Gravity analysis to estimate the mud stream direction in porong by applying the delaunay approach

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Abstract. Lumpur Lapindo eruption at Porong, Sidoarjo is still continuing, it is suspected triggered by the flow of high-pressure mud. Measurements were performed for analyzing the subsurface structure where there was subsidence of soil and mudflow in the affected areas of Lumpur Lapindo with gravity method. The results of gravity data measurements are not always regular according to planning due to unpredictable field conditions. Therefore in this research writer used geostatistics method in interpolation of gravity anomaly data. Second Vertical Derivative (SVD) is a method used to determine the fault structure. The gravity anomaly value in the Porong area is 8 mgal to -32 mgal. High-value gravity anomalies in the northwest region with the highest anomaly value of 8 mgal indicates an increased of mass density and soil degradation. While the gravity anomaly of low value in the northeastern region with the lowest anomaly is -34 mgal which indicates a decrease in subsurface mass density. The fracture structure that has been obtained can be used to determine the direction of Sidoarjo mud movement.

1. Introduction
Lumpur Lapindo eruption at Porong, Sidoarjo is still continuing, it is suspected triggered by the flow of high-pressure mud. Measurements were performed for analyzing the subsurface structure where there was subsidence of soil and mudflow in the affected areas of Lumpur Lapindo with gravity method. The results of gravity data measurements are not always regular according to planning due to unpredictable field conditions. Therefore in this research writer used geostatistics method in interpolation of gravity anomaly data. Second Vertical Derivative (SVD) is a method used to determine the fault structure. The gravity anomaly value in the Porong area is 8 mgal to -32 mgal. High-value gravity anomalies in the northwest region with the highest anomaly value of 8 mgal indicates an increased of mass density and soil degradation. While the gravity anomaly of low value in the northeastern region with the lowest anomaly is -34 mgal which indicates a decrease in subsurface mass density. The fracture structure that has been obtained can be used to determine the direction of Sidoarjo mud movement.

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2. Regional Geology

Administratively Sumur Banjar Panji-1 in Porong sub-district of Sidoarjo district of East Java Province. Meanwhile, geographically it is coordinated on 703°-70034’ S and 112039’-112405’ E. The Stratigraphy of Sumur Banjar was initialized by the form of limestone in Pliocene epoch, then it was covered unevenly by sandstone sediment of late plocine vulcanic, bluish clay, alternate sandstone and shale of early Pleistocene age. Those group of rocks were struck unevenly by vulcanic rock of Notopuro volcano of late pleistocene age and Brantas alluvial delta of Resen age.

Vulcanic sandstone in Sumur Banjar Panji has 962 m of thickness and it is diminished to the east direction, Sumur Porong. This layer is a sedimentation of vulcanic eruption lied in the west or southwest of late plocine. The bluish clay on top is the bottom side of Late Pleistocene old of Pucangan formation. In the late plocine there were numbers of vulcanic activities located around Surakarta and at the same time in the east region was suspected that there were activities of old Wilis & old Anjasmoro Volcano complexes as the east point of Solo zone. The eruption of those volcano complexes produced lava deposit pyroclastic flow and/or fluvial deposit of pyroclastic deposit ‘reworked’. Layer of vulcanic sandstone in Porong region is the product of the volcano complex eruption [1].

![Figure 1. Simplified Geology map of Porong region [2].](image)

3. Theoretical background

3.1 Gravity method

Gravity method is a geophysical method that its measurement based on gravity field. Generally gravity method reviews the gravity field variety caused by the density variation of rock mass below the surface. Practically it observes the differences of gravity field from one point of observation against the other point of observation.

The basic of gravity method is Newton’s law of gravitation, which states that a particle attracts every other particle with a force which is directly proportional the product of their masses and inversely proportional to the square of the distance between their centers. Newton’s Law of Gravitation [3]:

\[ F(r) = -G \frac{m_1 m_2}{r^2} \]  

Where F is the gravitational force acting between two objects (N), G is the gravitational constant \(6637 \times 10^{-11} \text{Nm}^2/\text{kg}^2\), \(m_1, m_2\) is the masses of the objects (kg) and r is the distance between the center of their masses (m).
3.2 SVD Method (Second Vertical Derivative)
SVD Method (Second Vertical Derivative) is one of methods which is able to be utilized to interpret the structure of Bouguer anomaly data. This method is able to determine the type of subsurface fracture. Potential Field without source within will meet the Laplace equation match with the equation [3]:

$$\Delta^2 U = 0$$  \hspace{1cm} (2)

On gravity method, the equation is:

$$\frac{\delta^2 \Delta g}{\delta x^2} + \frac{\delta^2 \Delta g}{\delta y^2} + \frac{\delta^2 \Delta g}{\delta z^2} = 0$$  \hspace{1cm} (3)

In SVD method its equation is matching with the equation (5) [3]:

$$\frac{\delta^2 \Delta g}{\delta z^2} = -\left(\frac{\delta^2 \Delta g}{\delta x^2} + \frac{\delta^2 \Delta g}{\delta y^2}\right)$$  \hspace{1cm} (4)

U is potential field and ”g” is gravitational acceleration (m/s²).

3.3 Delaunay Triangulation
The Delaunay triangulation D of V, introduced by Delaunay in 1934, is the graph defined as follows. Any circle in the plane is said to be empty if it contains no vertex of V in its interior. (Vertices are permitted on the circle.) Let u and v be any two vertices of V. The edge uv is in if and only if there exists an empty circle that passes through u and v. An edge satisfying this property is said to be Delaunay.

The Delaunay triangulation of a vertex set is clearly unique, because the definition given above specifies an unambiguous test for the presence or absence of an edge in the triangulation. Every edge of the convex hull of a vertex set is Delaunay. Figure 2 illustrates the reason why. For any convex hull edge e, it is always possible to find an empty circle that contains e by starting with the smallest containing circle of e and “growing” it away from the triangulation [4].

![Figure 2](image-url)

Figure 2. Each edge on the convex hull is Delaunay, because it is always possible to find an empty circle that passes through its endpoints [5].

3.4 Hydrostatic Pressure
One of the most important of fluid characters is pressure concept where the tension of the pressure is defined as force per acre. Mathematically it is written as follow:

$$P = \frac{F}{A}$$  \hspace{1cm} (5)

P is pressure (Nm²/Pascal), F is force (N), and A is acre (m²). In the case of a space filled by liquid with density of ρ dan depth of h, so there is gravitation that affect the liquid pressure. The amount of pressure force on each acre is hydrostatic pressure, thus the hydrostatic pressure formula is:

$$P = \frac{F}{A} = \frac{m.g}{A} = \frac{(\rho.v)g}{A}$$  \hspace{1cm} (6)

P is hydrostatic pressure (Nm²), ρ is liquid density (kgm⁻³), g is gravitational acceleration (ms⁻²), h is liquid depth (m). From the equation above that pressure in the liquid is caused by gravitational force which the amount of it is based on its depth. Hydrostatic point at a point is based on its depth and all point with equal depth get equal hydrostatic pressure as well.
4. Research method
This research used gravity data that is processed to obtain a Bouguer anomaly map. Then this Bouguer anomaly map is processed using the SVD or Second Vertical Derivative method to get the SVD map and used the Bernoulli principle calculation to get the pressure value. The SVD maps are then sliced to obtain SVD graph. The analysis was done using SVD graphs and the pressure values until conclusions are obtained.

5. Result and discussion
Result of the process of gravity data is anomaly bouger map. Some locations do not have gravity value since measurement was not conducted on the location. The gravity value on the location was retrieved by using geostatistics approach. Anomaly bouger map after using gestatistic approach:

Figure 3. Anomaly bouger map

Figure 4. SVD map

As figure 3 illustrated, the spread of anomaly bouger in Porong is around 12 mgal until -36 mgal. To be able to analyse the geology subsurface structure, the Second Vertical Derivation analysis method was used. SVD method is used to determine the structure of subsurface fracture in Porong, Sidoarjo where it is the migration stream of Lapindo mud. The map of filter second vertical derivative result was retrieved from process of using oasis montaj software as illustrated in figure 4. To acknowledge the category of the fracture, slicing was performed on those 3 locations as shown at figure 5.

Figure 5. Slice for SVD map

Slicing was done at southeast region since there was an obvious high anomaly collide with low anomaly. The drastically decrease of anomaly value is guessed as a fracture region. Three slicing were made as red lines on the map and it is given information as A-A’ West-east direction, B-B’ Southwest-Northeast and C-C’ Northwest-Southeast direction. From data result of slicing were performed
derivative analysis to know the subsurface structure of region with contrast anomaly. Then it was plotted to graphic below.

![Graphic SVD Slice A-A'](image1)

**Figure 6.** Graphic for SVD Map 1 Slice A-A'

![Graphic SVD Slice B-B'](image2)

**Figure 7.** Graphic of SVD Map 1 Slice B-B'

The graphic above is a graphic of second vertical derivative analysis on anomaly bouger map from gravity data of Porong. From the graphic, it is identified that there is a fracture at the slice region. From SVD graphic calculation result shows that the absolute value of maximum SVD is higher than the absolute value of minimum SVD that shows the normal fault characteristic.

On the second slicing, Slicing B-B’ is the region with medium and low anomaly. In this region the curve characteristic as well as the the slice A-A’ region where the absolute value of maximum SVD is higher than the absolute value of minimum SVD, so in this region is also suspected that have a normal fault.

On the third graphic suspected for having two fractures. Because there are two lines which pass the 0 point. First at the distance of 0.005 and the second is at 0.01 to 0.015 lateral . Both lines have the same characteristic, which is the the absolute value of maximum SVD is equal with absolute value of minimum SVD. Thus, it is suspected in this region has two strike-slip fault.

![Graphic SVD Slive C-C'](image3)

**Figure 8.** Graphic of SVD Map 1 Slice C-C'

![Graph of Pressure against Depth](image4)

**Figure 9.** Graphic of Pressure against Depth [6]

Fracture is one of cracks that can be the line out of the mud. The rising mud through these line might be affected by pressure factor, in this case is fluid hydrostatic. According to gravity data of Porong, Sidoarjo, the density of the Lapindo mudflow region is 1.8 kg/m³ with 1500 m of depth. Thus, the pressure is $P_h = 270$ Ksc. According to the available source, the hydrostatic pressure in Lumpur Sidoarjo (LUSI) region is illustrated on the figure 9.

Porong, Sidoarjo region is one of regions that is passed by active magma line, where active magma can affect the activities of the region’s subsurface. The other factors that affects on the emergence of Lumpur Lapindo disaster is pressure. The pressure on subsurface can affect the mud flow below the surface of Porong, Sidoarjo and cause the eruption of mud. The gained pressure value is quite big according to the calculation using the gravity data of Porong Sidoarjo. The pressure is 270 Ksc.
Due to the value of the pressure is quite big, it can cause the mud rises to the surface. If it is compared to the result of data calculation, Hochstein and Sudarman in 2010 had done observation on the pressure of Sumur Banjar Panji subsurface, stated that The pressure in the subsurface of 1500 m depth with the density of 2 kg/m$^3$ is 300 Ksc. It means the margin between observation result and gravity data calculation is 20 Ksc. The margins is quite small with the density difference of 0.2 kg/m$^3$. So, the density value of Rocks in Porong is around 1.8 kg/m$^3$ to 2 kg/m$^3$. The amount of pressure is also affected by the amount of gravitation force and its depth. In the certain depth, with the effect of magma stream below which move continously and with big enough pressure can cause movement of the fractures and cracks and create new line out of mud.

6. Conclusion

According to the spread of anomaly bouger is known that the region with high value of anomaly bouger lies on Southwest region and the region of low anomaly bouger lies on northeast. This contour pattern shows the fracture is from southwest to northeast. Geostatistical method has role in the data of interpolation stage at the region where is not passed by the measurement line. The result of this interpolation is found that new gravity anomaly value in the region that is not passed by the measurement. By the utilization of Second Vertical Derivative (SVD) method is known that some fractures is the migration location of Lumpur Lapindo. The Fractures possibly become the line out of mud from the subsurface. According to the review and observation, it is suspected that mud erupts continously since the high pressure below the surface. The continous high pressure might cause new lines as the mud line out to the surface.

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