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VIETNAM ACADEMY OF SCIENCE AND TECHNOLOGY

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Volume 2

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in the Era of a Nation's Rise



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AND ENVIRONMENTAL SCIENCES FOR SAFE
AND SUSTAINABLE DEVELOPMENT**

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**Earth, Mine, and Environmental Sciences for Green, Sustainable,
and Prosperous Development in the Era of a Nation's Rise**

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Construction of a gravity model for the East Sea for application in wave energy potential assessment

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Abstract: In wave energy potential assessment, an approximate gravity value is often used, however, to achieve accurate results, it is necessary to determine the gravity value at each location with recorded significant wave height. The objective of this paper is to develop a gravity model for the East Sea to support the assessment of wave energy potential. To achieve the stated objective, modern global Earth Gravitational Models and ship-derived gravity in the East Sea were collected. The methods for deriving gravity anomalies/gravity values from global Earth Gravitational Models were examined. By comparing with ship-derived gravity, the most suitable global Earth Gravitational Model for the East Sea was identified. The gravity model for the East Sea, serving the assessment of wave energy potential, was developed based on the integration of the global EGM model with ship-derived gravity. The gravity values at locations requiring wave energy potential estimation were computed by interpolating from the gravity model using the inverse distance weighting method. Experimental results indicate that the SGG-UGM-2 model is the most suitable for the East Sea. The accuracy of the gravity model for the East Sea reaches ± 3.17 mGal.

Keywords: wave energy potential, gravity, East Sea, Earth Gravitational Model.

INTRODUCTION

In the context of increasing energy demand and the depletion of fossil fuel resources, the development of renewable energy has become an urgent requirement. Among marine renewable energy sources, wave

energy is considered to have great potential due to its stability, environmental friendliness, and large-scale exploitation capability. For the East Sea, several domestic and international studies have focused on assessing wave energy potential based on oceanographic observations, ECMWF reanalysis wind data, or numerical models such as SWAN and WAVEWATCH III (Ministry of Natural Resources and Environment, 2022; Curto et al., 2020; Miao et al., 2012; Do et al., 2022; Burhanudin et al., 2019; Le et al., 2017). However, these studies still face limitations such as low resolution, lack of analysis of long-term wave energy stability indices, and especially, the absence of direct utilization of satellite altimetry data.

Meanwhile, worldwide, numerous studies have applied satellite altimetry data to determine wave height and wave energy potential, achieving high accuracy when compared with buoy measurements (Jayaram et al., 2015; Hector et al., 2015; Uti et al., 2018; Kudryavtseva & Soomere, 2016; Queffelec & Bentamy, 2007; Su et al., 2017; Wan et al., 2015). These results confirm that satellite altimetry is an advanced, effective, and suitable method for developing wave energy potential maps.

Thus, it can be seen that although many successful studies worldwide have used satellite data to determine wave energy potential, in Vietnam and the East Sea, no research has deeply explored this application. Notably, no study has yet considered the factor of precise gravity in the problem of determining wave energy potential—a factor that significantly affects the calculation and mapping of wave energy resources.

In the East Sea, direct marine gravity surveys have been conducted since the 1990s with the participation of Vietnam and international partners. However, the collected data remain sparse, of uneven accuracy, and mainly served oil and gas exploration purposes (Bui, 2008). In contrast, satellite altimetry has demonstrated its ability to determine marine gravity anomalies with increasingly high coverage and accuracy, around $\pm 3-7$ mGal in many regions (Hwang & Parsons, 1995; Sandwell & Smith, 1997; Andersen, 2010). In Vietnam, some initial studies have applied satellite data such as ENVISAT, Saral/AltiKa and CryoSat-2 to compute gravity anomalies in the East Sea, but the results are still limited in scale, with errors usually ranging from ± 2.6 to 8.5 mGal (Nguyen, 2012; Nguyen et al., 2020). To date, there is still no accurate gravity model for the East Sea. Therefore, it is necessary to develop a gravity model for the East Sea by integrating direct measurements and satellite data to improve accuracy and effectively support the assessment of marine wave energy potential.

STUDY AREA AND DATA

Study Area

The study area is in the East Sea, bounded by latitudes $[5.5^{\circ}\text{N} - 25^{\circ}\text{N}]$ and longitudes $[104.5^{\circ}\text{E} - 117.5^{\circ}\text{E}]$ (Fig. 1). This sea region exhibits complex oceanographic conditions with various tidal regimes: the northern part is mainly diurnal, the central part is irregular diurnal, while the southern part varies from semidiurnal to diurnal tides with large amplitudes (Ha, 2015). The surface currents show distinct seasonal characteristics, forming large-scale cyclonic eddies and convection under the influence of monsoons and the Intertropical Convergence Zone (Rong, 1994; Xu et al., 1980). Wave heights in this area vary significantly, from less than 3 m in the Gulf of Thailand to over 12 m in the northeastern East Sea due to typhoons and the northeast monsoon (Le, 2005).

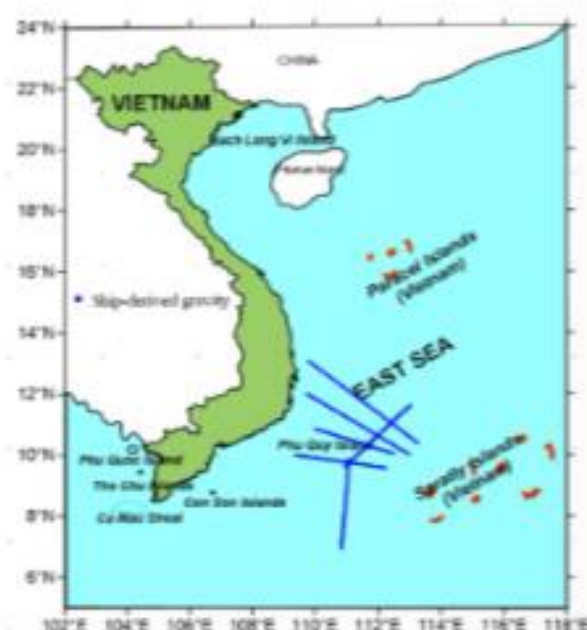


Figure 1. Study area and ship-derived gravity measurements

Research Data

a) Global Gravity Field Model Data

Global gravity field models have been developed by various organizations from 1966 to the present, amounting to 178 models. These data are provided by ICGEM (Ince et al., 2019). The accuracy of these models has been evaluated by comparing them with GNSS/leveling data at 24,014 points, and the standard deviations were computed. Specifically: Australia - 7,224 points, Brazil - 1,154 points, Canada - 2,702 points, Europe - 1,047 points, Japan - 816 points, Mexico - 4,898 points, and the USA - 6,169 points. Fig. 2 illustrates the accuracy of these models (Ince et al., 2019).

From this comparison, six recent models (EGM2008, EIGEN-6C4, GECO, SGG-UGM-1, XGM2019E, and SGG-UGM-2) were selected as the best fit with GNSS/leveling data for evaluation in the East Sea.

b) Shipborne Gravity Data

The gravity anomaly dataset (CSL07) was measured onboard the vessel Professor Polshkov in 2007 and 2008. The data were

processed by ARK Geophysics Ltd. in Ho Chi Minh City. The coordinates are given in the WGS-84 reference frame. The dataset includes bathymetry, gravity, Free-air and Bouguer anomalies, and magnetic data. Detailed information about this dataset is presented in (Institute of Marine Geology and Geophysics, 2007). In total, 86,162 measurement points were collected. The distribution of ship-derived gravity measurement points is shown in Fig. 1.

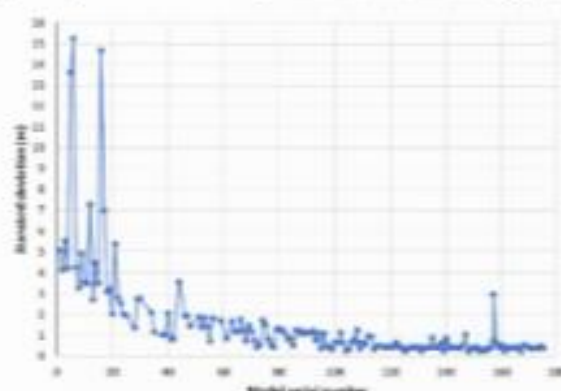


Figure 2. Standard deviations of global gravity field models compared with GNSS/leveling data (Ince et al., 2019).

RESEARCH METHODS

Overview of the Problem of Determining Marine Wave Energy

Wave power density is the most important parameter for evaluating wave energy resources. This parameter has often been calculated in recent studies by integrating spectral models based on numerical wave models. In this case, the wave power density (P_w) per unit crest length is calculated as follows (Iglesias et al., 2009):

$$P_w = \rho g \int_0^{2\pi} \int_0^{\infty} C_g(f, d) S(f, \theta) df d\theta \quad (1)$$

where ρ is the density of seawater (kg/m^3); g is the gravitational acceleration (m/s^2); C_g is the group velocity of wave energy propagation (m/s); $S(f, \theta)$ is the wave spectrum, f is the wave frequency (Hz), and θ is the wave propagation direction ($^\circ$); and d is the water depth (m) (Iglesias et al., 2009).

Wang & Lu (2009) pointed out that P_w is equivalent to the hydrodynamic pressure (p) on a vertical plane perpendicular to the propagation direction multiplied by the particle velocity (u) crossing the vertical plane, which can be expressed as follows:

$$P_w = \frac{1}{T} \int_0^T \int_{-d}^0 (p + \rho g z) u dt dz \quad (2)$$

where t is time (s); T is the wave period (s); and z is the water depth (m). The above equation can be integrated over the wave period and water depth. Therefore, P_w can be calculated using the following formula (Wang & Lu, 2009):

$$P_w = \bar{E} C_g = \bar{E} \left(\frac{g T_e}{2\pi} \tanh kd \right) P_e \quad (3)$$

where $\bar{E} = (1/16) \cdot \rho g H_s^2$ is the wave energy density (J/m^2); $k = 2\pi/\lambda$ is the wave number (m^{-1}), λ is the wavelength (m); and

$$P_e = \frac{1}{2} \left(1 + \frac{2kd}{\sinh 2kd} \right) \quad (4)$$

Thus, in order to calculate P_w , it is necessary to know the gravitational acceleration g at each point where wave height is measured. In previous studies, g was often assumed to be 9.81 m/s^2 (Deng et al. 2013; Sorek et al. 2023). Some other documents choose $g = 9.80665 \text{ m/s}^2$ (PyGNOME documentation; Seabird Scientific). However, this is only an approximate value and can affect the accuracy of the P_w calculation results.

Evaluation and Selection of EGM Models in the East Sea

The general formula for calculating gravity anomalies from the EGM model is as follows (Barthelmes, 2013; Sneeuw, 2006; NIMA, 2000):

$$\Delta g_{EGM} = \frac{GM}{r^2} \left[\sum_{n=2}^{N_{max}} \left(\frac{a}{r} \right)^n (n-1) \sum_{m=0}^n (\bar{C}_{n,m} \cos(m\lambda) + \bar{S}_{n,m} \sin(m\lambda)) \bar{P}_{n,m}(\sin \varphi) \right] \quad (5)$$

where: GM – geocentric gravitational constant; r – geocentric radius of the considered point; γ – normal gravity on the reference ellipsoid; a –

semi-major axis of the ellipsoid; φ , λ - geocentric latitude and longitude of the considered point; $\bar{C}_{n,m}$, $\bar{S}_{n,m}$ - fully normalized spherical harmonic coefficients of degree n and order m ; $P_{n,m}(\sin \varphi)$ - fully normalized associated Legendre functions; N_{max} - maximum degree of the model.

To evaluate the accuracy of the global gravity field models in the East Sea, we compared the gravity anomalies computed from the EGM models with those derived from shipborne gravity measurements. At ship-derived measurement points, both the observed gravity anomaly (Δg^{ship}) and the EGM-derived gravity anomaly (Δg^{EGM}) are available. The gravity anomaly deviation is calculated as follows:

$$\delta g_i = \Delta g_i^{EGM} - \Delta g_i^{ship}, i = 1, 2, \dots, n, \quad (6)$$

where: n is the number of measurement points.

The mean deviation is calculated as:

$$\delta g_{mean} = \frac{1}{n} \sum_{i=1}^n \delta g_i \quad (7)$$

If the mean deviation is approximately zero, it indicates that the difference between the ship-derived gravity anomalies and those determined from the EGM model has no systematic bias but is purely random. In this case, the root mean square error (RMSE) is calculated using the following formula (Hoang & Truong, 2003):

$$RMS_{\Delta g} = \sqrt{\frac{\sum_{i=1}^n (\delta g_i)^2}{n}} \quad (8)$$

If the mean deviation is not equal to zero, it indicates that the difference between the ship-derived gravity anomalies and those determined from the EGM model is systematic. In this case, the standard deviation is calculated using the following formula (Hoang & Truong, 2003):

$$STD_{\Delta g} = \sqrt{\frac{\sum_{i=1}^n (\delta g_i - \delta g_{mean})^2}{n-1}} \quad (9)$$

Gravity anomalies computed from the EGM model can also be evaluated using the correlation coefficient R with respect to the ship-derived gravity anomalies. The correlation coefficient R is a measure of the relationship between two datasets. R can range from -1 to $+1$. If $R = 1$, the two datasets are perfectly linearly correlated. If $R = -1$, the two datasets are perfectly negatively correlated. If $R = 0$, the two datasets have no linear correlation. Thus, if the EGM model fits well with the ship-derived measurements, their correlation coefficient will be approximately 1. The correlation coefficient R is calculated as follows (McKean & Sheather, 2003):

$$R = \frac{\sum_{i=1}^n (\Delta g_i^{ship} - \Delta g_{TS}^{ship})(\Delta g_i^{EGM} - \Delta g_{TS}^{EGM})}{\sqrt{\sum_{i=1}^n (\Delta g_i^{ship} - \Delta g_{TS}^{ship})^2 \sum_{i=1}^n (\Delta g_i^{EGM} - \Delta g_{TS}^{EGM})^2}} \quad (10)$$

Determination of Gravity at Points for Wave Energy Calculation

The gravity values at the points where wave energy is to be calculated are determined using the inverse distance weighting (IDW) interpolation method (Shepard, 1968). According to this method, within a circle of radius R around the target point (e.g., $R = 0.1^\circ$), gravity data points are selected. A minimum of four points should be used. If the number of points within the circle is fewer than four, R is increased by a factor of 1.5. This process can be automated in computational programming.

The weights are calculated using the inverse distance weighting formula (Shepard, 1968):

$$P_i = 1/D_i \quad (11)$$

where D_i is the distance from the target point to the i -th point with known gravity.

The gravity value at the target point for wave energy calculation is interpolated using the following formula (Shepard, 1968):

$$g_{inter} = \frac{\sum_{i=1}^n g_i P_i}{\sum_{i=1}^n P_i} \quad (12)$$

This method has the advantage of being applicable both when gravity data are provided as a grid and when they are available as discrete measurement points. The computational load is not too large, and it is suitable for regions with either strong or weak gravity variations. Therefore, in the problem of determining gravity values at satellite altimetry points for wave energy potential calculations, we propose using this method.

RESULTS AND DISCUSSION

Evaluation Results and Selection of EGM Models

Based on the above theoretical framework, we evaluated six EGM models: EGM2008, EIGEN-6C4, GECO, SGG-UGM-1, XGM2019E, and SGG-UGM-2 by comparing them with 86,162 ship-derived gravity measurement points. The evaluation results are summarized in Table 1.

Table 1. Evaluation results of the accuracy of six EGM models compared with ship-derived gravity data.

Model	δg_{max} (mGal)	δg_{min} (mGal)	δg_{mean} (mGal)	RMS (mGal)	STD (mGal)	R
EGM2008	22.05	-33.11	-0.45	3.70	3.68	0.968
EIGEN-6C4	23.69	-27.30	-0.50	4.06	4.03	0.963
GECO	21.83	-33.24	-0.61	3.75	3.70	0.975
SGG-UGM-1	21.72	-33.83	-0.63	3.70	3.65	0.975
XGM2019E	19.45	-27.44	-0.67	3.33	3.26	0.980
SGG-UGM-2	21.22	-23.40	-0.74	3.25	3.17	0.976

From the results in Table 1, it can be seen that all evaluated models show small mean deviations compared with the ship-derived gravity data, ranging from -0.45 mGal to -0.74 mGal. The standard deviations of the models vary from ± 3.17 mGal to ± 4.03 mGal. The smallest deviation is obtained with the SGG-UGM-2 model. Its accuracy reaches 3.17 mGal, with a very small mean deviation (-0.74 mGal), and the correlation between the SGG-UGM-2

model and the ship-derived data is very high (0.976).

The frequency distribution of the deviations of the SGG-UGM-2 model is shown in Fig. 3. From this figure, it can be observed that deviations with large values occur infrequently, while those with small values occur more frequently. This indicates that the frequency distribution of the deviations follows the normal distribution law of random errors. The number of deviations exceeding three times the root mean square error is small.

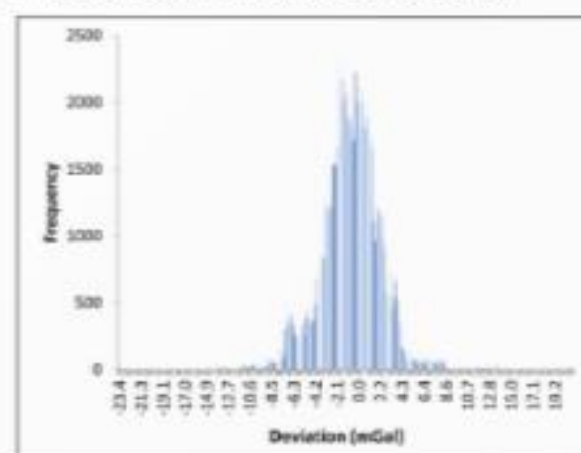


Figure 3. Frequency distribution of deviations for the SGG-UGM-2 model.

Thus, the comparison results indicate that the SGG-UGM-2 model is the most accurate in the East Sea. This is consistent with the fact that SGG-UGM-2 was the most recently developed among the six models evaluated and incorporated a wide range of available datasets. Furthermore, compared with the other models, SGG-UGM-2 utilized shipborne gravity measurements collected in Chinese seas adjacent to the Vietnamese East Sea, making it more suitable for this region.

Construction of the Gravity Model in the East Sea

Based on the SGG-UGM-2 model data combined with shipborne gravity measurements, we constructed a gravity model for the East Sea. The results are presented in Fig. 4. The maximum gravity value is 978,911.6 mGal, the minimum is 977,103.5 mGal, and the mean value is 978,389.4 mGal.

From Fig. 4, it can be seen that the gravity distribution over the East Sea exhibits spatial variation: higher gravity values are generally concentrated in the northern part of the basin, while lower values appear in the southern waters. This distribution reflects the general pattern of the gravity field and highlights the necessity of using an accurate gravity model to support the assessment of wave energy potential.

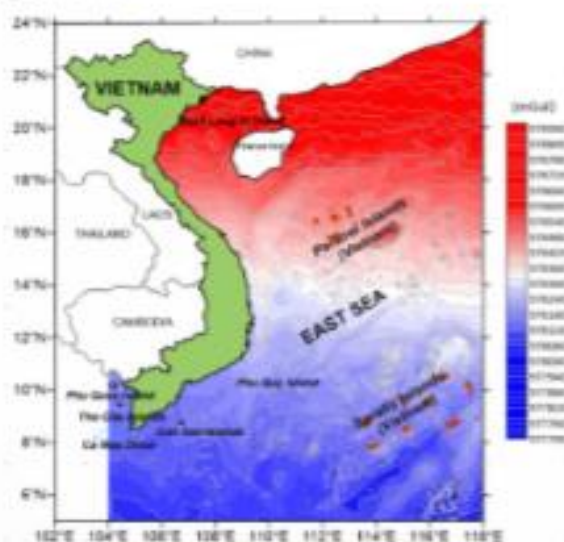


Figure 4. Gravity model over the East Sea for assessing wave energy potential.

CONCLUSION

This study evaluated six modern global Earth gravity models (EGMs) against ship-derived gravity data and identified SGG-UGM-2 as the most accurate for the East Sea. The model shows random deviations with a negligible mean bias (-0.74 mGal), the lowest standard deviation (± 3.17 mGal), and a strong correlation with shipborne observations ($R = 0.976$).

Using SGG-UGM-2 in combination with ship-derived measurements, a regional gravity model of the East Sea was developed to support wave energy assessments. The model yields gravity values ranging from $977,103.5$ to $978,911.6$ mGal, with an average of $978,389.4$ mGal. Its application is expected to enhance the accuracy of wave energy potential estimation based on satellite altimetry.

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