 115.5^{o}$	151,200
2	Shipborne gravity and depth measured points	$7.5^{o} \leq \varphi \leq 14.5^{o}$; $109.5^{o} \leq \lambda \leq 115.5^{o}$	19,226
3	Shipborne depth measured points	$7.5^{o} \leq \varphi \leq 14.5^{o}$; $109.5^{o} \leq \lambda \leq 115.5^{o}$	9,403

2.2.4 Data preparation

A total of 28,629 shipborne points were used, including 19,226 points measured in the period of 1987, 1990-1993 and 9,403 points measured in the period of 2009-2016. After processing, these points have both depth and gravity anomaly values. For analysis, these 28,629 shipborne points were further randomly divided into two parts (Figure 2): Part 1 consisted of 14,404 points (black points in Figure 2) and was used to compute the seafloor depths. While Part 2 contained 14,225 points (red points on Figure 2) and was employed for estimating the accuracy of the depths.

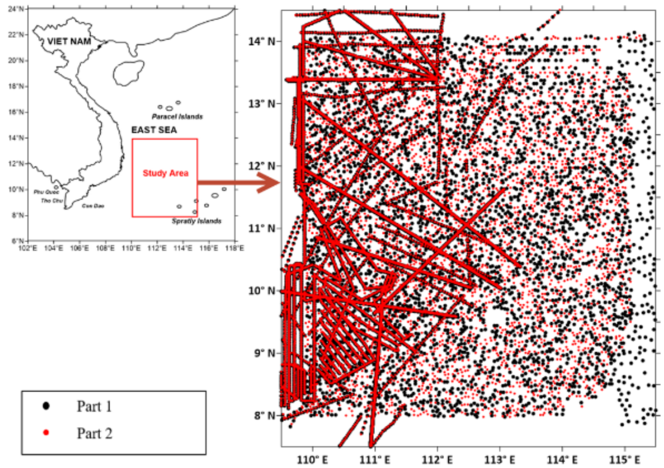

Figure 2. Shipborne data preparation.

3. THE METHOD OF DETERMINING THE OPTIMAL DENSITY CONTRAST IN THE SEAFLOOR DEPTH INVERSION FROM GRAVITY ANOMALIES

3.1 Principle of the seafloor depths inversion from gravity anomalies

To determine the depth of the gravity anomalies, according to studies (Yeon et al., 2018), (Yu et al., 2011), (Xueshuang et al., 2017), the gravity anomaly (Δg) is divided into 2 parts: the long-wavelength gravity anomaly (Δg^{long}) associated with deep and wide seafloor matter; and the short-wavelength gravity anomaly (Δg^{short}) related to the convexity of the seafloor topography.

For the points where the gravity anomalies and depths were known simultaneously, the short wavelength gravity anomaly is calculated using the equation:

$$\Delta g^{short} = 2\pi G\delta(D^{ship} - D_{max}) \quad (1)$$

where: G is the gravitational constant ($6{,}672 \times 10^{-8}$cm^3/gs^2); δ is the density contrast between the seawater and the ocean bottom topographic mass; D^{ship} is the shipborne seafloor depth; D_{max} is the maximum depth of the seafloor in the study area.

Then, the long-wavelength gravity anomaly is calculated by the equation:

$$\Delta g^{long} = \Delta g^{ship} - \Delta g^{short} \quad (2)$$

For the points where only gravity anomalies are known, depths should be determined (points of the DTU17GRAV model have been fitted with shipborne gravity anomaly, Δg^{fit}) and long-wavelength gravity anomalies are interpolated from the available points (Δg_{int}^{long}). Then, the short wavelength gravity anomalies of these points are calculated:

$$\Delta g^{short} = \Delta g^{fit} - \Delta g_{int}^{long} \quad (3)$$

The gravity anomaly-derived depth (D^{grav}) can be calculated using the equation:

$$D^{grav} = \frac{\Delta g^{short}}{2\pi G\delta} + D_{max} \quad (4)$$

3.2 Determination of the optimal density contrast between the seawater and the ocean bottom topographic mass by iterative method

To determine the optimal density contrast, the seafloor depth inversion from gravity anomalies is performed iteratively several times. At each time, a different density contrast is used: (1) First, a theoretically consistent density contrast value is given; (2) Next, the gravity anomaly-derived seafloor depths are calculated and compared with the shipborne seafloor depths to estimate the accuracy of these depths. Then, the density contrast value is changed and the calculation process is repeated. Finally, the optimal density contrast is determined corresponding to the smallest deviation between the gravity anomaly-derived depth and the shipborne depth. In other words, the accuracy of gravity depth is the best. The comparison between the gravity anomaly-derived depth with the shipborne depth is made as follows (Nguyen, 2023):

Depth deviations are calculated according to the equation:

$$\delta D_i = D_i^{grav} - D_i^{ship},\ i = 1, 2, \ldots, n; \tag{5}$$

where: n is the number of shipborne depth points; D_i^{ship} is the shipborne depth; D_i^{grav} is the gravity anomaly-derived depth.

The average depth deviation is calculated according to the equation:

$$\delta D_{ave} = \frac{1}{n}\sum_{i=1}^{n} \delta D_i \tag{6}$$

Standard deviation of the depth:

$$STD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\delta D_i - \delta D_{ave})^2} \tag{7}$$

Root mean square of the deviation:

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \delta D_i^2} \tag{8}$$

The Pearson correlation coefficient between the gravity anomaly-derived depths and the shipborne depths (McKean et al., 2003):

$$R = \frac{\sum_{i=1}^{n}\left(D_i^{ship} - D_{ave}^{ship}\right).\left(D_i^{grav} - D_{ave}^{grav}\right)}{\sqrt{\sum_{i=1}^{n}(D_i^{ship} - D_{ave}^{ship})^2 . \sum_{i=1}^{n}(D_i^{grav} - D_{ave}^{grav})^2}} \tag{9}$$

Based on the root mean square of the deviation (RMSD), the standard deviation (STD), the Pearson correlation coefficient (R), the average depth deviation (δD_{ave}), the maximum deviation and the minimum deviation between the gravity anomaly-derived depths and shipborne depths and the optimal density contrast is selected in the study area.

4. RESEARCH RESULTS

According to the theory presented above, the experiments were performed with different density contrast options. Since the theoretical density contrast is 1.67 g/cm^3, the density contrast was investigated from 1.10 g/cm^3. The density contrast value in the next calculation time is determined based on the results of the previous calculation time, with the target being to minimize the *RMSD* value and maximize the *R* values. To find the optimal density contrast, the eight experimental options were calculated. The experimental results are summarized and presented in (Table 2).

Table 2. Summary results of the experimental options.

Expe. Options	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8
DC (g/cm^3)	1.10	1.20	1.30	1.40	1.50	1.67	2.0	3.0
(m)	849.3	887.2	918.8	944.3	964.9	1,012.9	1,075.1	1,148.5
(m)	-913.7	-931.7	-948.5	-964.0	-972.9	-991.9	-1,023.7	-1,137.0
(m)	-1.5	-1.4	-1.3	-1.2	-1.1	-1.1	-1.0	-0.9
RMSD (m)	±87.9	±86.4	±85.7	±85.5	±85.9	±86.5	±87.7	±90.8
STD (m)	±87.9	±86.4	±85.7	±85.5	±85.9	±86.5	±87.7	±90.7
R	0.99679	0.99691	0.99697	0.99699	0.99697	0.99693	0.99685	0.99663

The chart of RMSD according to the experimental options is shown in (Figure 3).

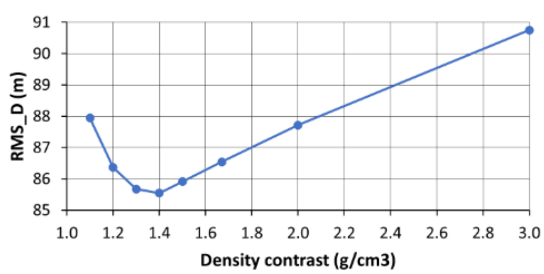

Figure 3. RMSD chart of the experimental options.

The chart of the Pearson correlation coefficient (R) according to the experimental options is presented in (Figure 4).

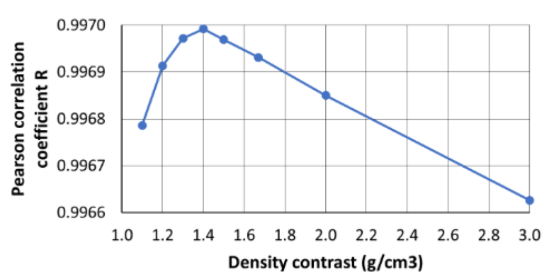

Figure 4. R chart of the experimental options.

The results of (Table 2), (Figure 3) and (Figure 4) show that as the contrast density (DC) increases from 1.10 g/cm^3 to 1.40 g/cm^3, the RMSD decreases from ±87.9 m to ±85.5 m, the Pearson correlation coefficient increases from 0.99679 to 0.99699. As the contrast density continued to increase from 1.40 g/cm^3 to 3.0 g/cm^3, the *RMSD* increased from ±85.5 m to ±90.8 m and the Pearson correlation coefficient decreased from 0.99699 to 0.99663. These results prove that the optimal density contrast in the study area is 1.40 g/cm^3.

5. CONCLUSION

The iterative method has been studied and applied to determine the optimal density contrast in the seafloor depth inversion from the gravity anomalies on the central East Sea. First, the density contrast is assigned a theoretically appropriate value. Then, the seafloor depths were calculated from the gravity anomalies corresponding to the given density contrast. Gravity anomaly-derived depths are compared with shipborne depths to evaluate their accuracy. Next, based on the accuracy evaluation results of the previous step to, change the density contrast value and repeat the calculation process. Finally, the optimal density contrast is selected based on the results of the accuracy evaluation of the experimental options.

From the experimental results of the eight options, the optimal density contrast on the central East Sea was selected as 1.40 g/cm^3. Corresponding to this optimal density contrast shows that the root mean square deviation is the smallest, RMSD = ±85.5 m and the Pearson correlation coefficient between gravity anomaly-derived depths and shipborne depths is the largest, R = 0.99699.

6. ACKNOWLEDGMENTS

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