The determination of depth anomaly in archaeo-magnetic using an Euler deconvolution: Case study in Kuta Lubok fortress

M Zainal, M Yanis, D Darisma, Marwan and N Ismail
1Department of Geophysical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Darussalam, Banda Aceh, 2311, Indonesia
2Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Darussalam, Banda Aceh, 2311, Indonesia

E-mail: muzakirzainal@unsyiah.ac.id

Abstract. Geophysical surveys have been conducted using magnetic in the archaeological site of Kuta Lubok fortress, Aceh Besar. The fortress was built in 13th century by the Lamuri Sultanate in the northern part Aceh coast. To map an estimated area of archaeological objects, 420 stations have been measured. The data were measured by 21 profiles across of the area with the length of profiles vary from 40 to 60 m. To get a complete resolution, data is taken with a distance of 20 m between lines and a distance of 5 m between stations. From the total magnetic field map that has reduced to the poles, the anomaly is generally able to delineate buried building sites. Then based on Euler deconvolution analysis, the structure of the fortress building can be seen using a 5-meter depth level. But a clearer structure is seen in the use of 10 m in depth. Based on the interpretation of the two tolerance layers it can be concluded that the Kuta Lubok fortress was found stretching parallel to the line along the 400 m to the east of the fort building which is still intact.

1. Introduction

Application of the geophysical method is widely used for exploration of mineral resources, environmental and geotechnical in Indonesia. While in the archaeological prospecting, the method is still very lacking [2]. The use of magnetic methods to study the archaeological sites has to be able to give the right results and accuracy [3]. In another side, Ref. [4] were combined the total magnetic field that obtained from PPM and the susceptibility relative from EM induction or a more comprehensive result. However in the modeling case, the method is high of data ambiguity, so the data enhancement is one of direct interpretation to understand the depth of anomalies.

Magnetic surveys at the archeological site were carried out by identifying magnetic properties beneath the surface, where the method is very sensitive to the presence of objects in the form of metals, pottery and various types of rocks [1]. Most archaeological objects are made of this material, while the objects around them are non-magnetic materials, i.e. soil and organic waste. Therefore it will be easier to identify the existence of archeological objects.

In this research, the depth estimation of the method was calculated using Euler deconvolution. The method has been used successfully in several potential cases, even in archaeological studies [5,6]. Euler deconvolution works by minimizing the effects of the surrounding anomalies that can provide a

3 To whom any correspondence should be addressed.
good understanding of the target anomalies, and the horizontal anomalies will be very well determined using Euler deconvolution based on the Structural Index [7,8]. The archaeological site of this study is the 13th century fort of Kuta Lubok; one legacy of Lamuri Sultanate the 9th century. According to Ref. [9] the Lamuri was disappeared after a giant tsunami disaster that hit Aceh in the early of 14th century.

2. Theory and methodology
The Euler deconvolution method uses the first derivative of the components in the x, y, z-direction to determine the location and depth of various sources of the anomaly. The Euler method of deconvolution has a relationship with the magnetic field intensity measured in the direction (x, y, z), followed by equation 1:

$$(x - x_o) \frac{\delta T}{\delta x} + (y - y_o) \frac{\delta T}{\delta y} + (z - z_o) \frac{\delta T}{\delta z} = N(B - T)$$

(1)

where \((x_o, y_o, z_o)\) is the source position of the total magnetic field intensity, \(T\), observed at \((x, y, z)\). \(B\) is a magnetic regional field and \(N\) represents the structural index of the source. For the index structure is equal to zero as in the contact structure magnitude \(A\) [8]. Thus Euler's equation can be written in the form of equation 2:

$$(x - x_o) \frac{\delta T}{\delta x} + (y - y_o) \frac{\delta T}{\delta y} + (z - z_o) \frac{\delta T}{\delta z} = A$$

(2)

where \(A\) is an amplitude factor anomaly, strike and dip remanence in magnetic and induction. Euler deconvolution principle is by determining the boundary and the depth of the anomalous source response obtained by doing variations in Structural Index (SI). The choice of SI values depends on the geometric assumptions of the anomaly, where the values vary from 0 to 3. For round objects, the SI value is 3, vertical rods and cylinders are 2, and for dyke models such as fractures are 1 and 0.5 for contact-shaped material [9]. Euler deconvolution has 7 factors that influence the response model obtained [7]. This factor becomes a reference for the accuracy of the results obtained; geological model, dominant magnetic anomaly, data sampling range, grid range, accuracy of gradient values, window size, and selection of the right SI.

The results obtained from the Euler deconvolution method are in the form of distribution of anomalous points based on depth so that in archeological surveys this method is applied to obtain the structure and depth of archaeological objects. Data acquisition is finished by measuring the magnetic field for 21 lines with the length of each track varies between 30 - 95 m, the distance between measurement points is 5 m, and the distance between tracks is 20 m. Based on the distribution of measurement points, there are 213 points of Euler anomaly with a measuring area of 500 m². Thus the area indicated by the archaeological remains of Kuta Lubok can be mapped properly. The complete design of measurement lines and field conditions are shown in Figure 1 that modified from Ref. [10]. All measurement lines cover the suspected area of archeological objects.

3. Result and discussion
The magnetic field intensity measured at the location varies according to the distribution of magnetized objects. The difficulty of surveying magnetic methods is at the stage of data interpretation. One reason is due to variations in the direction of inclination of the earth's magnetic field. The profile deviation from the position of the anomalous object changes according to the change in the direction of the earth's magnetic field inclination. Thus the intensity data of the measured magnetic field anomaly is still challenging to determine the location of archeological objects.
Figure 1. Description of magnetic survey in the Kuta Lubok Fort, the 21 profiles are conducted crossing the archaeological object. The fort is located in an area closes to the pond that will be eventually eroded and negative impact to the existing site.

Figure 2. (a) The magnetic field anomaly has been carried out for 21 profiles by the process of reduction to the pole, the circle point shows the distribution of data stations and the white lines are indicated as an archaeological object in the study area (b) the ancient of Kuta Forts that still available on the West side of the area (c) an archaeology site like a tomb, road, and cemetery that has been buried in the subsurface.
The total magnetic field anomaly data measured at a particular latitude of the earth is transformed to the north pole of the earth’s magnetic direction of vertical inclination towards the surface of the earth. Anomalies presented by magnetic field data after reduction to the poles can be interpreted directly. The method of reducing to pole transformation is calculated using the MagPic program developed by Geometric. The amount of inclination angle is 4.89° and declination -0.80° obtained from IGRF calculations. The magnetic field anomaly after reduction to the pole is shown in Figure 2.

The anomalous contour map after being transformed to the poles is obtained by magnetic field intensity that varies from -1000 to 1400 nT, to facilitate interpretation, the magnetic field intensity below 100 nT is plotted into one colour scale. The high-intensity value is located east of the measurement path, and there is a low-intensity value in the west. Contour patterns that are formed from reduction to polar data reach the maximum point, namely the angle of inclination 90°, this is very different from the magnetic field anomaly before to the pole reduction, where there are contour patterns in pairs making it challenging to make interpretations.

In some places, there are remnants of archaeological objects characterized by high-intensity values, for example at a measurement distance of 160 - 320 m at ±20 m. Contour patterns formed from reduction to polar data do not show structural alignment that resembles the geometry of archaeological objects. According to Ref. [10], the location of archaeological artefacts is in a very complex geological area, where there are volcanic lumps of rock and iron ore distribution. Thus, anomalous data from the results of reduction to poles need to be carried out by several filtering to separate regional effects, so that residual archaeological objects can be appropriately mapped. Euler deconvolution is one of the data filtering for magnetic data processing. This method can predict location and depth sources of magnetic objects below to the surface. Using the first derivative of the components x, y, and z to determine the location and depth of the source anomaly. Based on observations of archeological structures at the location of measurement of subsurface anomaly data can be assumed to be horizontal, so structural index two is used to obtain a depth solution based on Euler deconvolution. The method was calculated using the Euler v.1.15 program developed by G.R.J Cooper 2004. To obtain a depth solution from archaeological objects, a depth of 5 and 10-meter tolerance was chosen. The depth distribution of magnetic field residual anomalies for 5 and 10-meter depth tolerances can be seen in Figures 3 and 4.

**Figure 3.** Solution to the depth anomalies of magnetic fields based on a 5-meter depth tolerance. The anomaly pattern that produced from 5-meter depth is not good a connection to the archaeological site, however the rectangular pattern in west side is also corresponds to the fort.
Figure 4. Solution to the depth anomalies of magnetic fields based on tolerance of 10 m. The pattern anomalies with the 10 m depth solution show an agreement with the archaeological outcrop that founded in the area of survey and also correspond to the magnetic field anomaly.

Depth predictions obtained from the Euler method are numerical solutions of residual magnetic fields. Based on Figure 3, the depth solution obtained with a tolerance of 5 m does not show a clear structure of the existence of a fortress. At a measurement distance of 0 - 100 m, where the remains of archaeological objects are present in this location, it is characterized by varying depth responses, but the structure is similar to a fortress building. Overall the Euler deconvolution method can clearly describe the structure of subsurface archeological objects. However, the depth tolerance given significantly affects the anomalous pattern produced. The greater the tolerance given, the higher the depth solution obtained. When viewed from the dimensions of the remains of archaeological objects on the surface, the height of a 3-meter fort is expected to affect the depth solution of the Euler method, so that a solution of a depth of 10 m can map well the overall structure rather than a fortress.

4. Conclusion
Based on the result, it can conclude the use of Euler deconvolution in the magnetic data can work very well in distinguishing between magnetic responses around with magnetic responses from building structures that can provide the depth information of the ancient basement. While the solution for depth with a tolerance of 10 m, there is a clear geometric pattern of subsurface anomalies. In locations that are estimated to be archeological objects, namely the measurement distance of 200 - 400 m, there are two structures of magnetic anomaly source alignment with a depth of 4 - 8 m, this is estimated as a response to the fort building.

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