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A comparative study on some regional and local - residual separation of gravity anomalies for synthetic example and a case study from Mekong River, Vietnam

NGUYEN Hai[1,2,5*], NGUYEN Thanh[1,5], DANG Duy[3,5], TO Loan[4,5*]

[1] Climate Change Institute, An Giang University, An Giang, Vietnam
[2] Faculty of Science, Nong Lam University, Ho Chi Minh City, Vietnam
[3] Faculty of Physics and Engineering Physics, University of Science, Ho Chi Minh City, Vietnam
[4] Personnel Office, An Giang University, An Giang, Vietnam
[5] Vietnam National University, Ho Chi Minh City, Vietnam
[*] *Corresponding email: nguyenhonghai.1987vn@gmail.com*

Abstract: *The division of anomalies into regional and local components is a critical and preliminary step when analyzing potential field data, including magnetic and gravity datasets. The regional component represents long-wavelength variations in the potential field associated with large-scale geophysical features, including crustal structures, tectonic boundaries, and density variations within the Earth's interior. Conversely, the residual component corresponds to shorter-wavelength variations linked to local geological structures or specific anomalies of interest. In Vietnam, researchers have employed various analytical methods such as the moving average (MA) and the quadratic least squares (QLS). However, due to the nonlinear and non-stationary nature of magnetic and gravity fields, these methods may not provide optimal solutions. In this study, we suggest a different method that utilizes bidimensional/image empirical mode decomposition (BEMD/iEMD) instead of Fourier and wavelet transforms. To assess the effectiveness of our method, we conducted validation using a gravitational anomaly model consisting of six spherical blocks, which yielded reliable results. Furthermore, we applied the MA, QLS, and iEMD methods to analyze Bouguer data from the Mekong River (in Vietnam), covering the region from the west of the Saigon River to the southwestern coastal area. Comparative analysis demonstrated that the iEMD method outperformed the MA and QLS methods as it allowed for simultaneous analysis of multiple local and regional components. This approach facilitated the generation of local maps and regional maps corresponding to the source field at various depths.*

Keywords: *gravity field, regional component, residual component, separating field technique, bidimensional/image empirical mode decomposition, Mekong river*

1. Introduction

Potential field data (e.g., magnetic and gravity data) are common in geophysical surveys. These data are used not only in geological structure investigation and natural resource surveys but also widely in geotechnical and environmental geology. The observed magnetic/gravity anomaly field is the total field reflecting all geological factors, in which each geological element contributes to the observed field. In gravity/magnetic data processing, the separation of gravity anomalies provides regional anomalies and local anomalies, which is the first and the most important step. Because it helps define the right object of study in the next step of the analysis. There have been many separation methods, such as the moving average (MA) method [1], and the quadratic least squares (QLS) method [2]. These separation methods are only applied to fields (gravity and magnetic field) that are considered stationary and linear while they are non-stationary and nonlinear. So the Empirical Mode Decomposition (EMD) method is suitable in this case. In 2003, Nunes et al. [3] developed this 2D method for image structure analysis, which later found broad applications across various fields. In geophysics, Pei et al. [4], Al-Rahim [5], Mandal et al. [6] used it to separate the gravity field; Hou et al. [7], Ma et al. [8] used it to separate the magnetic field; Chen et al. [9] separated both the magnetic and gravity fields. Recently, this method has also been applied in mineral exploration, such as searching for various types of ores, such as copper-tin, tungsten-lead ores, and gold mines in many places in China [10-13], studying the crustal structure of the Earth in the Gangdise Range, Tibet [14].

Therefore, a study is needed to compare the effectiveness of these methods in extracting anomalies from the original data source. This paper presents our evaluation of the iEMD method applied to an simulated gravity model and actual data – the Bouguer gravity data of the Mekong River (Vietnam) and its adjacent areas – and assesses the results alongside those obtained using two typical methods used in Vietnam: the MA method and the QLS method.

2. Methodology

2.1. The Moving Average (MA) method

MA method is a technique that can be employed to differentiate between regional and local anomalies/residuals through a similar approach to low-pass filters. This method permits low-frequency signals from gravity anomalies to pass through, yielding regional anomalies (ϕ_{reg}) as the result. The residual anomaly (ϕ_{res}) is then determined by subtracting the total Bouguer anomaly (ϕ) from the regional anomalies. MA method is applied by computing the average anomaly values. The MA filter works by dividing the input signal by a threshold value to create boundaries on the output signal. The mathematical equation is stated [15]:

$$\phi_{reg}(x,y) = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{\phi(x,y)}{\frac{n+m}{2}} \qquad (1)$$

and its corresponding residual anomaly is given by [15]:

$$\phi_{res}(x, y) = \phi(x, y) - \phi_{reg}(x, y) \quad (2)$$

where: x is row, and y is column; n and m are the window size.

The moving average method uses a window size [n, m] in its calculation process, where the window size determines the amount of data included in the averaging process. This window size is determined through spectrum analysis, which involves carrying out the Fourier transformation process to break down a signal into several component signals.

2.2. The Quadratic Least Squares (QLS) method

The QLS method is a mathematical technique used to fit a quadratic function to the observed gravity data. It aims to approximate the regional component by modeling it as a quadratic surface. This method involves solving a system of equations that minimizes the cumulative squared deviations between the measured gravity values and the values generated by the quadratic function. For the case of the simple plane, the resulting quadratic surface represents the regional component $\phi_{reg} = Ax + By + C$, and the residual component ϕ_{res} is obtained by subtracting the predicted values from the measured data ϕ.

For the case of the complex plane, the equation of the regional anomaly would be [15]:

$$\phi_{reg} = Ax^2 + By^2 + Cxy + Dx + Ey + F \quad (3)$$

and the residual anomaly would be: $\phi_{res} = \phi - \phi_{reg}$ (4)

The system of equations (5) to determine the coefficients A, B, C, D, E and F is as follows[15]:

$$\begin{aligned}
&A\sum_{i=1}^{n}x_i^4 + B\sum_{i=1}^{n}x_i^2y_i^2 + C\sum_{i=1}^{n}x_i^3y_i + D\sum_{i=1}^{n}x_i^3 + E\sum_{i=1}^{n}x_i^2y_i + F\sum_{i=1}^{n}x_i^2 = \sum_{i=1}^{n}x_i^2\Delta\phi(x_i,y_i)\\
&A\sum_{i=1}^{n}x_i^2y_i^2 + B\sum_{i=1}^{n}y_i^4 + C\sum_{i=1}^{n}x_iy_i^3 + D\sum_{i=1}^{n}x_iy_i^2 + E\sum_{i=1}^{n}y_i^3 + F\sum_{i=1}^{n}y_i^2 = \sum_{i=1}^{n}y_i^2\Delta\phi(x_i,y_i)\\
&A\sum_{i=1}^{n}x_i^3y_i + B\sum_{i=1}^{n}x_iy_i^2 + C\sum_{i=1}^{n}x_i^2y_i^2 + D\sum_{i=1}^{n}x_i^2y_i + E\sum_{i=1}^{n}x_iy_i^2 + F\sum_{i=1}^{n}x_iy_y = \sum_{i=1}^{n}x_iy_i\Delta\phi(x_i,y_i)\\
&A\sum_{i=1}^{n}x_i^3 + B\sum_{i=1}^{n}x_iy_i^2 + C\sum_{i=1}^{n}x_i^2y_i + D\sum_{i=1}^{n}x_i^2 + E\sum_{i=1}^{n}x_iy_i + F\sum_{i=1}^{n}x_i = \sum_{i=1}^{n}x_i\Delta\phi(x_i,y_i)\\
&A\sum_{i=1}^{n}x_i^2y_i + B\sum_{i=1}^{n}y_i^3 + C\sum_{i=1}^{n}x_i^2y_i + D\sum_{i=1}^{n}x_iy_i + E\sum_{i=1}^{n}x_iy_i + F\sum_{i=1}^{n}y_i = \sum_{i=1}^{n}y_i\Delta\phi(x_i,y_i)\\
&A\sum_{i=1}^{n}x_i^2 + B\sum_{i=1}^{n}y_i^2 + C\sum_{i=1}^{n}x_iy_i + D\sum_{i=1}^{n}x_i + E\sum_{i=1}^{n}y_i + F.n = \sum_{i=1}^{n}\Delta\phi(x_i,y_i)
\end{aligned} \qquad (5)$$

The equations presented above constitute a linear system with variables A, B, C, D, E, and F. By resolving this system, we can acquire the values of these variables, which will subsequently facilitate the calculation of the anomaly value in the area [15].

2.3. The Image Empirical Mode Decomposition (iEMD) method

The sifting process employs morphological techniques to identify local maxima in the region and utilizes radial basis interpolants to create surface estimations. In this approach, the potential data can be represented as a two-dimensional grid signal ϕ (x, y) (x = 1, …, M; y = 1, …, N). The following steps outline the details of this approach:

(1) Calculate the mean boundary by deriving it from the maximum boundary (u_{max}) and the minimum boundary (u_{min}). This process necessitates identifying the local extrema of ϕ (x, y) and executing surface estimations to define these boundaries. Note: To ensure valid interpolation and mitigate boundary condition issues, data extension is typically employed.

$$u_{mean} = (u_{max} - u_{min})/2 \tag{6}$$

(2) Calculate δ_{ik} (x, y) by removing the mean boundary from the measured value. It represents the kth iteration during the ith sifting process.

$$\delta_{ik} = \phi - u_{mean} \tag{7}$$

(3) Verify whether the stopping condition is met. If this is not the case, set δ_{ik} as ϕ (x, y) and go through steps 1 and 2 again to carry out a single iteration. Conversely, if the stopping condition has been achieved (indicating that δ_{ik} is an image intrinsic mode function (IF)), calculate the residue by subtracting δ_{ik} from the measured value and assign the residue as ϕ (x, y).

$$r_1 = \phi - \delta_{1k} \tag{8}$$

(4) Perform steps 1 to 3 repeatedly until the residue is below the threshold or becomes constant or exhibits monotonic behavior. The resulting decomposition is represented as follows:

$$\phi(x, y) = \sum_{i=1}^{n} \delta_{ik} + r_n \tag{9}$$

where, r_n is the the last image intrinsic mode function); δ_{1k}, δ_{2k}, δ_{3k} …are IF components, and they correspond with decreasing frequency ranges [3].

3. Results

3.1. Analyzing a gravity field model

To examine the efficiency of separating methods a synthetic geological model is constructed. The model consists of 6 spherical blocks with parameters given in Table 1. The gravity field of the model is calculated on a grid of 61x61, where sphere A1 (at the center of the grid) is considered the source of the regional field, and spheres B1-B5 (at the center and near the four corners of the grid) are considered as the sources of the local anomalies. The gravity field of the model is represented in Fig.1 as contour lines. The local anomalies are relatively small and located near the corners, and no local field caused by the small sphere at the center is observed. Gravity field of the model was calculated using MATLAB, applying the knon densities and geometies of the spheres, and the resulting gravity anomalies were computed at each grid point based on the contributions from each spherical source.

The outcomes of the model analysis, which utilizes the iEMD method, QLS method, and MA method with an 11x11 window, are presented in Fig.2 and Fig.3. The findings indicate that the results obtained from the iEMD method align with the outcomes from the other two methods. All three methods effectively separate the observed anomaly into two components: the local field (Fig.2) and the regional field (Fig. 3).

Tab. 1. *The parameters of the model with 6 sphere objects*

Object	**A1**	**B1**	**B2**	**B3**	**B4**	**B5**
X (km)	31	31	11	11	51	51
Y (km)	31	31	11	51	11	51
Depth (km)	40	7	7	7	7	7
Radius (m)	25	5	5	5	5	5

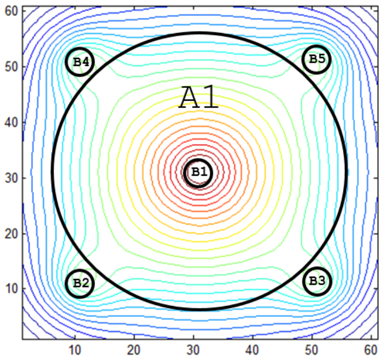
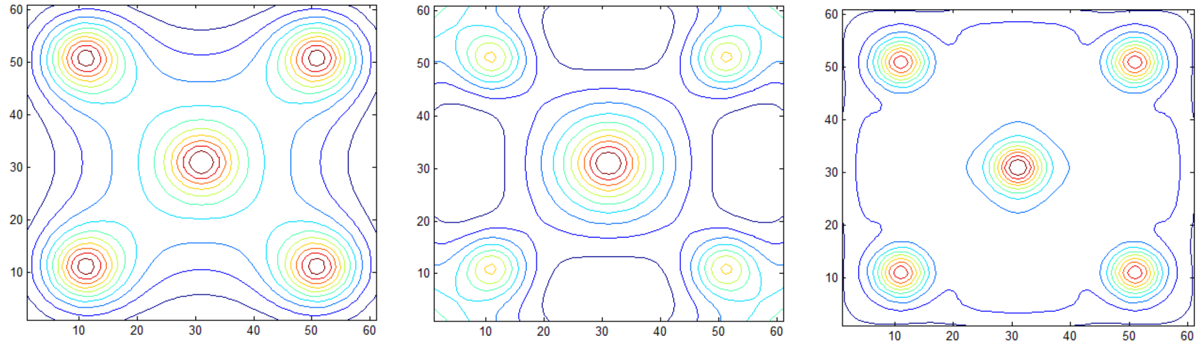
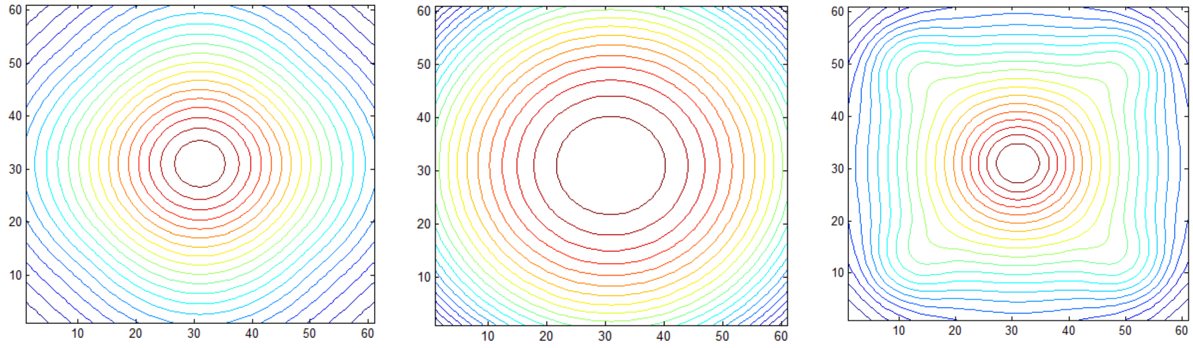


Fig. 1. Gravity field of the model with 6 sphere objects



(a) (b) (c)

Fig. 2. The local fields sifted by: (a) the iEMD; (b) the QLS and (c) the MA method



(a) (b) (c)

Fig. 3. The regional fields sifted by: (a) the iEMD; (b) the QLS and (c) the MA method

Due to the fields of the model having only one maximum in the center and four small maxima near the four corners, the analysis using the iEMD method was performed with one intrinsic mode function (IF) and one residual fumction. Fig.2a depicts the intrinsic mode function (corresponding to high frequency) calculated by the iEMD method, which showcases the patterns of the fields from the five small spheres (B1-B5), including the central sphere B1. Hence, it can be concluded that this intrinsic mode function corresponds to the local fields of the model. Fig. 2b represents the residual (corresponding to low frequency) calculated by the iEMD method, illustrating the field pattern of sphere A1, which represents the background field of the model (the regional field). These results align with the analysis outcomes using the QLS method and the MA method. The regional field separated by the iEMD method (Fig.3a) closely resembles the results of the QLS analysis (Fig.3c). Meanwhile, the local fields (Fig.2a) obtained through the iEMD analysis exhibit greater clarity and more accurate positioning of the small spheres compared to the other two methods (Fig.2b-c). This demonstrates the reliability of the iEMD method, leading us to apply this method for analyzing the gravity data of the Mekong River in Vietnam.

3.2. Applying the iEMD method on the gravity data of the Mekong River (Vietnam)

In this study, the research area is primarily focused on the lower Mekong River region in Vietnam (Fig.4) [16]. Situated in the southern part of Vietnam, this region encompasses the vast and dynamic delta of the Mekong River, along with its surrounding areas. The lower Mekong River region holds great significance both ecologically and economically.

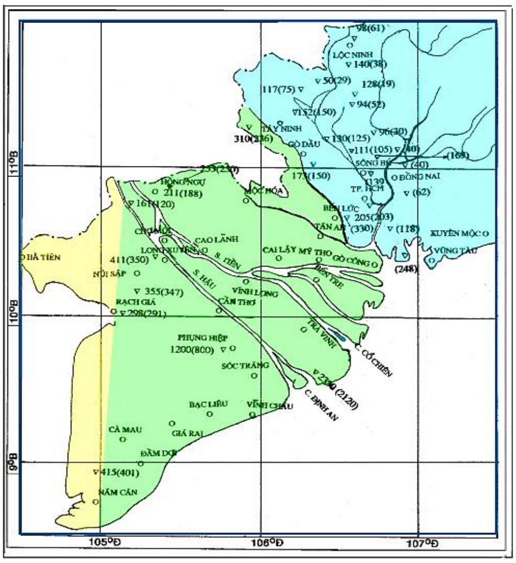
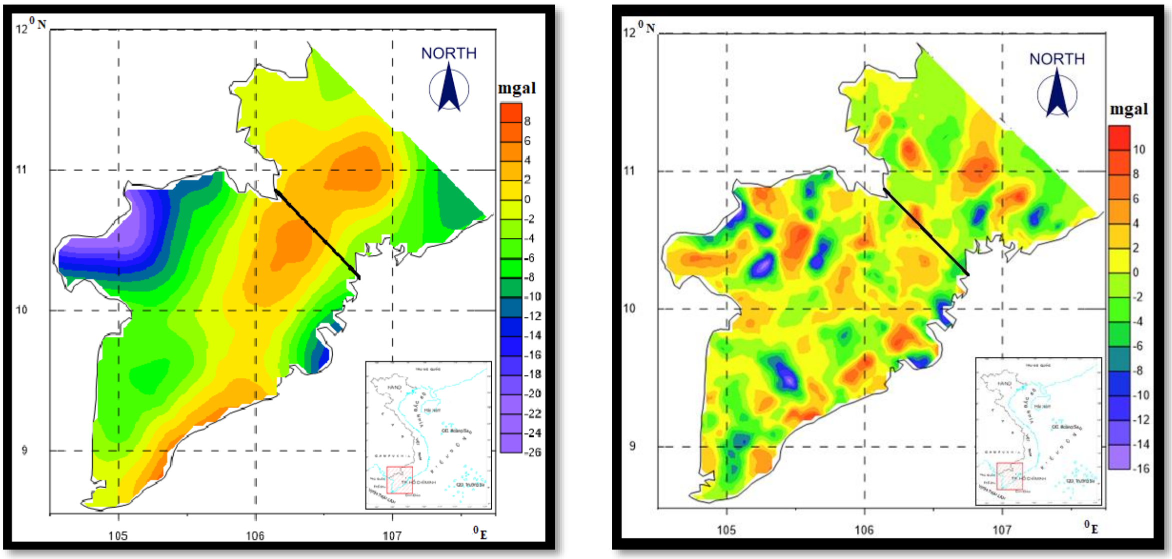


Fig. 4. The geological framework of Southern Vietnam: Bien Hoa subzone (cyan), Can Tho zone (green) and Ha Tien zone (yellow) [16]

To evaluate the performance of the three methods, the Bouguer gravity anomaly map provided by PetroVietnam is chosen as the dataset. This map, with a scale ratio of 1/500,000 and contour interval of 2mgal, was originally developed by Phan Quang Quyet et al. in 1981 based on the gravity anomaly map of the Petro-Mekong Delta Association. For analysis purposes, the map data was interpolated into a grid format measuring 84x52, with a grid spacing of 5km [17].

3.2.1. The MA map

The "averaging with 11x11 window" map exhibits the characteristics of regional anomalies, with relatively large anomalies oriented along the meridian (Fig.5a), including a positive anomaly region encompassing Bien Hoa and Soc Trang that is sandwiched between two negative anomaly regions, Can Tho - Ca Mau and a negative anomaly region along the coast. In contrast, the residual averaging map (Fig.5b) is a local map with small-sized anomalies that correspond to agricultural and noise sources. The anomalies are distributed along the boundaries between positive/negative anomaly regions of the area.

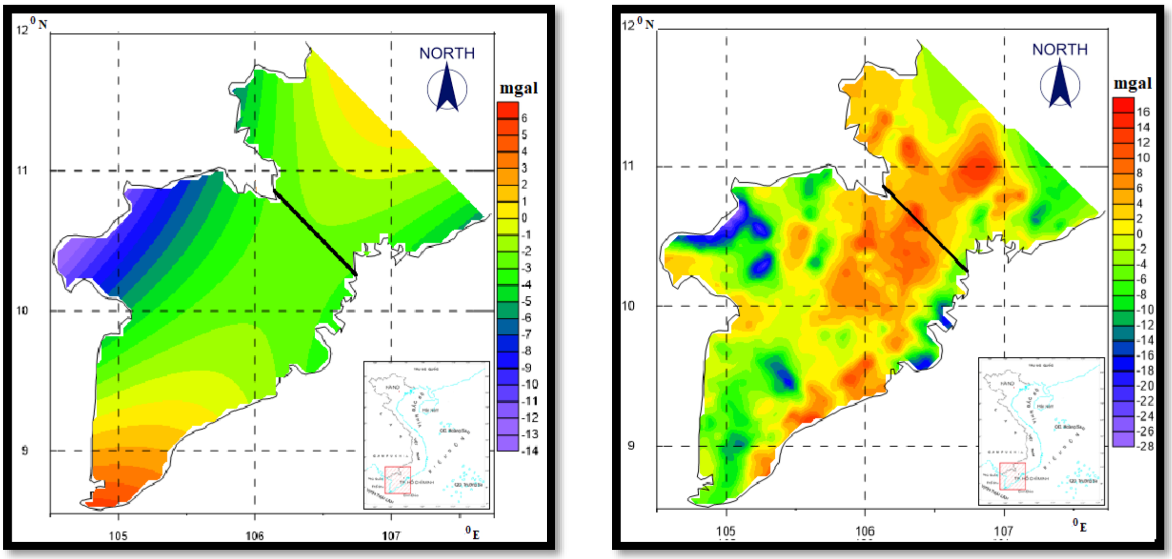


(a) regional (b) residual – local

Fig. 5. Separation of the Mekong gravity field by the MA method

3.2.2. The QLS map

The QLS map reflects the structure of a regional map (Fig.6a), with the prominent anomaly of Bien Hoa connected to the Kien Giang - Ca Mau anomaly dividing a negative anomaly region along the Cambodian border and a negative anomaly region in the coastal area.



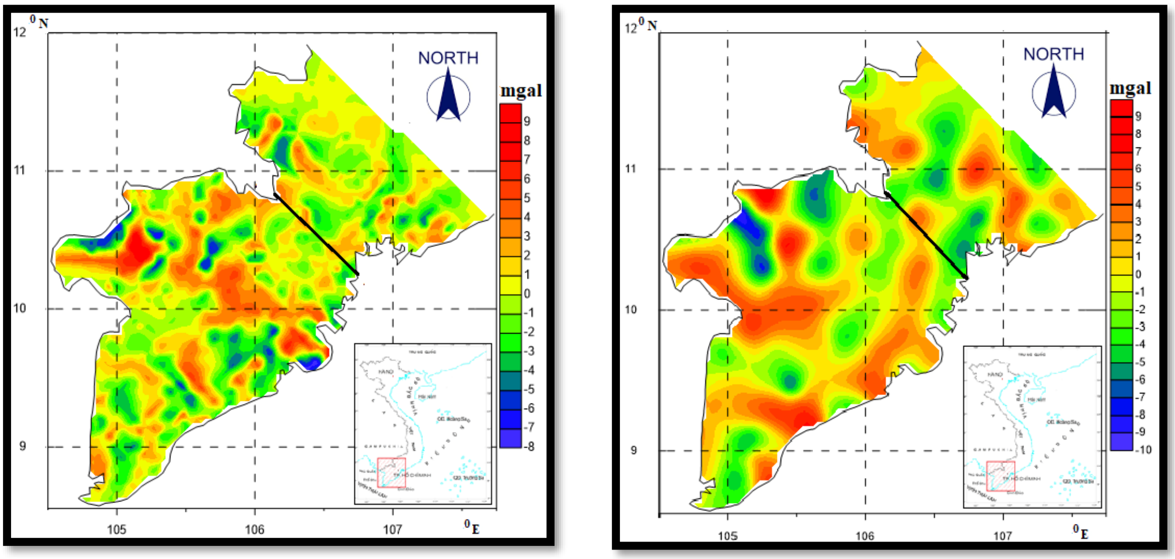
(a) regional (b) residual – local

Fig. 6. Separation of the Mekong gravity field by the QLS method

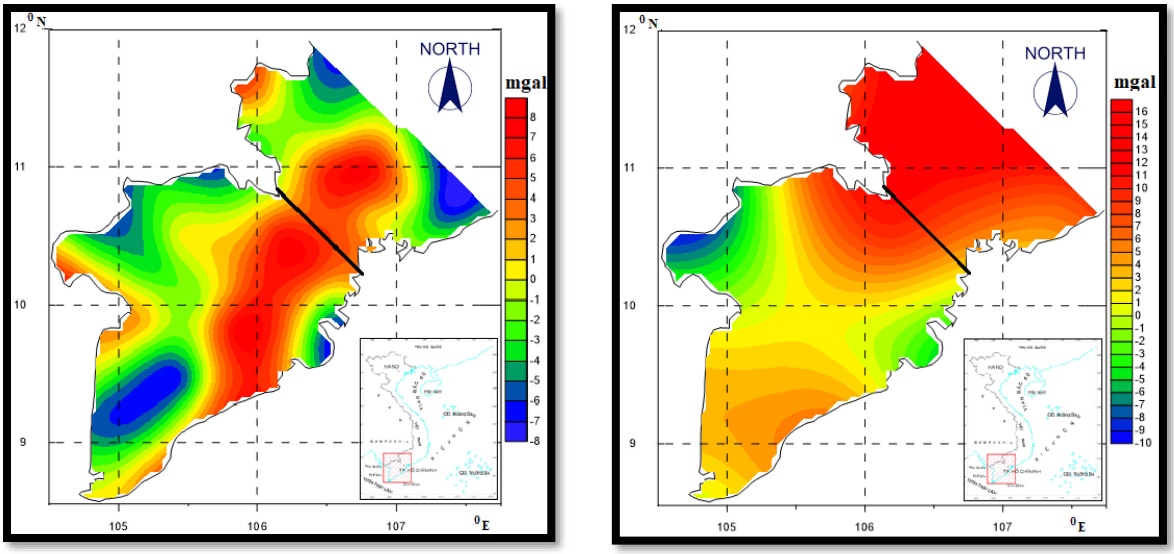
The residual QLS map (Fig.6b) maintains the shape of the Bouguer gravity anomaly map. The anomaly field still consists of alternating positive and negative anomalies with a NE-SW trend running along the boundary of the uplifted and subsided regions. The structure shows a positive anomaly region consisting of two positive anomalies of the Bien Hoa and Soc Trang fault zones connected; the negative anomaly region of Ca Mau - Dong Thap to the west and the negative coastal anomaly region to the east from the Dinh An to Xuyen Moc estuary.

3.2.3. The iEMD method

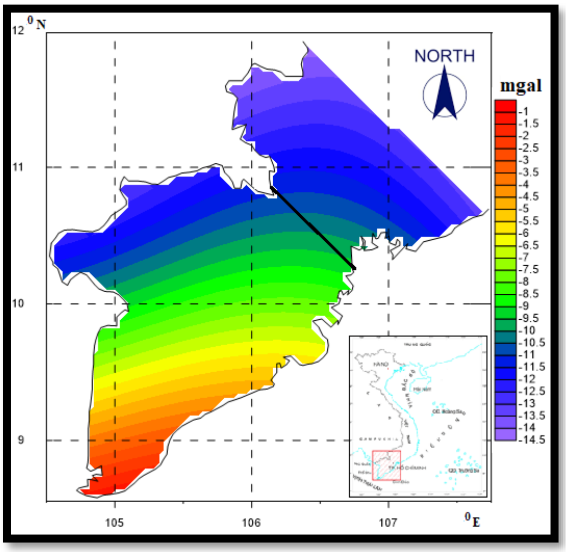
As illustrated in Fig. 7, the analysis yields four image intrinsic mode function (IF) maps, each representing gravity values at distinct levels. The fifth map corresponds to the trend of the measured signal, which aligns with the regional gravity field. The total of IF1 + IF2 + IF3 + IF4 + IF5 matches to the measured data.



(a) IF1 (b) IF2



(c) IF3 (d) IF4



(e) IF5

Fig. 7. Separation of the Mekong gravity field by the iEMD method

These findings highlight the significance of the iEMD method in effectively delineating gravity values with finer details.

The first image intrinsic mode function map – IF1 primarily captures shallow or subsurface faults, exhibiting the highest frequency component and revealing local anomalies with more intricate features compared to the Bouguer anomalies map. The anomalies observed in IF1 (Fig.7a) manifest along the boundaries between contrasting anomalies on the Bouguer map, providing substantial support for the main tectonic framework of the Mekong Delta and its neighboring areas.

The second image intrinsic mode function map – IF2 (Fig.7b) focuses on local anomalies at greater depths than IF1, exposing fault systems that run in the northwest-southeast and northeast-southwest directions with enhanced clarity and distinct structural divisions, particularly in the crystalline basement.

The third image intrinsic mode function map – IF3 (Fig.7c) represents regional anomalies originating from intermediate depths. Most small anomalies vanish, leaving behind significant positive and negative anomalies situated within the uplifting and subsiding geological structures of the region. Notably, the positive anomaly resides on the Bien Hoa uplift and the adjacent Soc Trang uplift, while the negative anomaly dominates the entire Dong Thap - Can Tho basin, extending towards Tay Ninh.

The forth image intrinsic mode function map – IF4 (Fig.7d) exhibits the shape of the deep source, possibly corresponding to the Moho discontinuity surface. Along the Mekong River in Vietnam, two positive anomalies are discerned, with a prominent and extensive anomaly in the north, serving as an extension of the central anomaly, and a weaker and smaller positive anomaly in the south. These anomalies are separated by a transition zone around the Hau River fault, which rises centrally and gradually descends towards the east and west.

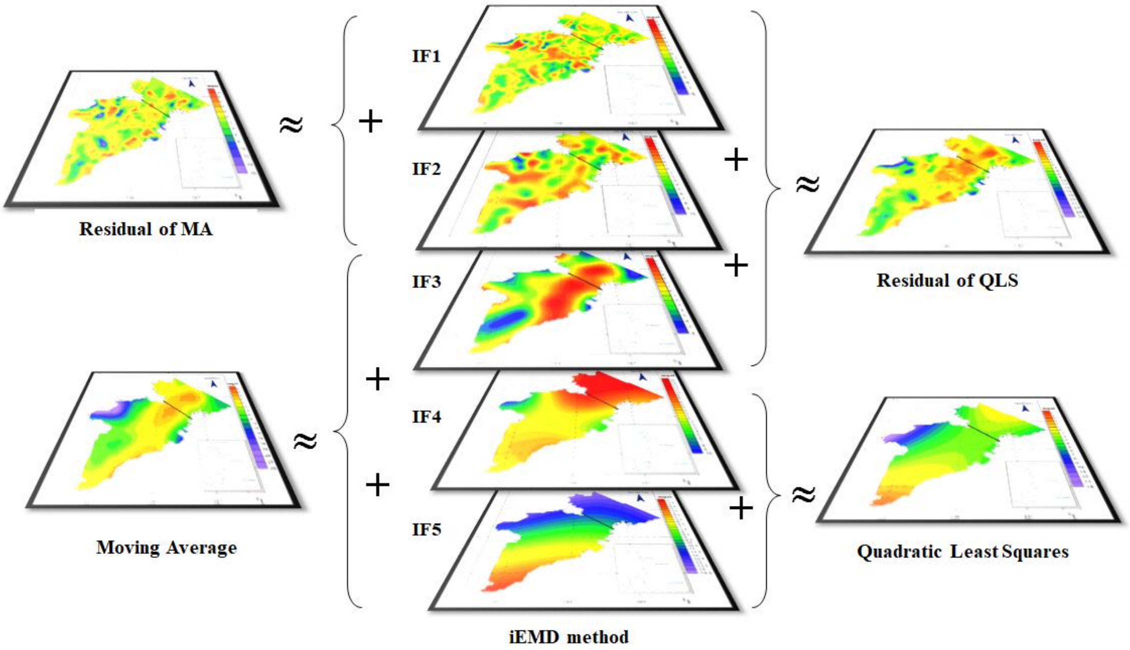
The last image intrinsic mode function map – IF5 (Fig.7e) assues the shape of a deep source with a monotonic pattern, potentially representing the deeper surface of the Earth's crust, aligning with the overall gravity field "trend".

5. Discussion

Until now, here has been no universally defined criterion for distinguishing between local anomalies and regional anomalies, which depends on the research field and the scale of the map used. The map used in this chapter has a scale of 1/500,000 with each measurement step being 5 km.

Striving to evaluate the iEMD method against the QLS method to isolate the Bouguer gravity data (Fig. 4), the regional map (Fig.6b) has nearly similar to the IF4 map (Fig.7d). It means that the regional value of the QLS method is equal to the sum of the IF4 and the IF5; and the local value of the QLS method is equal to the sum of IF1, IF2, and IF3 (Fig.8). In this case, IF4 and the regional map of the QLS method clearly show regional structural blocks; but, IF4 is sharper and has strengthened (especially, showing Bien Hoa lifting block).

In comparison with the MA method (Fig.5), several tests are done and the window 11x11 is selected because a regional anomalies map (Fig.5a) was found to be nearly similar to the IF3 (Fig.7c), the two maps are smooth, and it reflects the region anomalies with smaller size. The positive anomaly located in the Bien Hoa uplift is connected to the adjacent Soc Trang uplift anomaly, having the form of a saddle. It means that the regional value of the MA method is equal to the sum of IF3, IF4, and the residual value; and the local value of the MA method is equal to the sum of the F1, and the IF2 (Fig. 8).



Note: IF4 is similar to the QLS map; thus, IF4 + IF5 approximates the regional map (QLS), while IF1 + IF2 + IF3 approximates the local map (QLS residual). In the MA method, IF3 is similar to the MA map; hence, IF3 + IF4 + IF5 approximates the regional map (MA), and IF1 + IF2 approximates the local map (MA residual).

Fig. 8. Comparison of iEMD methods with QLS and MA

Therefore, the iEMD method allows for the simultaneous analysis of multiple intrinsic mode function components, corresponding to both local anomaly maps and regional anomaly maps corresponding to field sources at different depths, while the MA and QLS methods can only find one local anomaly map and one regional anomaly map. Therefore, it can be said that the iEMD method can be well applied in the separation of fields and yields rich results.

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6. Conclusion

This paper compares three different methods for processing gravity field data: the moving average method, the quadratic least squares method, and the nd the Image Empirical Mode Decomposition method, a cutting-edge technique for processing nonlinear and non-stationary signals which are widely used in many fields of research. Testing on a gravity model shows that the result analyzed by iEMD similarities to two other methods. In analyzing the real gravity data of lower Mekong River region, iEMD has been established as a more fitting option than the MA and the QLS method. The MA method is a straightforward and computationally efficient technique that is suitable for quick regional-residual separation. However, it may overlook complex features in the gravity field. The QLS method provides a quadratic surface approximation of the regional component. It is more suitable for capturing subtle variations in the gravity field. However, it assumes a quadratic nature for the regional field, which may not always be appropriate for complex and nonlinear datasets. On the other hand, iEMD is a more advanced technique that adaptively divides the data into Image Intrinsic Mode Functions (IFs). This allows for a more detailed and adaptive separation of regional and residual components, especially in complex and nonlinear datasets. iEMD does not require any preset parameters, making it more suitable for analyzing observed anomalies in the gravity field. The results obtained from iEMD show similarities to the results from the moving average and quadratic least squares methods, but with sharper and strengthened local anomalies.

Overall, iEMD proves to be a more advanced and powerful technique for analyzing gravity field data compared to the MA and QLS methods. Its adaptive decomposition capabilities and ability to extract detailed components make it a valuable tool for studying complex and nonlinear datasets in geophysical research. This separation is crucial for interpreting and understanding the underlying geophysical features in the area, such as crustal structures, tectonic boundaries, and density variations within the Earth's interior.

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