Subsurface Modeling using Gravity and TDEM in Jiken, Blora Regency

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Abstract. Geophysics plays an essential role in imaging the subsurface condition of the earth. Gravity and time-domain electromagnetic method is geophysical method that can be used to visualize the subsurface condition. In this research, gravity and TDEM surveys have been carried out in Jiken, Blora Regency. Modeling technique is needed to obtain the subsurface model that bring information related to subsurface condition. Inversion modeling is applied separately to the gravity data and TDEM data, respectively. The density interface inversion modeling is used to gravity data. Subsurface condition is approached by three layers model with different density contrast values in each layer. In these schemes, the modeling process will determine the thickness for every layer. While for TDEM modeling, differential evolution technique is applied to model the TDEM data. The subsurface condition is approached by four layers model. In these schemes, the modeling process will determine the resistivity and thickness for every layer. Finally, the model obtained from gravity inversion modeling is integrated into the model from TDEM inversion data by overlaying the model.

1. Introduction

Earth is composed of various types of rocks that vary both on the surface and subsurface. Rock variations on the surface can be observed directly, while changes that occur below the surface cannot be observed directly. One way to determine subsurface conditions is by conducting geophysical surveys. Geophysics plays an essential role in imaging subsurface conditions to obtain information related to subsurface conditions. Subsurface conditions are characterized by the physical properties of the rocks making up the earth. In this study, two geophysical methods will be discussed, namely the gravity method and time-domain electromagnetic (TDEM). The gravity method can be used to characterize subsurface conditions based on variations in the density of subsurface rocks. The TDEM method can be used to describe subsurface conditions based on differences in the conductivity value of subsurface rocks. To obtain subsurface images from both the gravity method and the TDEM method, a modeling technique is needed. In this study, inversion modeling techniques are applied to gravity data and TDEM data. The density interface inversion technique is used to gravity data, while the differential evolution inversion technique is used to TDEM data. The case study discussed is data from the Jiken area, Blora Regency.

2. Gravity Modeling using Interface Density Inversion

Modeling using gravity data for this work briefly illustrated as seen in figure 1. For computation of inverse problems we can set-up using simple body as model in the subsurface. Several series of prism (M-series model) are placed below each gravity data (N-series data). For each gravity data in the surface, we have two layers of vertical prism. Two layers in the subsurface will be used to provide sedimentary layer density ($\rho_s$) and basement density($\rho_b$). The densities for sedimentary and basement will be set as homogeneous for each vertical prism.
The 3rd International Conference on Geoscience and Earth Resources Engineering

IOP Conf. Series: Earth and Environmental Science 1031 (2022) 012005
doi:10.1088/1755-1315/1031/1/012005

Figure 1. Illustration of the subsurface model to explain: (a) the interface of homogeneous basement layer ($\rho_b$) and sediment layer ($\rho_s$) (flat topography) and (b) the interface between first ($\rho_{s1}$) & second ($\rho_{s2}$) layer of sedimentary rock ($\rho_s$).

Model in the subsurface (as discretization of sedimentary layer and basement) has three dimensional of $dx$, $dy$, and $dz$. Maximum depth will be set-up as as lower bound of basement, while the topography or elevation data will be used as constraint of upper bound of sedimentary layer. The solution of iterative calculation will be targeted for interface layer between the basement and sedimentary layer. The solution will be updated iteratively in the scheme of inverse modeling.

Misfit data evaluation will be determined using the differences value between observed ($g_{obs}$) and calculated ($g_{cal}$) data. The calculation of calculated data conducted using the equation described by Plouff [1]. The thickness of sedimentary layer ($dz(j)$) will be updated as solution using simple formulation (with modification from previous work [2]), as follow:

$$ dz^{(k+1)}(j) = dz^{(k)}(j) + \frac{Rand \times (g_{obs}(i) - g_{cal}(i))}{G \rho_s}, $$

where $i$, $j$, and $k$ respectively are mathematical notation for index number of data observation, prism model, and iteration number. Rand is random number and G is gravitational constant. In the equation (1) we use the last term of nominator and denominator to provide a rough estimation of updated solution.

We set the maximum iteration number to optimize the misfit value of observed ($g_{obs}$) and calculated ($g_{cal}$). After we get the thickness of the sedimentary layer ($dz(j)$) we continue to divide the sedimentary layer into two layers with different density. The observed data to be fitted in the next iteration (replaced observed gravity) is calculated by subtracting our $g_{obs}$ with $g_{cal}$ (gravity calculated of the basement) from the previous iteration. Model designed and formulated using lower bound of depth from the previous iteration. The illustration of model design and data to be fitted are shown in figure 1a. From figure 1b, we can see the similarity of the problem, as shown in figure 1a. The interface of the sedimentary layer then calculated with the same scheme as shown in equation (1). Brief procedure of iterative calculation described in the flow-chart in figure 2. Several steps of flow chart will be started with the input and initialization - initial model - iterative process - stopping criteria - output.
Figure 2. Flow-chart of the program to seek a model solution of two interface density in the subsurface.

Next, we describe the modeling of the study area using iterative calculation, as mentioned previously in the methodology part. Considering preliminary study [2] and well data, the input (density contrast) of the first (upper) layer is -0.10 g/cc and the input (density contrast) of the second (lower) layer is +0.10 g/cc. We calculate with 100 realizations to provide an average solutions from the statistical experiments using a random number. The solution of the interface between the basement-sedimentary layer (first interface) is iteratively computed using 200 times of iteration number for each realization. Vertical prisms dimension (dx and dy) used in the modeling are 250 m. Considering preliminary study [2], residual anomaly and topographic data as input. Residual anomaly variation shows subsurface correlation as well as the seismic data [3]. five kilometers depth is also used as maximum depth of the subsurface model. Total of 441 data observation (residual anomaly) and 441 vertical series (each series consist of two layers) of the subsurface models are calculated. Topographic data with 250 m interval data in the Northing and Easting direction also incorporated in the calculation.

Misfit data changes during 200 iterative calculation of the first interface (basement-sedimentary layer) are shown in figure 3a. Misfit data that are shown in figure 3a is an average value of 100 realizations from the optimization process to find the solution first interface. Until 200 iterative calculation, average misfit data stuck in the value of misfit data around 67 mGal. From these results, we get optimization of the first interface, and the remaining data misfit (with higher frequency or small wavelength) most likely will be fitted with a shallower density interface above the first interface.

Residual anomaly from the first modeling process is used to model two sedimentary layers above the basement. The following input of the upper and bottom layer density will separate the sedimentary layer into two layers, they are -0.15 and +0.05 g/cc (the value is average value from previous iteration for first (upper) layer). For the second optimization process, we also calculate with 100 realizations and iteratively computed using 200 times of iteration number for each realization. Vertical prisms dimension (dx and dy) used in the modeling are 250 m. Varying depth in the grid form of figure 1a (sedimentary layer) will be set-up as constraint second iterative scheme as maximum depth. The calculation of 441 data then replaced with the value from the results of substraction the residual anomaly with basement response (from first scheme iteration).

Misfit data changes during 200 iterative calculation of the second interface (between two sedimentary layers) are shown in figure 3b. After 200 iterative calculation, average misfit data stuck in the value of around 0.5 mGal. From these results, we have inversion results as shown in the 3D view (figure 4).
Figure 3. Misfit data changes vs. 200 iteration number (in log scale): (a) misfit data in the average value of 100 realizations in the process of optimization first interface (basement-sedimentary layer) and (b) misfit data in the average value of 100 realizations of the second interface (between two sedimentary layers).

Figure 4. Visualization of the 3D inverse model from 441 vertical series of subsurface model.

3. TDEM Modeling

TDEM method is included in the category of controlled electromagnetic sources [4]. The TDEM method has the principle of injecting current into the ground at certain time intervals and turning off the injection of the current [5]. Model parameters in the TDEM method are the conductivity and thickness of the layer. While the data is the decay of the magnetic field to time. Model parameters and data linked to future modeling. The forward modeling equation for the TDEM method with long-wire configuration [6] is as follows:

$$ H_z = \frac{I}{4\pi} \int_0^\infty \frac{y}{R} \left(1 + r_{TE}\right)e^{\nu_0} \frac{j^2}{\mu_0} J_1(\lambda r) d\lambda dx $$  \hspace{1cm} (2) 

Where $H_z$ vertical magnetic field (A/m), $I$ is electric current (A), $R$ is the distance between transmitter and receiver (m), $x$ and $y$ are receiver coordinate (m), $r_{TE}$ is reflection coefficient, $\lambda$ is integration variable of Hankel transform, and $J_1$ is first-order Bessel function.

In the calculation of calculated data from TEM using the forward modeling equation written in equation (2) will generate data in the frequency domain (Hz). The inverse Fourier transform technique can be applied to transform from calculated data into the time-domain. Mathematically the inverse Fourier transform process can be done by using cosine filters to the vertical magnetic field data ($H_z$) according to the equation formulated in published paper [7].
Next, for the modeling process, we use a differential evolution algorithm (DEA). DEA is population-based global optimization [8]. DEA is consist of two main stages that are initiation and evolution by mutation, crossover, and selection [9]. Brief flowchart of the inverse modeling is shown in figure 5.

**Figure 5.** Flow-chart of TDEM inverse modeling.

We modeled 16 TDEM sounding points that form the NW – SE line. The position of the TDEM line can be seen in figure 6. The inversion process is done by 50 iterations. The model approach used is four layers model. Then, the result of TDEM modeling is overlayed by the model from gravity modeling (figure 7).

Based on the model in Figure 7, it appears that the uppermost layer of gravity modeling has varying resistivity values when referring to the results of TDEM modeling. In the middle of the track, the resistivity value is relatively high and is getting lower towards NW and SE. Next, the second layer of gravity modeling has a consistent resistivity value that is relatively low. So it can be said that low resistivity values characterize the second layer. While on the third layer, the resistivity values tend to vary. At some TDEM sounding points, relatively high resistivity values were found, and at other locations, the resistivity values were low.

**Figure 6.** Position of TDEM line and gravity section.
Figure 7. Overlay of the model from TDEM modeling and the model from gravity modeling.

4. Summary
Based on the modeling process that has been done, gravity density interface inversion modeling can produce a model of layer thickness variation based on variations in density contrast. Whereas TDEM inversion modeling can characterize each layer based on resistivity contrast. When modeling is applied to field data in Jiken, Blora Regency, the integration between the results of gravity inversion modeling and TDEM inversion modeling can characterize areas with low resistivity values with contrast density values of +0.05 g/cc. The area is under the layer with a density contrast value of -0.15 g/cc which has varying resistivity values that are higher in the middle of the path, and above the layer with a density contrast value of +0.10 g/cc which also has a resistivity value varies in each TDEM sounding point.

Acknowledgments
The authors acknowledge support from FTTM ITB.

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