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EFFECT OF GRID STATIONS AGAINST THE MEASURED DEPTH GRAVITY FIELD AND THEIR EFFECTS TO ORDER OF POLYNOMIAL TSA

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ABSTRACT

In gravity survey it well known that the grid between measurement stations gives effect to resolution of the measurement results. Grid station also was influential in the depth of the target. However, in reality, most of surveyor in such oil and gas exploration and geothermal exploration has paid less attention to this aspect. Some measurements even consider the ease of access along the road rather than consideration of the homogeneity of the grid. Simulation tests have been conducted on a data anomaly shallow depth (geotechnical and archeological cases), moderate depth (case of mineral) and deep in depth (geothermal case). The aim of research is to examine the relationship between grid stations with depth and its effect on the use of the polynomial order of trend surface analysis. The polynomial method is usually used to obtain regional anomaly from the Bouguer anomaly data. The simulation results show that the grid to depth ratio ($\Delta x/z$) is about 9%, meaning that the larger the grid the station, the deeper of measurable gravitational field effect. Also obtained the result that to detect the anomaly object at certain depth, the more width of grid station, the higher-order polynomial to use. This means that the higher-order polynomial is used, the shallower the cut-off areas of regional-residual anomaly data. However, if the grid station meets the criteria of $\Delta x/z \approx 9\%$ it is recommended to order polynomial TSA used is a second order polynomial ($n = 2$).

INTRODUCTION

Geophysical methods were conducted to determine subsurface condition by involving measurements on the surface and from physical parameters which are owned by the rocks in the earth. So from these measurements can be interpreted how the properties and the condition of subsurface either vertically or horizontally. One such geophysical method is the gravity method. This method measures the variation of the gravitational field caused by density variations in the subsurface rock.

The gravity method is a passive geophysical method that can be applied in various fields, both geotechnical and exploration. The difference of the geotechnical and exploration survey lies in the depth scale. There is a shallow depth scale (e.g. geotechnical surveys, 5-50 m), medium depth (e.g. gold mineral survey, 10-200 m) and deep (geothermal survey, 3000 m).

There are three main steps in geophysical exploration, the acquisition, processing and interpretation. The acquisition process is an initial phase that is data collection phase. This process can not be done carelessly though no fixed rules in making an acquisition design. Good acquisition design is a design that can plan the best size of the data points so that can achieve the desired target. In the survey of gravitational method, it is determined by the width of the grid (spacing) which is used in the acquisition. Currently, surveyor generally determines the acquisition grid randomly so that, frequently, data generated from the field is less satisfactory because it does not achieve the desired target depth. For that we need a reference that can be used to estimate a design's acquisition of the gravity method, so as can achieve the desired target depth. In this study, we try to get a solution by finding how is the relationship between station grid and dept, so it can be used to create the best design of gravity acquisition.

After the acquisition, the next step is data processing. The processing in this study only use trend surface analysis method (polynomial fitting). This method is one of the regional-residual separation methods using a polynomial equation approach. Because there is no specific provision in determining the best order polynomial until now, then the interpreter usually determine the order of the polynomial only by trial and error. Giving to rise ambiguity in interpretation. So we need a provision in determining the polynomial order to avoid the ambiguity. It is also one of the basic problems in conducting this research.

In this study the data used is a synthetic data which are made in various depth (well depth is shallow, medium, and deep). The aim of this research is to determine the width of the grid that should be used in the acquisition, so it can reach the desired anomalous object's depth and the optimum polynomial order used in further processing so get a residual anomaly which we interest in the gravitational method.

THEORY AND METHOD

1. Forward Modeling

Forward modeling is done by calculating the model response theoretically of a certain model parameters (Grandis, 2009). Trial and error process conducted to get the model response suitable to the data. And modification of the model is done by changing the values of model parameters so get the most suitable response of fit with observational data.

Synthetic models used in this study using rectangular prism approach. A collection of rectangular prisms is a simple approach that represents a mass volume under the surface as shown in Figure1 below where each unit prism (smallest) assumed possessed a constant density. The principle superposition stating that the gravitational potential of a collection of mass represent the sum from tensile gravitational on each masses (Blakely, 1995). Then the gravitational anomaly on various points could be obtained by summing the effects of gravity from all prisms.

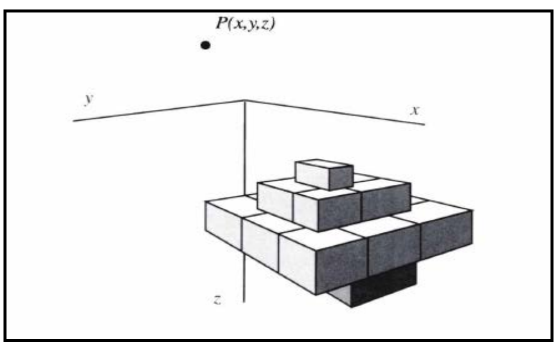

Figure 1. Three dimension mass volume model by rectangular prism approach (Blakely, 1995)

Blakely (1995) stated mathematical equations to calculate the value of the gravitational response of a collection of mass volume prism in Figure 1 above is

$$g_m = \sum_{n=1}^{N} \rho_n \psi_{mn} \qquad (1)$$

g_m is the vertical tensile force at the point of observation to-*m*, ρ_n is the density of the prism and ψ_{mn} is the gravitational pull on the point *m* due to prism n.

2. Spectral Analysis

This analysis is intended to determine the limits of low and high frequency signal through the value of the wave number, so that the regional and residual depth limit can also be known. For 1D spectral analysis, Fourier transform performed on a particular track on Bouguer anomaly contour map. Fourier transformation process is carried out with the aim of converting the data from the time domain or spatial domain to frequency or wavenumber domain. Fourier transform $F(k)$ in general is a function of a complex number which can be written in the equation:

$$|F(k)| = |(Re\ F(k))^2 + (Im\ F(k))^2|^{\frac{1}{2}} \qquad (2)$$

$$\Theta(k) = arctan\ \frac{Im\ F(k)}{Re\ (k)} \qquad (3)$$

Function $|F(k)|$ namely *spectral amplitude (A)* and $\Theta(k)$ is *phase of spectral*.

In the spectral analysis method of gravity equations derived from the gravity potential *($U = \gamma\mu/r$)* at a mass point μ with gravitational constant γ observed on a horizontal plane. So the Fourier transform of the gravitational anomaly is as follows (Blakely, 1995)

$$F(g_z) = 2\pi\gamma\mu e^{|k|(z_0 - z')} \qquad (4)$$

where

g_z : gravitational anomaly
z_0 : height of observation point
z : depth of anomalous objects
k : wavenumber

equation (4) can simplified to be:

$$A = Ce^{|k|(z_0 - z')} \qquad (5)$$

with A = amplitude dan C = constant. Then the equation (5) changed as a linear equation which wavenumber component k be proportion to the amplitude.

$$ln\ A = (z_0 - z')|k| \qquad (6)$$

From equation (6), graph between $ln\ A$ against *k* for classifying anomalies was made (shown in Figure2). By linear regression we could obtain the depth of regional and residual value.

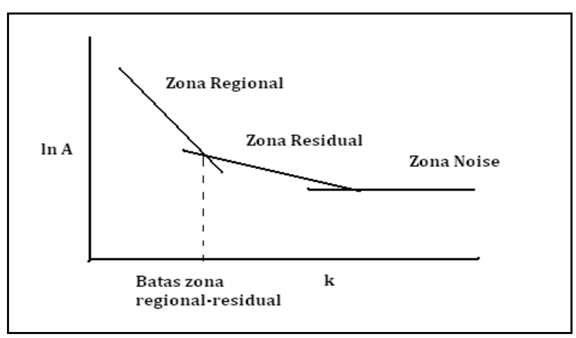

Figure 2. Anomalous zoning through graph $ln\ A$ against k (Sari, 2012).

3. Trend Surface Analysis

Trend Surface Analysis is a method used to describe the distribution of observation data that are spatially distributed into components associated with the regional trend of the data and components associated with local effects (Unwin, 1975). So in principle, this method search for anomalous values regional and assume that the regional anomaly is a polynomial function of n-th order equation as follows (Abdelrahman *et al.*, 1985):

$$z(x, y) = g_i = \sum_{n=0}^{p}\sum_{n=0}^{s} a_{n-s,s} x^{n-s} y^{s} \qquad (7)$$

$a_{n\text{-}s,s}$ is polynomial constant valued $^1/_2$ $(p+1)(p+2)$, coefficient p is an order at 2D polynomial equation, s and n are the indexes, x and y is the spatial coordinates. Then the residual anomalies obtained by calculating the difference in Bouguer anomaly with this regional anomaly.

SYNTHETIC MODELS

1. Geotechnical Models and Anomaly Bouger Synthetic

Geotechnical synthetic models used in this study took a sample model of the statue in the case of archeology. Its a fine arts statue in the form of three-dimension and is the result of culture in prehistoric times. Because natural events have passed, the building is buried by sedimentary rocks and soil that cover the surface. The statue was made by andesit with a density of 2.8 gr/cm^3. This building have been in a sedimentary soil at depth of 22.5 m with a density of 2.0 gr/cm^3 and its shaped have symmetrical geometry which assumed as one of the abstract and conceptual prehistoric building.

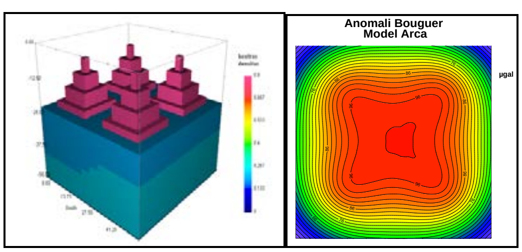

Figure 3. Geotehcnical synthetic Model and synthetic Bouguer anomaly.

In this synthetic models, the peak statue located at a depth of 5 m in subsurface the bottom in 22.5 m with each size of 5 x 5 m. this size only an approach based on statistical approximation for the size statues in general. And regional anomalies are theoretically created at a depth of 22.5 m and is limited to 50 m were filled by two layers of sediment discontinue, which is have density of 2.2 gr/cm^3 and 2.25 gr/cm^3 (Jacoby and Smilde, 2009).

The gravity response is described as synthetic Bouguer anomaly contours in Figure 3. Because the statue deliberately constructed and arranged symmetrically so then the Bouguer contour anomaly also form a symmetric cluster.

2. Gold Exploration Model and Synthetic Bouger Anomaly

Mining exploration models in this study is a gold exploration model. Type gold deposits were used vein models. Gold is usually found in volcanic environments and has high density. In this synthetic model, the vein was filled with gold minerals associated with silica. The density values are used to indicate the vein in this model is 2.79 gr/cm^3. This vein located on the cracks of sediment of limestone. Density of limestone took as 2.4 gr/cm^3. The vein size at depth of 10-200 m is 120 x 150 m.

The vein is derived from igneous intrusion which is at depth of 200-500 m below the surface, with density value of 2.9 gr/cm^3. While basement density is 2.45 gr/cm^3. The objects at below 200 m depth (basement and intrusion) are assumed to be a theoretically regional model. While anomaly located at a depth of 200 m to the surface is a theoretical residual anomaly.

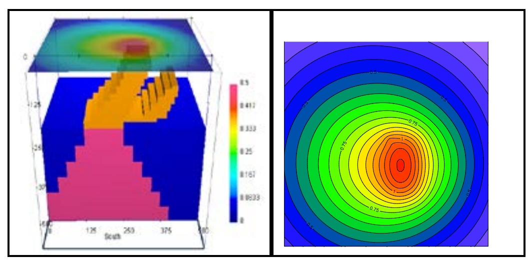

Figure 4. Gold mineral exploration synthetic Model and synthetic Bouguer anomaly.

3. Geothermal Model and Synthetic Bouguer Anomaly

Gravity method can also be used in geothermal exploration. In this study, the depth scale is categorized into great depth scale. Structure of graben indicates the reservoir as a permeable sedimentary layer with low porosity at depth of 2000 – 3000 m with density of 2.1 gr/cm^3. It's covered by clay cap (impermeable layer) with a thickness of about 500 m at a depth of 1500 m below the surface with density of 2.3 gr/cm^3.

This shallow structures (up to 3000 m in subsurface) are categorized into residual anomaly and the deeper structures at of 3000-7000 m are categorized as regional anomaly. This regional anomaly contain of intrusion of magmatic rocks with density of 2.8 gr/cm^3 within the basement with density of 2.5 gr/cm^3, where the top basement is located at depth of 3000 m.

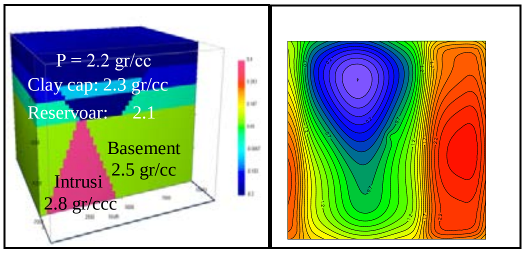

Figure 5. Geothermal synthetic Model and synthetic Bouguer anomaly.

TEST OF MODEL

1. Spectrum Analysis

Spectrum analysis was calculated on synthetic Bouguer anomaly data which was made by three different depths scale and its doing by used variation of grid acquisition. It can be obtained a relationship between the grid and depth as the objectives to be achieved in this spectral analysis method.

Geotechnical Model

Spectral analysis of the geotechnical model is carried out by using 9 variations of the grid acquisitions. It's used 1.2 - 2.8 m grid at 0.2 m intervals. The purpose is to see the depth estimation from each grid. All calculations on its variation of the grid is intentionally using the same slice so its the only factor that affecting the differences in the results grid depth.

Tabel 1. The depth value based on spectral analysis of geotechnical model by using grid variation

Grid (m)	The depth of regional-residual border (m)	*True depth* (m)	Deviasi (%)
1.2	17.94	22.5	20.27
1.4	19.20	22.5	14.67
1.6	20.22	22.5	10.13
1.8	21.07	22.5	6.36
2	22.59	22.5	0.4
2.2	23.65	22.5	5.11
2.4	24.33	22.5	8.13
2.6	25.31	22.5	12.49
2.8	26.77	22.5	18.98

The depth value in Table 1 is plotted against the deviation values which shown in Figure 6. Then its obtained a new parabolic equation which is the equation of the curve. This equation has an extreme point. This extreme point is the point where the value of *x* reaches the optimum value. This optimum point physically informs the point where the grid (*x*-axis) has a minimum deviation, so the depth is at least close to the true depth.

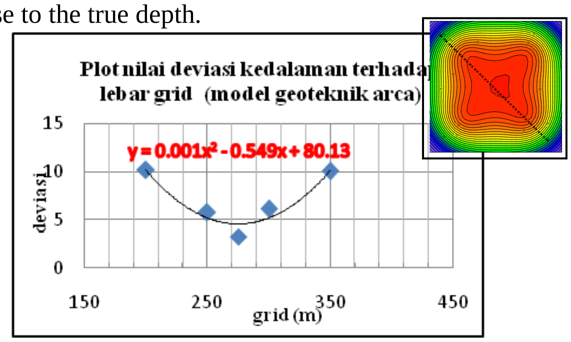

Figure 6. The curve deviation of depth based on spectral analysis of geotechnical model plotted against the used grid.

Hence the relationship of the grid and its depth can be described as:

$$x_{op} = \frac{-b}{2a} = \frac{103.1}{2 \times 25.43} = 2.027133 \qquad (8)$$

$$\frac{grid\,(\Delta x)}{depth(z)} = \frac{2.027133}{22.5} = 0.090095 \quad \text{or} \quad \pm 9\% \qquad (9)$$

From Table 1 it is seen that the smallest deviation value is the grid of 2 m. This is proven by equation (8). When the grid is greater or smaller the x_{op} showed the deviation will be greater too.

Gold Exploration Model

The variations grid used in the spectral analysis of the gold exploration model is 12.5 - 25 m with interval of 2.5 m. The depth of regional anomalies which resulted from the analysis spectrum was shown in table and figure below.

Tabel 2. The depth value based on spectral analysis of gold mineral exploration model by using grid variation

Grid (m)	The depth of regional-residual border (m)	*True depth* (m)	Deviasi (%)
12.5	174.9	200	12.55
15	182.1	200	8.95
17.5	193.5	200	3.25
20	207.6	200	3.8
22.5	217.4	200	8.7
25	225.7	200	12.85

Just like the previous synthetic model, the depth variation values in Table 2 are plotted into curve as shown in Figure 7 below to get the optimum value or the best grid to used in the grid-to-depth-ratio of its depth.

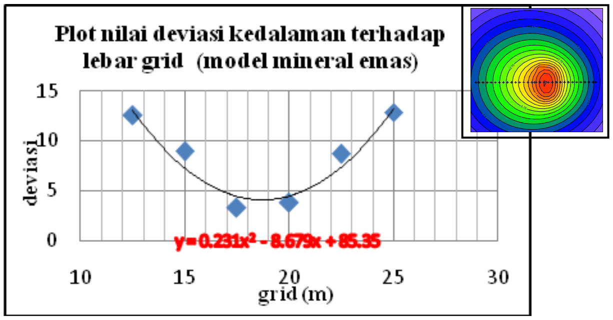

Figure 7. The curve deviation of depth based on spectral analysis of gold exploration model plotted against the grid used.

by using Eq. 8 the extreme point is obtained as:

$$x_{op} = \frac{-b}{2a} = \frac{8.679}{2 \times 0.231} = 18.78571 \quad (10)$$

So the relationship of the grid and its depth are described as:

$$\frac{grid(\Delta x)}{depth(z)} = \frac{18.78571}{200} = 0.093929 \quad \text{or} \quad \pm 9\,\% \quad (11)$$

From above equation, the best grid that should be used is 9% of the target depth. In this synthetic model with the depth of 200 m then the recommended grid is 18 m, which is 9% of the depth.

Geothermal Model

The variations of grid which used in the geothermal model are ranged from 200-350 m at intervals of 25-50 m. With the same process of spectral analysis of two previous models, the depth of regional anomalies of its synthetic model was shown in figure below

Tabel 3. The depth value based on spectral analysis of geothermal model by using grid variation

Grid (m)	The depth of regional-residual border (m)	*True depth* (m)	Deviasi (%)
200	2702	3000	9.93
250	2832	3000	5.6
275	2905	3000	3.17
300	3179	3000	5.97
350	3302	3000	10.07

By still using the same equation as before, the extreme/optimum point is:

$$x_{op} = \frac{-b}{2a} = \frac{0.549}{2 \times 0.001} = 274.5 \quad (12)$$

So the relationship of the grid and its depth are described as:

$$\frac{grid(\Delta x)}{depth(z)} = \frac{274.5}{3000} = 0.0915 \quad \text{or} \quad \pm 9\,\% \quad (13)$$

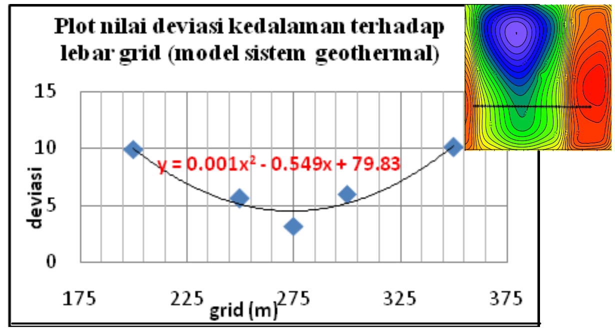

Figure 8. The curve deviation of depth based on spectral analysis of geothermal model plotted against the grid variation.

Based on the calculation of the optimum point, its obtained that grid-to-depth-ratio is equal to 9%. This ratio is constant for three synthetic models used in this study. So these results can be considered.

2. Separation of Regional-Residual Anomaly by Using Polynomial Trend Surface Analysis

After calculating the spectrum analysis, then the synthetic Bouguer anomaly of the three models are separated to distinguish regional and residual anomaly using Polynomial Trend Surface Analysis (TSA).

The process to determine the best order in aim of getting the residual anomaly as close as subsurface model conditions. This calculation also done by used variations of the grid to see its effect on the order of the polynomial. Then the TSA polynomial and spectral analysis results are combined into a graph that connects the three parameters used in this study which is the grid, depth and order of polynomial. The same process is performed on three synthetic models of the different depths scale.

Test of Polynomial TSA on Geotechnical Model

Variation of the grid used in the separation on this synthetic model was made starting from the grid of 1 m until 15.5 m. Because this model has very shallow depth, then the interval of variation grid is increased by only 0.5 m to get more accurate value. On the grid of 1 - 5 m the best order of TSA is 2nd order. When the grid is increased up to 9 m the best order is turn to 3rd. And then when the grid is increased until 15 m, the best order is increased as well to 4th. And order 5th started when the grid is increased at 15.5 m. The resume of result can be seen in Figure 9 below.

Based on the spectral analysis result, it's determined that best grid to obtain the depth as closest as the real depth of this model is 2 m. Its seen in Figure 9 that the 2 m grid is in the range of 2nd order of TSA. The process of determining the appropriate order is done mathematically based on the value of rms error for each order. Then when the order of TSA is increased the depth of each grid value is calculated. This curve obtained the pattern of relationship between the order of polynomial, grid and depth of this model. The process of determining the order is done mathematically based on the value of rms error in each order by using Eq.14 (Sherrif, 2002).

$$\delta = \sqrt{\left(\frac{1}{n}\sum\left(m_i - \overline{m}\right)^2\right)} \qquad (14)$$

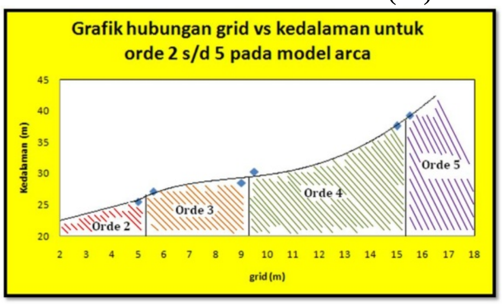

Figure 9. The curve pattern of relationship between the used grid against the depth of interface of regional-residual anomaly for the increasing of each order of Polynomial TSA of geotechnical model.

Test of Polynomial TSA on Gold Mineral Exploration Model

In the middle depth scale model the grid used during the process of separation is 12.5 - 180 m with grid interval is 5 m. Starting from grid 12.5 - 65 m the best order is 2nd. While the 3rd order is happened on the grid of 70 - 115 m. When the grid is 120 – 175 m the best order is gone up to 4th. And up to order 5th at the grid of 180 m. Based on result of spectral analysis its has the best grid is 18 m, then the best order should be used for the separation is of 2nd order (Figure 10). Just like before, when grid is increased, not only the best order of polynomial but also the estimated depth is increased. So we can obtain the patterns of relationships of these three factors from this synthetic model as shown in Fig. 10.

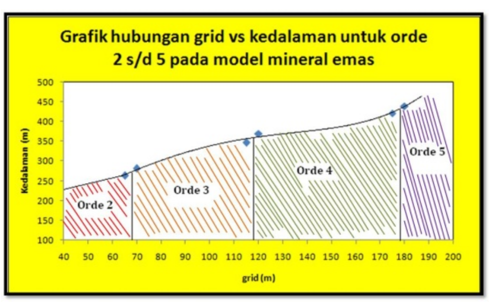

Figure 10. The curve pattern of relationship between the used grid against the depth of border of regional-residual anomaly for the increasing of each order of Polynomial TSA of gold mineral exploration model.

Test of Polynomial TSA on Geothermal Model

Due to the geothermal model has greater deep, this models used larger grid too. The variation grid used is 275 - 1800 m by interval of 50 m. Just like the synthetic model was used before, when the grid is increased then the best order of polynomial is increased too (Fig. 11). Based on the result of spectral analysis, the best grid of this model is 275 m and best order polynomial at that grid is 2nd order. Depth values were also calculated at the points where the best order is increased. So we can see how the grid, order and depth are related to each others in this geothermal models.

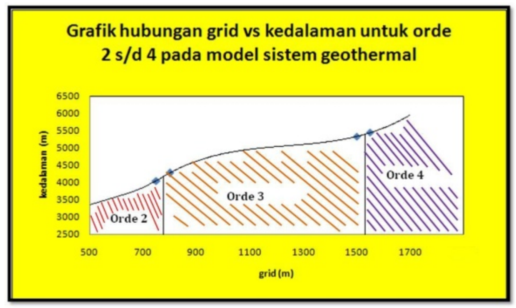

Figure 11. The curve pattern of relationship between the grid used against the depth of interface of regional-residual anomaly for the increasing of each order of Polynomial TSA of geothermal model.

ANALYSIS AND INTERPRETATION

Analysis spectrum and polynomial TSA produced a relationship between the grid, depth and order of polynomial in gravity method that can be used in acquisition and processing gravity data. In this study, the three factors are varied in each other so we can get a particular pattern of its correlation.

The first is grid variation on the depth. Grid in gravity method is correlated with penetration of gravitational field. If the grid used is greater, then the measured gravitational field will be deeper. Its made the depth estimation from spectrum analysis also becomes greater. And if grid is smaller, the depth of penetration will be shallower; the effect on the depth estimation by spectral analysis also becomes shallow too. But the depth of penetration of the gravitational field will not affect the depth of real anomalies, it just the 'penetration'. These results indicate that in order to achieve a certain of target depth, the used grid should be ± 9% of the target depth. If the used grid is smaller then the penetration will not achieve the desired target depth, because the penetration of gravitational field is too small.

Next is grid variation to order of polynomial. The greater grid affect to the order of polynomial growing up. And vice versa, if the grid is smaller then the order will becomes smaller too. So the increased of the grid will effect on the increase the order of polynomial. When the grid is enlarged, the depth of penetration becomes deeper, while the depth of the real anomalies is constant thus its need the higher order to separate the regional and residual anomalies. In the case of a greater grid is used, its causing low order is not able to separate regional and residual anomalies optimally, thus its requiring a higher order. Based on these results, we can conclude that the grid, depth and the order of polynomial are correlated with each other as illustrated in Figure 9, 10 and 11. If the used grid is larger, then the depth of penetration will be deeper (could even exceed the target depth) so the effect on the data processing is the order of polynomial also become higher. Because it exceeds the desired target depth, the result becomes ineffective and will affect its resolution. Oppositely, if the used grid is too small, the depth of penetration becomes shallower and order of polynomial becomes smaller too. So the results are not density contras representative because of its depth does not reach the desired target depth.

So finally we found a pattern of relationship between the grid, depth and the order of polynomial by integrating the results obtained from the two methods used in this study which is Spectrum Analysis and Polynomial Trend Surface Analysis. From these two methods are produced that in acquisition, the recommended gridd is ± 9% of the target depth and then the recommended order of polynomial TSA is 2^{nd} order.

CONCLUSION

- Based on these results, the grid should be used in the acquisition of gravity method is ± 9% of the target depth.
- In the processing with Polynomial Trend Surface Analysis for grid-to-depth-ratio of 9% the recommended order of polynomial in the process of separation of regional and residual anomaly is 2^{nd} order.
- The higher order of polynomial represents shallower depths and heterogeneous rocks.
- If the used grid is greater, then the penetration of gravitational field will be deeper and its affect to the order of the polynomial will be increased too. And vice versa if the used grid is smaller.

REFERENCES

Abdelrahman, E. M., Riad. S., Refai, E., and Amin, Y. (1985), On The Least-Squares Residual Anomaly Determination, *Geophysics*, **50**, 473-480.

Blakely, R.J. (1995), *Potential Theory in Gravity & Magnetic Application*. Cambride: Cambridge University Press.

Grandis, Hendra (2009), *Pengantar Pemodelan Inversi Geofisik*, Himpunan Ahli Geofisika Indonesia, Jakarta.

Jacoby, Wolfgang and Smilde, Peter L. (2009), *Gravity Interpretation. Fundamentals and Application of Gravity Inversion and Geological Interpretation*, Berlin: Springer.

Sari, Indah P. (2012), *Studi Komparasi Metode Filtering untuk Pemisahan Anomali Regional dan Residual pada Data Anomali Bouguer*, Geophysics Program Study, Department of Physics, University of Indonesia, Depok.

Sherrif, R. E., 2002. *Encyclopedic Dictionary of Applied Geophysics*, *4^{th} Ed*., SEG.

Unwin, D.J. (1975), *An Introduction to Trend Surface Analysis*. Geo Abstract Ltd.