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Lineament Trend Analysis for Designing of Fault Deformation Monitoring Network in the Sermo Reservoir Area, Yogyakarta, Indonesia

Yulaikhah[a,1], Subagyo Pramumijoyo[b], Nurrohmat Widjajanti[a,2]

[a] Geomatics Engineering Doctoral Study Program, Department of Geodetical Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
E-mail: [1]yulaikhah@ugm.ac.id; [2]nwidjajanti@ugm.ac.id

[b] Department of Geological Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
E-mail: bagyo@ugm.ac.id

Abstract— **The Sermo Reservoir plays a vital role in the livelihood of the surrounding community. However, based on the geological map, a fault crosses the reservoir and possibly through the dam body. Therefore, disaster needs to be mitigated by monitoring the deformation of both the fault and the dam body. Deformation monitoring network design needs to consider the accuracy, reliability, and sensitivity in detecting and measuring any displacement. Geological conditions affect the sensitivity of the network. This research aims to analyze the geological structure based on the lineament interpretation of the deformation monitoring network design of the fault. The study was conducted by interpreting lineaments using the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) image with 30 m resolution and then representing the lineament patterns with a rose diagram. The lineament analysis was related to the rock formation of areas surrounding the Sermo Reservoir. Furthermore, the deformation monitoring network will be designed considering the geological phenomenon resulting from lineament analysis and other factors used in previous research, such as the distance and direction of the control point from the fault. From the lineament analysis, initial information showed that the fault was estimated in the direction of northwest-southeast and may be active. Deformation monitoring stations should be established along the fault plane, in both the right and left sides, and within various distances. The stations should be evenly distributed to cover the areas around the reservoir, the area outside the reservoir but still within the fault area, and the area outside the reservoir and the fault. The distribution of the stations should also form a transverse baseline to the fault.**

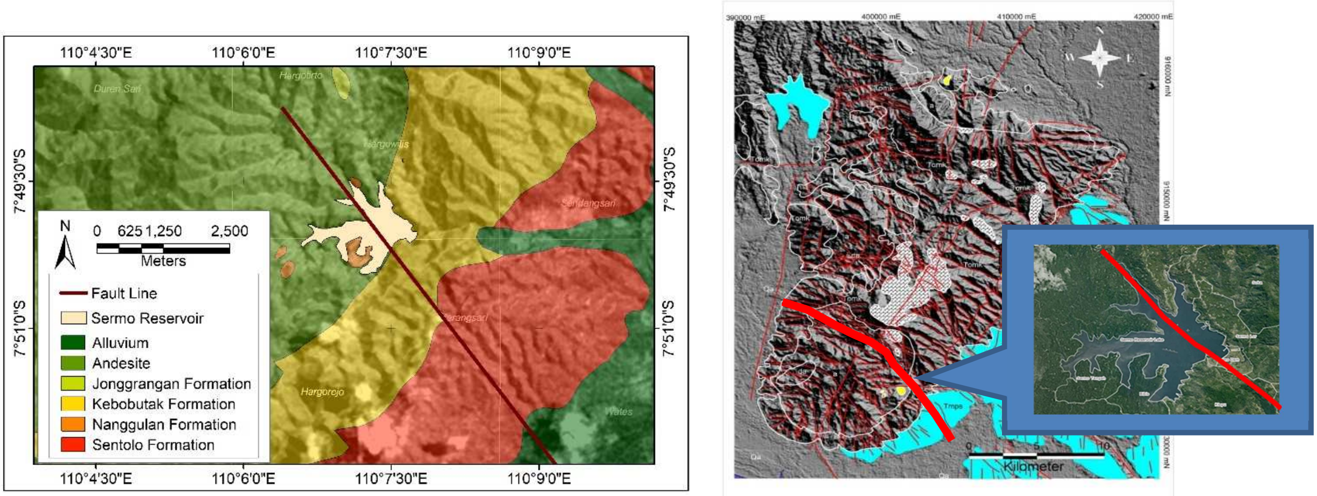
Keywords—**lineament; rose diagram; fault deformation monitoring; network design.**

I. INTRODUCTION

The Sermo Reservoir is located in the region of Hargowilis village, Kokap district, Kulon Progo Regency, Daerah Istimewa Yogyakarta, Indonesia. The reservoir plays a vital role in the livelihood of the local community. It holds a vital role as a water reservoir from which water is then distributed by the Water Utilities (PDAM), serving the needs of clean water, irrigation, and flood prevention.

The geological conditions surrounding the Sermo Reservoir have a special phenomenon. Overlaying geological maps and Landsat images show that reverse and thrust faults cross the reservoir (Fig. 1(a)). This has also been shown in another research [1] about the geological structure of rock distribution in the Kulon Progo area. The authors concluded that the secondary structure that controls the rock distribution in the Kulon Progo mountain is in the form of a northwest-southeast normal fault structure, southwest-northeast reverse fault, and north–northwest lateral fault. The fault crosses the Sermo Reservoir, as shown in Fig. 1(b). The same description is also found in the main report of Sermo Reservoir Project Details Design [2].

The geological structure in the area surrounding the Sermo Reservoir consists of the major fault with northwest-southeast direction, passing through the Ngrancah River in the inundation area. The syncline fold structure with northeast and southwest directions passes through the dam abutment. The bedding's dip and strike, as well as joints, show local disorientation. Comparing the reference from the Kulon Progo region and southern mountain, the northwest-southeast main fault is a part of the pre-plutonic tectonic. The planar structure phenomenon, which is likely a flow-like structure in brecciated andesite, is a syngeneic structure or plutonic volcano formed during the Old Andesite Formation [3]. Investigating the existence of a fault in the Sermo Reservoir is very interesting because the reservoir has the potential to increase the seismic activity of the surrounding faults.



(a) (b)

Fig. 1. Fault passing through the Sermo Reservoir (a) resulted from the geological map and Landsat image overlaying (b) resulted from the previous study [1]

The inundation of the reservoir causes a change of tension and pore water pressure, which further affects the seismic force, resulting in the triggering of an earthquake. The Coulomb-Mohr model is used to quantify the effect of the existence of the reservoir against the seismic force and the chance of earthquake occurrence [4], [5].

On the other hand, a reservoir built near a fault structure can potentially cause deformation due to the existence of the fault [6]. The movement of the earth's crust is a factor that causes the deformation of a dam, in addition to other factors such as the type of materials used, construction method and irrigation condition, pressure changes against the dam, and temperature change [7], [8].

Based on these factors, mitigation on the Sermo Reservoir needs to be conducted through fault deformation monitoring, which is preceded by developing a monitoring control network. The network control design of the fault monitoring needs to be carefully planned in order to detect the movement optimally. One of the factors/criteria that need to be considered in the network control design of deformation monitoring is the sensitivity criterion. The sensitivity criterion of the network represents the capability of the network in detecting the movement or deformation in the area covered by the network [9]. Sensitivity analysis cannot be separated from the geological phenomenon of the monitored area. Therefore, to design a deformation monitoring network around the Sermo Reservoir, geological structure analysis needs to be conducted in the area. One of the methods that can be used to analyze the geological structure is observing the lineament trend through satellite imaging. This paper analyzes the geological structure in the area around the Sermo Reservoir based on lineament analysis using satellite imagery. Furthermore, it is used to design the deformation monitoring network of the Sermo Fault.

II. MATERIALS AND METHOD

One of the applicable methods for geological structure analysis is identifying the lineament trend using satellite imagery. In an image, a fault is mostly indicated by a lineament. Hobb recognized a linear geomorphic feature, which is a surface expression of a weakness zone or structure displacement in the earth's crust [10]. Hobb defined a lineament as a significant line that can suggest the architectural shape of rock hidden below. A lineament is a linear or curvilinear feature on a surface, with a straight or slightly curved part that can potentially describe the presence of a fault or other weak objects [10]. Therefore, a lineament is not necessarily linear in form. A more significant fault can exhibit a linear and a very thin form, especially when the fault occurs in an area that is morphologically a hilly or alluvial surface in form. The lineament is not always related to a fault and cannot be used solely as a sign of a fault's presence. Only lineaments that are caused by plate tectonics can be used as an indicator of a fault's presence [11]. In a humid area, a fault could be buried by thick sediments or soil layers so that the geomorphological expression on the surface is subdued and sometimes undetectable [12]. In areas where the regional tectonic force is caused by a fault with a low/slow movement rate in a broad zone, fault characteristics are not easily identified.

The interpretation of a fault using an image could be used based on three criteria [11]: 1) layers traces, 2) the difference between the slope and inclination directions, and 3) color difference. A lineament pattern can be represented by a rose diagram as well as other illustrations. The use of images in analyzing geological structures has been extensively adopted; examples include the use of images in analyzing faults in Arjuno Welirang geothermal and Mount Telomoyo geothermal area [13], [14].

Satellite imageries used to analyze regional geological lineaments are mid-resolution imageries, such as LANDSAT (30 m resolution), ASTER (15 and 30 m resolutions), or altitude imagery, such as ASTER DEM and SRTM (each with 15 m and 90 m resolution). Altitude imagery using airborne mode such as IFSAR (9 to 10 m in resolution) is also used. Geological lineament in the form of a line is interpreted both manually (visually) and automatically. Using manual interpretation, the line that is formed can be saved in a vector-format file, while for automatic interpretation, the line is saved using an automatic lineament function with the help of the specific algorithm of a software [15].

As a preliminary study, this research analyzes lineament trends using *Shuttle Radar Topography Mission Digital Elevation Model* (SRTM DEM) in 30 m resolution. The analysis is conducted in steps, namely 1) interpretation of the lineament of the SRTM DEM image, 2) presentation of rose diagrams, 3) analysis of lineament based on rock formations, and 4) designing of Sermo deformation monitoring network.

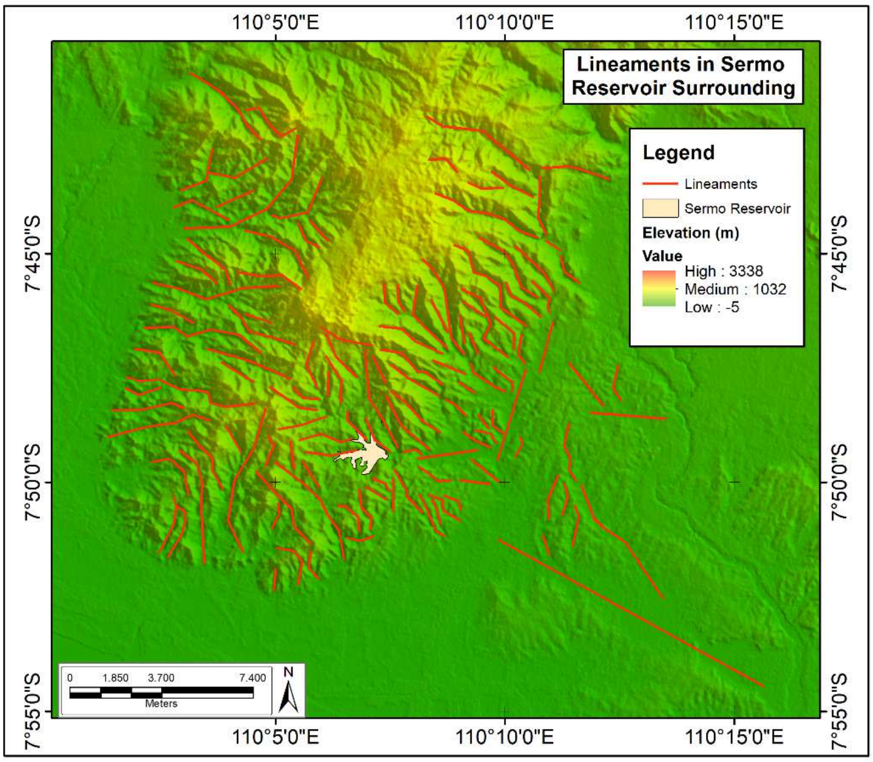


Fig. 2. Lineaments in the Sermo Reservoir surrounding

The DEM SRTM in the Yogyakarta region is used as a base image for delineating the lineament. In this image, reliefs on the earth's surface, such as mountains, mounts, valleys, and rivers, are presented more clearly. Fig. 2 shows the lineaments in the Sermo Reservoir and the surrounding area.

The lineaments are then presented in the form of rose diagrams. In this case, two rose diagrams are constructed: rose diagrams for quantity and length accumulations. The rose diagram for quantity accumulation presents the total lineaments in a certain direction, while that for length accumulation presents the total length of lineament in a certain direction. The presentation of rose diagrams for quantity accumulation requires azimuth data, while that for length accumulation requires the coordinates of two ends of lineament. The rose diagrams for the quantity and length accumulations are presented in Fig. 3.

The two rose diagrams show the lineament patterns, which are nearly similar; both show dominant lineament toward the northwest-southeast direction. The data in the form of these rose diagrams need to be analyzed considering the rock formations to know the geological structure representation in the area. Furthermore, the rose diagram can be used as a reference in the design of the fault deformation monitoring network.

III. Results and Discussion

A. *Stratigraphy of the Kulon Progo*

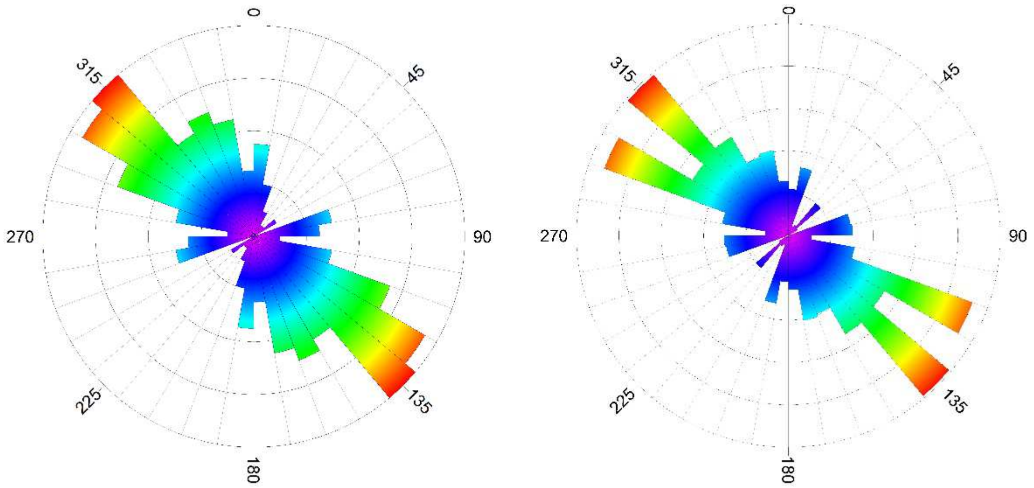
The Sermo Reservoir is located in Kulon Progo Regency. Therefore, the stratigraphy of this area is a part of the stratigraphy of the Kulon Progo mountainous area. According to [1], the stratigraphy of the Kulon Progo mountainous area can be differentiated into categories of sedimentary and volcanic rocks. The sedimentary rock as the base is composed of mostly clay-quartz sand and limestone and is called the Nanggulan Formation. The sedimentary rock formations are the base of the Kebobutak Formation volcanic rocks. The two formations are intruded by shallow intrusive rocks in the form of microdiorite, andesite, and dacite, which have generally changed. The volcanic cluster is inconsistently covered by Jonggrangan, and Sentolo Formations shallow sea sediments [1].

Based on the regional stratigraphy, there is some rock formation at Kulonprogo mountainous area as below [1].

1) Pre-tertiary rocks. Metamorphic rocks are found in the northern Kulon Progo mountains, especially in the area of the Kali Duren-Kali Sileng rivers, Borobudur District, Magelang Regency. These metamorphic rocks form fragments of the Kebobutak Formation volcanic breccia.

2) Nanggulan Formation: The Nanggulan Formation is spread equally in the Nanggulan region (the eastern part of the Kulon Progo mountains), especially in the Kalisongo region. Regionally, the formation is also found in the Sermo-Kokap area. Based on the planktonic foraminifera study, the formation is classified as being in the age range of the Mid-Eocene to the Oligocene period.

3) Kebobutak Formation/Old Andesite: This formation is sedimented inconsistently above the Nanggulan Formation. Based on the planktonic foraminifera fossils found in the napal, this formation can be assumed to be as old as the Old Andesite Formation, corresponding to the advanced Oligocene age. The area around the Sermo Reservoir is dominated by this type of rock. The eastern part of the north-south course is dominated by the Kebobutak Formation, and the western part of the reservoir is dominated by intrusive andesite rocks.



(a) (b)

Fig. 3. Rose diagram for quantity accumulation (a) and length accumulation (b)

4) Jonggrangan Formation: Above the Old Andesite Formation, the Jonggrangan Formation is inconsistently sedimented. This formation is hardly found in the surrounding area of the Sermo Reservoir, morphologically shown as a small and separated hilly area.

5) Sentolo Formation: Above the Old Andesite Formation, apart from the Jonggrangan Formation, the Sentolo Formation is sedimented inconsistently. The formation consists of limestone and napalan sandstone. The bottom part consists of a conglomerate stacked by napal tufan inserted with tuf. This formation is commonly found around the Sermo Reservoir, especially in the eastern part.

6) Alluvial Sedimentation and Sand Cluster: The alluvial deposit consists of gravel, sand, silt, and clay, which are sedimented along big rivers and coastal land. The river's alluvial is sided by the alluvial of the broken down deposits of the volcanic rock. Sand cluster along coasts is indicated as the source of iron sand. Alluvial sedimentation around the Sermo Reservoir is mostly seen in the eastern part of the area. Fig. 1(a) shows those formations, especially in the Sermo area.

The lineaments of each rock formation are described in the form of rose diagrams, with length accumulation parameters. This research found 110 distributed lineaments in the form of 5 lineaments located in the alluvial rock, 14 lineaments in the Sentolo Formation, 66 lineaments in the Kebobutak Formation, 6 lineaments in the Jonggrangan Formation, 44 lineaments in Andesite Intrusion rock, and 4 lineaments in Dacite Intrusion rock.

The rose diagrams of lineament in the alluvial deposit formation and Sentolo Formation are shown in Fig. 4 and Fig. 5, respectively. Based on Fig. 4, the length of the lineament in the alluvial rock formation is dominantly at the 325° and 295° directions. Therefore, the force direction can be assumed to be at 310° or 130° (middle). In the Sentolo Formation (Fig. 5), the most prominent length of lineament is shown at the 325° direction, which is similar to that of the alluvial rock. Therefore, the lineament at this direction in the formation can be ignored. By ignoring the lineament at the 325° direction in the formation, the lineament dominantly occurs in the 315° and 355° directions. Therefore, in this formation the force is probably at the 335° or 155° directions.

Furthermore, the rose diagram for lineaments in the Kebobutak Formation can be seen in Fig. 6. In this formation, the length accumulation lineaments are dominantly at the 315° direction, with the total lineament length of approximately 42,500 m.

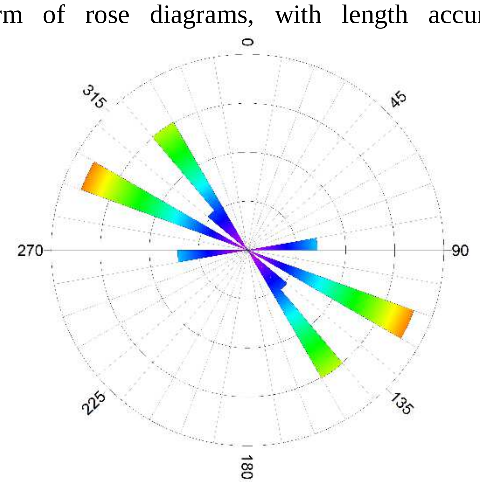


Fig. 4. Rose diagram of lineament in alluvial rock

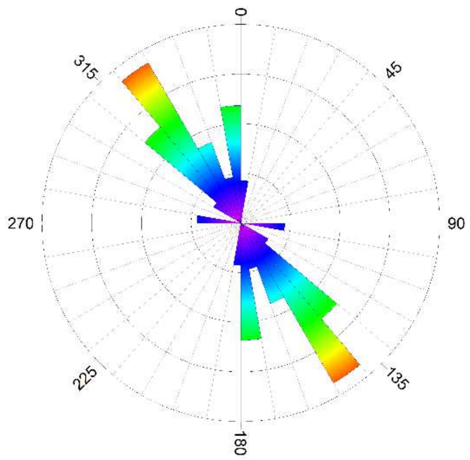


Fig. 5. Rose diagram of lineament in the Sentolo Formation

In the Sentolo Formation, lineaments are also dominantly in this direction, with a total length of around 5,000 m. In the Kebobutak Formation, the dominant lineaments in that direction can be ignored. By ignoring the lineaments at the 315° direction in the Kebobutak Formation, the force direction in the Kebobutak Formation can be predicted to probably be at the 280° or 100° direction.

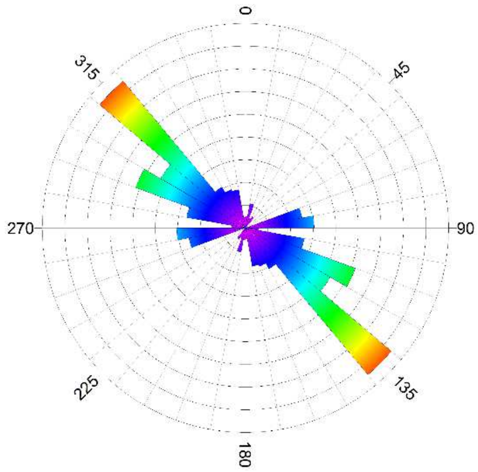


Fig. 6. Rose diagrams of lineament in the Kebobutak Formation (length accumulation)

The rose diagrams for dacite and andesite intrusion rocks can be seen in Fig. 7 and Fig. 8, respectively. In the dacite intrusion rock, the lineaments are four in total, and there is no trend (Fig. 7). Therefore, the lineaments are not representative for the analysis. In the andesite intrusion rock formation, many lineaments are present, 44 in total (Fig. 8). Lineaments are present in all directions, and their lengths are dominantly at the 305° and 295° directions. As previously explained, the lineament of the 295° direction is present in the alluvial rock formation; therefore, the lineament in this direction, in the andesite intrusion rock formation, can be ignored. This way, no force is present, even though lineaments dominant in the 305° direction are present.

Based on the analysis of lineaments rose diagrams, it can be predicted that there are probably three forces, which work at the 100°, 155°, and 130° directions. The presence of lineaments in all rock formations, including the youngest rock formation, is an indicator that the fault may be active. However, a field survey is still needed to confirm this result.

B. The Design of Sermo Fault Deformation Monitoring Network

Deformation surveys are usually conducted to identify and measure movement and deformation in investigated areas. The amount of the movement is usually only a few millimeters. Therefore, the monitoring networks used for this purpose should be optimal. An optimal deformation monitoring network needs to be designed and analyzed according to three essential criteria: accuracy, reliability, and sensitivity [9].

The accuracy refers to network quality in the case of random errors. The reliability is a representation of the network's ability in detecting and identifying gross errors in measurement. The network sensitivity refers to the capability of the network in detecting and measuring the movement and the deformation present in the area covered by the network. Since the geological phenomenon and its parameters of the investigated area have a significant contribution, the deformation monitoring network should be designed by considering the parameters. The parameters are used in the process of analyzing the sensitivity of a network.

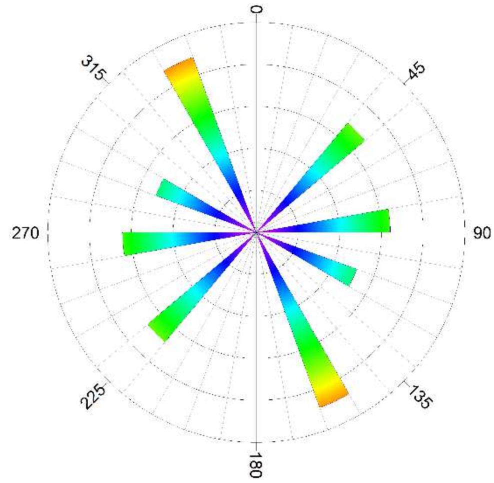


Fig. 7. Rose diagram of lineament in dacite intrusion rock (length accumulation)

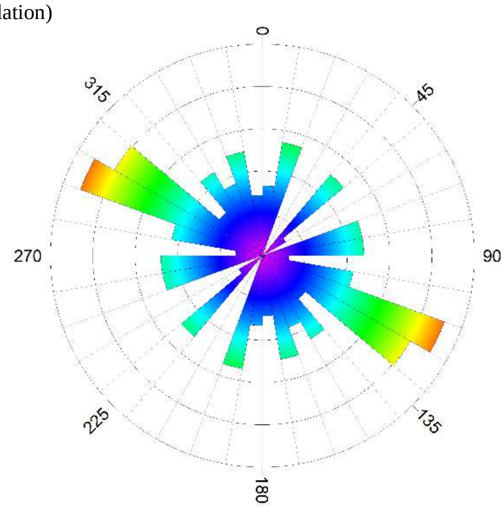


Fig. 8. Rose diagrams for lineament in andesite intrusion rock formation (length accumulation)

The deformation monitoring survey can be done using a multi-epoch GNSS measurement. In its development, the Global Navigation Satellite System (GNSS) technology is more promising in providing better coordinates accuracy. Therefore, this method is often used in monitoring deformations, both local and regional. The method is subject to monitor the deformation of the Thai Geodetic Control Network due to the Sumatra-Andaman earthquake of 2004 and the 2005 Nias earthquake [16].

The GNSS technology has also been used in many deformation monitoring studies, including the observation of the Kaligarang Fault deformation [17], the analysis of the active fault surface deformation of the Seulimum and Aceh Segment [18], the modeling of deformation in the Sunda Strait, and the deformation analysis of Opak Fault [19]. On a broader scale, the GNSS technology has been used to observe the movement of the earth's crust in Indonesia [20], analyze the earth's crust strains and associated earthquake in the eastern region of Sunda-Banda [21], and analyze the deformation of the earth's crust in Java [22].

The geological conditions of the monitored area should be considered in the design of the deformation monitoring network. Two fault models, namely Simple Transform and Locked Faults, were applied in the design of the GNSS vector configuration of a fault deformation network in Eastern Israel that is predicted to move toward the north–south direction [9]. Using the Simple Transform Fault model means that the baseline length will not contribute any significant effect to the network sensitivity. However, using the Locked Fault model implies that the baseline with the east–west direction contributes significantly to the network sensitivity. A longer baseline contributes significantly to the network sensitivity. When using a longer baseline is required, fewer baselines can be used [9]. It can be said that the baseline in a direction perpendicular to the fault movement direction contributes more to the network sensitivity.

Similarly, in the monitoring of the Aceh and Seulimum Faults, to obtain the parameters of optimum displacement mechanism in elastic dislocation design, a survey was conducted with a cross-path to the fault [18]. However, the station's distance from the fault area needs to be considered as well. Similar to the Kaligarang Fault deformation monitoring network, the monitoring control station is not far enough from the fault, and thus, the observation did not show the characteristics of the Kaligarang Fault. Hence, an additional control station design with a longer distance was conducted [17].

Since the characteristics of the Sermo Fault are not commonly known, the result of the preliminary study on lineament analysis as described above can be used as a reference in designing the fault deformation monitoring network. The results of deformation monitoring in Israel, Kaligarang, Semarang and of the monitoring of the Aceh and Seulimum Faults can also be considered. The Sermo fault crosses through the Sermo Reservoir; this condition needs to be considered when finding out whether the reservoir's presence affects the fault movements. The fault deformation monitoring should be developed based on these designs: Monitoring stations should be installed in the right and left sides of the fault to form baselines transversing the fault or to northeast–southwest direction. The monitoring stations should be placed at different distances from the fault area. The control stations are designed in two parts, namely the micro control stations, which are placed near the fault, and the macro control stations, which are placed far but still within the monitoring area of the fault. The monitoring stations should be placed along the fault, with the distribution of several stations around the reservoir, the area outside the reservoir but still within the fault area, and the area outside the reservoir and the fault area.

IV. CONCLUSIONS

Based on the lineament analysis using SRTM image, preliminary information related to the geological structure of the Sermo Reservoir is that the force is present at the northeast–southwest direction. It is predicted that the fault is at the northeast–southwest direction and may be active. However, the result of this current research needs to be further confirmed by a field survey.

By considering the geological condition and other factors, Sermo fault monitoring stations should be built along the fault area, both on the right and left sides of the fault area and with different distances from the fault area, but still within the monitoring area. The presence of the reservoir becomes an essential factor that determines the stations placement. Stations need to be placed in the area around the reservoir, in the area outside the reservoir but still within the fault area, and in the area outside the reservoir and the fault. Moreover, the station distribution should form a transverse baseline against the fault.

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