

Analysis of Baturagung Reservoir Leaking, Gedangrejo, Gunung Kidul Regency using Digital Outcrop Model Method

Analisis Kebocoran Embung Baturagung, Gedangrejo, Kabupaten Gunung Kidul Menggunakan Metode Digital Outcrop Model

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ABSTRACT

Water, serving as a vital resource, finds applications in diverse sectors such as agriculture (irrigation), drinking water supply, flood control, and hydroelectric power generation. On a smaller scale, the construction of "Embung" or small artificial reservoirs facilitates water storage during the rainy season for subsequent use in the dry season. Within the study area, a reservoir constructed in 2018 has never attained full capacity, a circumstance that piqued the author's interest. A combined approach utilizing aerial photogrammetry and ground observation is employed for comprehensive analysis. Aerial photogrammetry yields an extensive and accurately depicted geometric representation of geological structures. The investigation focuses on the Semilir Formation, a volcanic formation. Findings reveal that the study area manifests a division into nine (9) segments discerned from distinct structural trends. These segments are delineated by eight (8) faults, with the major fault identified as Fault F6. Fault F6 exhibits a prevailing NNE-SSW trend, consistent with the primary fault on the regional geological map. Notably, Fault F6 encompasses a substantial fault zone traversing the Baturagung Reservoir and stands accountable for the reservoir's leakage.

Keywords: Baturagung Reservoir, Fault, Segment, Water

ABSTRAK

Air sebagai sumberdaya yang penting dapat digunakan dalam berbagai kepentingan seperti pertanian (irigasi), air minum, pengendalian banjir; hingga pembangkit listrik tenaga air. Pada skala yang lebih kecil, "Embung" atau danau buatan kecil pada dasarnya dibangun untuk menampung air pada saat musim penghujan sehingga dapat digunakan pada musim kemarau. Daerah telitian terdapat embung yang dari pembangunanya pada tahun 2018 hingga kini tidak pernah terisi air dengan penuh. hal ini menimbulkan ketertarikan penulis. Metode fotogrametri udara dan observasi darat dilakukan dalam melakukan analisa lebih lanjut. Metode fotogrametri dapat memberikan gambaran secara lebih luas geometri dari suatu struktur geologi dengan akurasi yang baik. Penelitian dilakukan pada Formasi Semilir yang merupakan produk gunung berapi. Hasil yang didapatkan terlihat bahwa daerah telitian terbagi atas sembilan (9) segmen yang didapatkan dari pola trend struktur yang terlihat. Sembilan (9) segmen ini dibatasi oleh

delapan (8) sesar dengan sesar utama adalah sesar F6. Sesar F6 merupakan sesar utama yang berarah NNE - SSW sesuai dengan sesar utama pada peta geologi regional. Sesar F6 ini memiliki zona hancuran yang besar melewati Embung Baturagung, Gedangrejo dan bertanggungjawab atas bocornya Embung.

Kata kunci: Embung Baturagung, Sesar, Segmen, Air

INTRODUCTION

Water as a critical economic resource impacts the population and sustainable economic development (Wang *et al.*, 2019; Chen *et al.*, 2020). As a part of water conservation, reservoirs are vital for agricultural and urban water storage and delivery (Prigent *et al.*, 2012; Tharme, 2003). Reservoirs are also crucial to the regulation and management of surface water resources. Many reservoirs and dams have been constructed worldwide in recent decades for flood control, hydropower generation, and irrigation (Lehner *et al.*, 2011). In Indonesia, more and more small reservoirs called "Embung" are built for microwater conservation. In addition to being a water storage facility, the reservoir can be used as an agro-tourism object. According to Rustam (2010), Embung is an artificial building that accommodates and stores water with a specific small volume capacity, smaller than the capacity of the reservoir/ dam. Embung is usually built by damming a small river or can be built outside the river. The Embung will store water during the rainy season. Then the water is used by a village only during the dry season to meet the needs in order of priority, population, livestock, and gardens or rice fields. The amount needed will determine the height of the reservoir and the storage capacity of the reservoir.

The research was conducted in the Gedangrejo Gunung Kidul area in the Southern Mountain region at Semilir Formation (Lower Miocene). The Upper Oligocene to Lower Miocene volcanic rocks of the Batu Agung Escarpment (Kebo Butak Fm - Semilir Fm) were deposited in a subaerial to the shallow-marine setting. The volcanic activity culminated in a major explosive eruptive phase at about 20 Ma, then ceased at about 10 Ma (Smyth *et al.* 2005, 2008). As the boundary between Java's south-

ern and northern zones, the southern mountains develop a thrust fault (Volcanic Arc of Java). According to Hall, a thrust fault in the southern portion of Java has shifted Paleogene volcanic arc materials more than 50 kilometers to the north and 10 kilometers to the east (Hall *et al.*, 2007).

The author deliberately limits the focus to the geological aspects, with a specific emphasis on structural geology, in the vicinity of the Baturagung Reservoir. The chosen methodology for this investigation involves the application of the Digital Outcrop Model (DOM) method and direct measurement ground observation. By employing Unmanned Aerial Vehicles (UAVs) equipped with photogrammetric technology, the researcher aims to capture detailed aerial imagery that can be utilized to construct accurate three-dimensional models/ DOM of the geological structures. This approach enables a comprehensive and high-resolution analysis of the structural geology surrounding the Baturagung Reservoir.

Based on the Google Earth timeline (Figure 1) from 2018 until the latest data collection in November 2022 and local residents, the Baturagung Reservoir has never been completely fulfilled. This evidence makes the author suspect that a geological structure is responsible for the leaking reservoir. In conducting our analysis, the author employs photogrammetry analysis using UAV. Globally, UAVs are used for geological research, and the application of this technology is growing in popularity (Niethammer *et al.*, 2016; Bemis *et al.*, 2014; Nishar *et al.*, 2016). Photogrammetry can generate statistical data about spread and fracture trends, as well as fold trends, directions, types, and axes for the reconstruction of folds. Various studies attempt to establish the same stocky density values at regional, outcrop, and thin-cut scales. Diverse studies explain inevi-

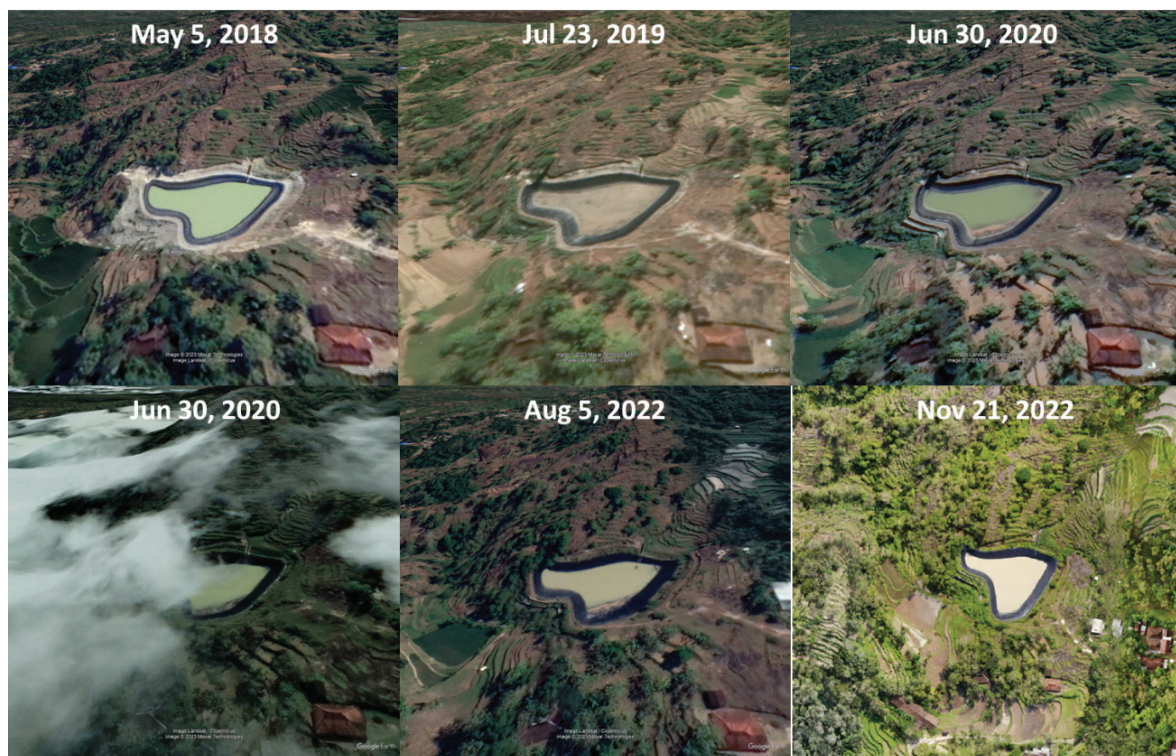


Figure 1. Google Earth timeline from May 5, 2018, to Nov 21, 2022 (collected data).

table perspective mistakes by concentrating on flat-surfaced outcrops (Vollgger and Cruden, 2016). Photogrammetry and remote sensing have always had as their principal objective the automatic reconstruction of geometric models for three-dimensional terrain surfaces and features from two-dimensional photographs. Complex three-dimensional solid models can be effortlessly mined for geometric and surface texture information (Pringle *et al.*, 2004; Hodgetts *et al.*, 2004).

This study elaborates on how Baturagung Reservoir leaks due to structural geology impact. Due to weathering, the major fault was not visible. Using aerial photogrammetry, we divide segmentation by the major direction of lineage. Every Group or Segment divided by major fault is responsible for reservoir leaking. We use Geospatial data such as DEMNAS (National Digital Elevation Model) with Open Source GIS Software QGIS as database and Photogrammetry software. In several studies, it has been found that geological structures play a role in the leakage of water from reservoirs and dams, in-

cluding the case of the Abu Baara Earthen Dam in Northwestern Syria. This research utilized electrical resistivity tomography data to reveal subsurface faults (Al-Fares and Asfahani, 2018). Additionally, Berhane *et al.* (2017) conducted an investigation into water leakage from two micro-dam reservoirs in Northern Ethiopia and found that geological structures are a major cause of the leakage.

Java Island is one of the archipelagic arcs resulting from Cretaceous convergent contacts (100-65 million years). Plate tectonic activity in the form of convergent interactions between the Indian-Australian Ocean Plate and the Sunda Shelf, which is part of the Eurasian continent's plate, subducts (slides down) the Sunda Shelf, establishing an archipelago (Asikin, 1974; Katili, 1975). The island is part of an island arc that originated above the north-dipping subduction zone and the border between the Indian-Australian and Eurasian (Sundaland) tectonic plates (Katili, 1975; Hamilton, 1979).

The research area is located in the northern Wonosari Platform at Semilir Formation. Based

on Surono *et al.* (1992) in Figure 2, the study area is interpreted as NW - SW structure. This interpretation strengthens the author's belief that a geological structure causes a reservoir leak.

The Semilir Formation was exposed throughout the Southern Mountains and along the southern coast of central Java; the Kebo-Butak Formation covers the lower portion of the Semilir Formation, while the Nglanggeran Formation covers the higher portion. Similar formations expand across the steep slopes of north Baturagung so that the Kebo-Butak Formation's lower portion reaches the south hills and meets the Nglanggeran Formation's upper portion.

The Crystal tuff, tuf lapilli, and pumice breccia comprise the majority of the Semilir Formation's volcanic materials. The bottom portion of this formation is formed of lithic-feldspathic wackes sandstone. Foraminifera and nannofossils in the lower calcareous indicate a marine environment and an early Miocene age (NN3). The higher portion consists of sandstone and andesite breccia. There are some thin lignite lenses and wood fossils in several locations above. The upper portion demonstrates the broad distribution of grain-flow sediments. The interpretation of this

section is terrestrial deposition. Using radiometric dating, the age of pumice-breccia was determined to be $17,0 \pm 0$ million years and $16,0 \pm 1$ million years, representing the end of the early Miocene.

The Semilir Formation's brightening environment indicates a shallow uplift from which the shallow sea turned ashore. The andesite breccia and sandstone facies are deposited in a relatively brief period. This signifies that voluntary activities are on the rise in the top section of the formation. Surono *et al.* (1992) inferred that the presumed epicenter of the major eruptions that formed the Bleary Formation is the Baturetno Basin.

METHODOLOGY

Geosciences require high-resolution three-dimensional (3D) data gathering at all sizes, from hand specimens to landscapes, and a variety of methods exist to handle different areas of the scale spectrum (McCaffrey *et al.*, 2005). Joints are fragile structures exhibiting surface extensional displacement (Pollard and Aydin, 1988; Fossen, 2010). These cracks are most prevalent in the top crust, where forces

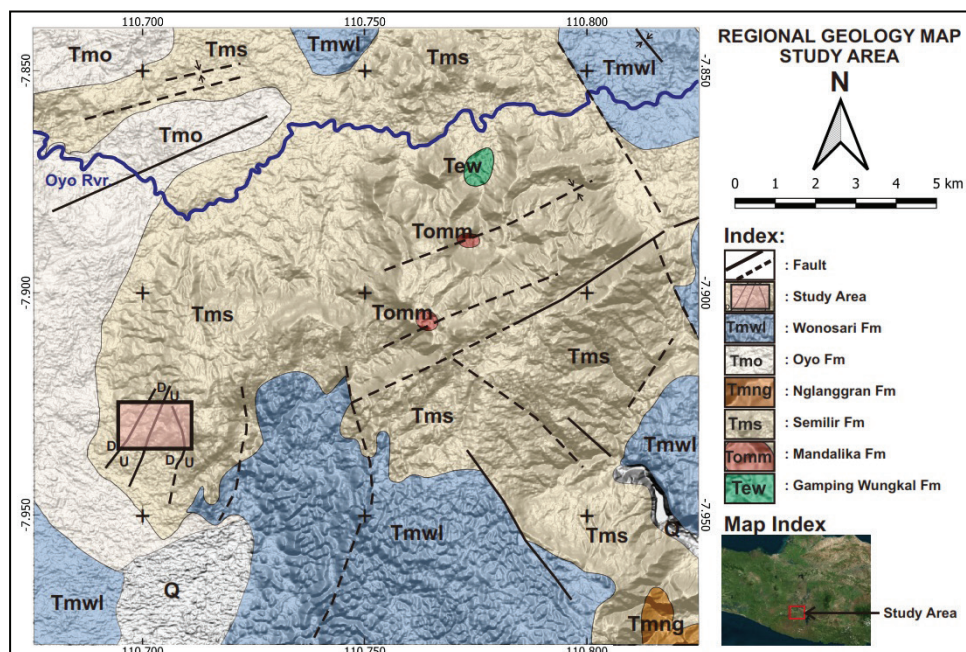


Figure 2. Regional Geological Map of Study Area (Modified from Surono *et al.*, 1992).

of diverse origins exceed the rock's strength (*e.g.*, tectonic, overburden, internal pore pressure, thermal expansion, or contraction). According to linear elastic fracture mechanics, inhomogeneous and anisotropic rock masses include faults from which joints originate. The concentration of stresses at the ends of joints favours and regulates the path and velocity of joint propagation (Gross, 1993).

Despite technological (*e.g.*, battery life/flight time), natural (*e.g.*, weather conditions), and legal (*e.g.*, flying within visual line of sight) constraints, UAV photogrammetry has excellent potential for structural geology applications. Even though traditional structural fieldwork was kept to a minimum in this study, we could remotely collect a full brittle and ductile structural dataset, which was then processed, interpreted, and utilized for 3D implicit modeling. The difficulty in obtaining valid sense-of-shear markers from aerial pictures at the working scale of our study, which are crucial for the kinematic and dynamic reconstruction of the tectonic past, was one of the limitations we encountered. The high-resolution aerial pictures could not resolve striations on fault planes or slickened lines, necessitating human field measurements (Vollgger and Cruden, 2016).

The photogrammetric acquisition was conducted utilizing an Unmanned Aerial Vehicle (UAV) type DJI Mavic Air 2 quadcopter equipped with a GPS/GLONASS satellite system and a 12 to 48-megapixel (max) camera. Table 1 lists the technical specifications of the UAV platform and camera. Baturagung Reservoir and its surroundings were the main targets of the photograph. We seek the finest opportunity to acquire data from bedrock (Semilir Formation). At the bedrock, the structural pattern is clearly visible.

Data acquisition is crucial because it depends not only on the flight itself but also on the taking of appropriate, photographic data in terms of exposure and overlap of the photographs, which will depend on factors such as the illumination of the outcrop in daylight (balance of targets), temperature, wind direction and speed, weather conditions, and all environmental variables associated with the flight (Hinge *et al.*, 2018). Photogrammetry is the basis for information gathering using UAVs. The technique is based on getting photos with various positions but a shared area between neighbouring images. Regarding UAV photos, at least 60 per cent overlap is advised. These photos can generate a point cloud, the base for interpolating 3D digital models (Villarreal *et al.*, 2020).

All 3580 photos within eight (8) acquisitions were georeferenced with GPS-onboard coordinates. Using the Structure-from-Motion (SfM) method and agisoft metafile software, the Photogrammetry 3D digital models were built. A total of 3,580 photos were aligned using the software's default accuracy and the pair pre-selection procedure that considers the image positions registered by the RPAS-GPS. The five (5) phases of the Agisoft Metafile workflow used to generate model data are as follows: 1) picture matching, bundle block modification, and generation of sparse Point Cloud; 2) generation of dense PC; 3) generation of mesh; 4) generation of texture. 5) Generation Orthophotographs. The result of Orthophotographs is quite good and appropriate to be interpreted (Figure 3). The Model was georeferenced in the WGS84/ EPSG7030 - UTM49S coordinate system using the UAV's registered onboard photos. Data processing also performs GIS analyses, including map registration and Structural Geology analyses.

Table 1. Drone specifications

Hardware	Sensor	Lens			
DJI Mavic Air 2	Effective: 12 - 48 MP (Max)	FOV: 84°	1/2" CMOS EQ 24 mm	Aperture: f/2.8	SR: 1 m to ∞

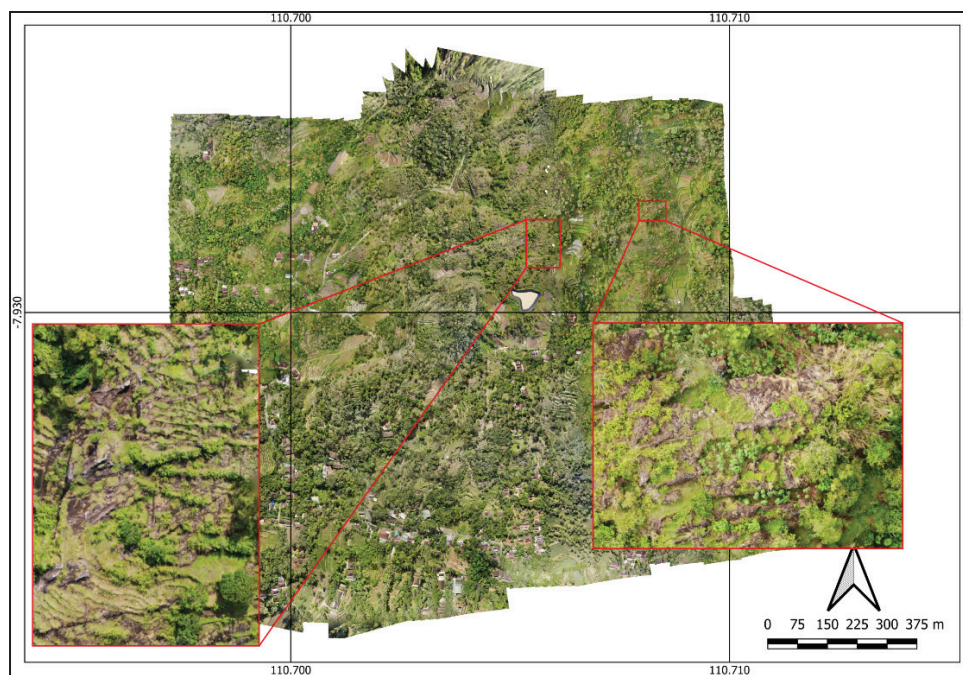


Figure 3. Digital Outcrop Model (DOM) results, the geological structure is visible and appropriately interpreted.

The Digital Outcrop Model result of data processing, as we explained in the previous subchapter, is quite good, and the data is appropriate to be interpreted (Figure 3). Data modeling requires: 1) Model interpretation requires regional geology data and previous studies to support research data. The data needed are regional geological maps compiled from Surono *et al.* (1992) and electrical resistivity tomography (ERT) geoelectrical measurements (Zakaria *et al.*, 2023). 2) Structural Geology analyses and modeling. The author conducted lineation measurements based on the Digital Outcrop Model (DOM) features from aerial data and performed field measurements accompanied by rock descriptions in the study area. The use of aerial DOM allowed the author to cover a broader area for interpretation and analysis purposes. 3) Model interpretation for proving the hypothesis and analyses. The full workflow for methodology can be seen in Figure 4.

RESULT

This investigation uses the results of the Digital Outcrop Model (DOM) in photogrammetry as a reference in interpreting geological structures.

The research method uses visual interpretation and quantitative analyses (statistics). The study reference uses the Geological Map of Surakarta and Giritontro quadrangle sheet (Surono *et al.*, 1992) in Figure 2. The Geological map (Figure 2) shows the study area inside the NE - SW fault zone. As seen in Figure 3, the results of the orthophotograph are suitable for use as a basis for interpretation. The complete results of the photogrammetric process in this study can be seen in Table 2.

In this section, we perform statistical analysis with structural geology data. The structural data we perform here are Fault and Fracture. Fault architectural elements consist of i) the fault core(s), which localizes the majority of deformation accommodated by fault zones, and ii) the damage zone, described as a zone of diffuse micro to mesoscale fractures surrounding the fault core. Micro-fracturing and cataclasis impact the matrix characteristics within fault zone domains, *i.e.*, the bulk permeability of the rock, at the microscale (Evans *et al.*, 1997).

The structural depiction of the bedrock form within the Semilir Formation was graphically

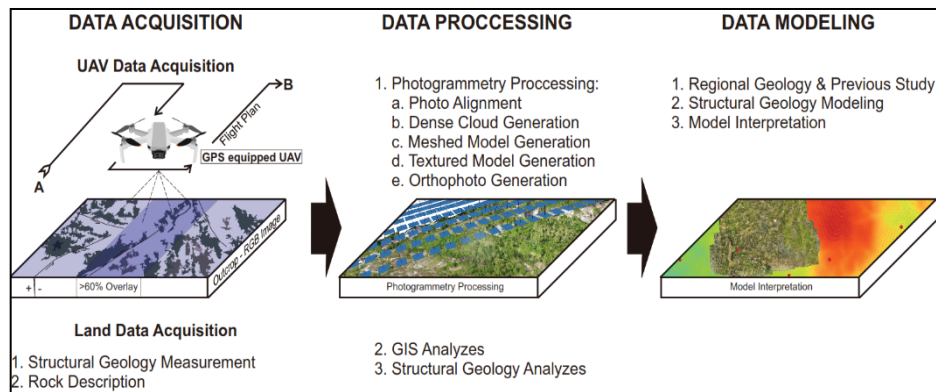


Figure 4. Schematic workflow followed for Acquisition, Data Processing, and Data Modeling integrating with essential data.

Table 2. Digital Outcrop Model (DOM) result

PARAMETER	Photo	Dense Cloud	Tiled Model	DEM	Orthomosaic	Area
RESULT	3580	118,260,880	9 levels	14,574 x 11,551	52,216 x 41,264	166.16
	photos	points cloud	4.12 cm/pix	16.5 cm/pix	4.12 cm/pix	hectares

represented using an aerial orthophotograph (Figure 5). The Semilir Formation, as evidenced by the visual representation, proves to be particularly conducive to elucidating structural geological features for our interpretative analysis. Structural geology interpretation was achieved through a synergistic integration of aerial observations and results obtained from ground-based geological observations. The author divided the research area into 9 (nine) segments. A lineation pattern (shown in the red line in Figure 5) characterizes every segment. The lineation or cracks can reveal a four-fold spatial organization: i) random if the fracture arrangement is statistically indistinguishable from random positioning; ii) uniform if the fracture spacing is constant (Nar and Suppe, 1991); iii) trend if the fracture spacing constantly increases or decreases; iv) clustering if the fracture network is characterized by the presence of regions where fractures have an abnormally close fracture spacing. Fracture corridors are the common name for the narrowly spaced segments of fractures (*e.g.*, Peacock *et al.*, 2016; Laubach *et al.*, 2018).

To strengthen the interpretation, the author conducted ground observations at observation

points L1 (Figure 6) and L2 (Figure 7), both corresponding to fault zone F6. To enhance the interpretation and clarity in delineating fractures, a more in-depth examination was carried out by zooming in on four distinct areas as samples: A1 (corresponding to Segment E in Figure 8), A2 (associated with Segment D in Figure 8), A3 (Segment I), and A3 (highlighting fault slip in Figure 9). This focused approach aimed to showcase the structural features within the research area vividly. For precise details regarding the locations, please refer to Figure 5.

Observation point L1 is located directly north of the reservoir embankment (Figure 5) and is implicated by the author as a potential source of the observed reservoir leakage. Observation point L1 revealed a conspicuous open crack exhibiting an orientation of N025°E. For a more detailed illustration, please refer to Figure 6. Segment I is characterized by fresh Semilir Formation on the western side of Fault F6, while on the eastern side lies a valley composed of weathered rock.

Located east of the Baturagung reservoir (Figure 5), observation point L2 features a fault plane associated with the fault in observation point L1. The damage zone, visible in Figure 7a, indicates

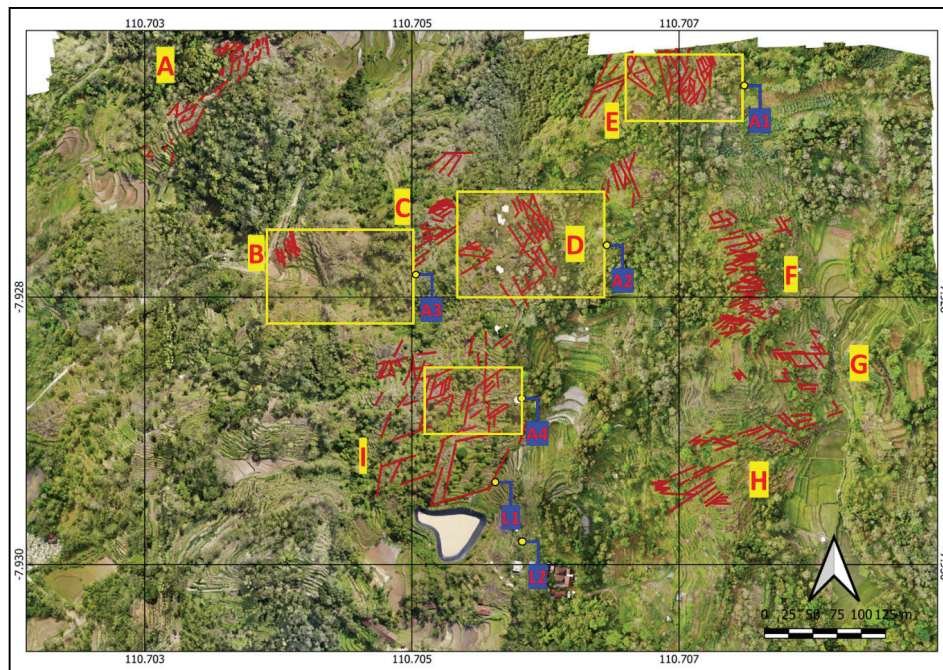


Figure 5. Aerial interpretation clustering for lineation or fracture trend.



Figure 6. Land observation L1 reveals a fault F6, which is suspected to be the main cause of reservoir leakage.

the presence of a fault with an orientation of $N029^{\circ}E/76^{\circ}$. On this fault plane, slickensides are observed with a rake of 32° (Figure 7b). Based on Rickard (1972), this fault is classified as a Normal Left Slip Fault. Describing the rock, it exhibits a fresh dark gray color, with weathering manifesting as a dark brown hue and coarse-lapillus grain size (0.06-64mm). The rock displays angularity and poor sorting, leading to its description as Lapili at this location.

In observation A1, we conducted a detailed examination by zooming in on the Segment E

area. Segment E is located in the northernmost part of the study area. By zooming in, it is possible to observe several clearly visible fractures in Figure 8a. Through quantitative analysis of their orientation, it can be concluded that the main direction of these fractures is from $N155^{\circ}E$ to $N335^{\circ}E$, with a total population count of 62. In observation A2 (Figure 8b), we employed a similar approach as in the previous point, conducting a detailed examination by zooming into Segment D. In Segment D, a population of 34 fractures was identified with a primary ori-



Figure 7. Land observation L2: a; Damage zone of Fault F6; b; Fault plane with orientation of N029°E/76° and Rake 32°.

entation ranging from 145° to 325°. The clearer zoom-in on Segments E and D is depicted in Figures 8a and 8b.

Observation A3 (Figure 9a) involves a zoom-in on Segment I, located north of the Baturagung Reservoir (Figure 5). In this segment, a total of 71 fractures were identified, showing main orientations ranging from 015° to 195° and 070° to 250°. For a comprehensive overview, the rosette diagram depicting Segments A to I is presented in Figure 12, and the population and trends of fractures from Segments A to I can be referenced in Table 3.

In Figure 9b, an offset is observed, indicating a faulting event where the northern part of fault F1 has relatively moved to the right compared to the southern portion of fault F1. Apart from in-

tersecting both the northern and southern blocks, fault F1 also intersects with fault F2. Based on the offset movement, it can be concluded that fault F1 is a right-lateral strike-slip fault.

Commonly, fault growth produces a fault core formed of slip surfaces, comminuted rock material, and a larger volume of dispersed deformation known as the damage zone. (McGrath and Davison, 1995; Caine *et al.*, 1996; Vermilye and Scholz, 1998, 1999).

The previous researchers conducted a grouping of fractures and found that each fracture group exhibits distinct characteristics, primarily constrained by fault as segment boundaries (Khodayar *et al.*, 2018). In our study area, we hypothesize that these different characteristics are damage zones caused by different faults. The

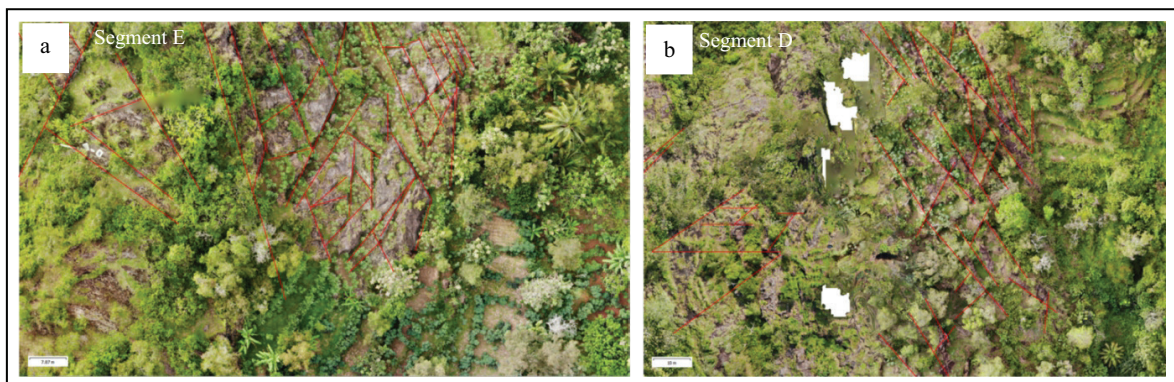


Figure 8 (a), a zoom-in of Segment E; (b), A zoom-in of Segment D. Both figures depict the population and orientation of fractures for clarity.

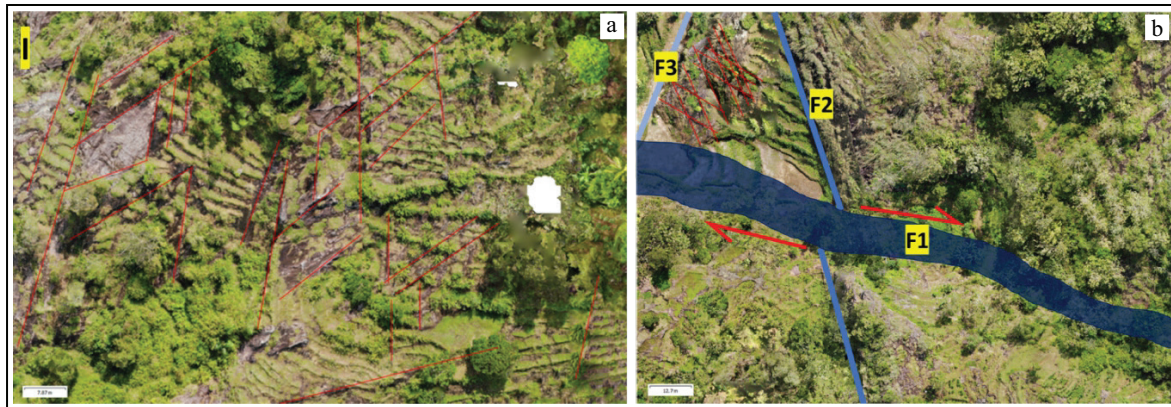


Figure 9 (a): A zoom-in of Segment I present population and orientation of fractures; (b) presents an offset of fault F1.

fault can become a boundary between segments. Some faults can be seen visually through aerial photography or ground observation. Statistical analysis was carried out using a rosette diagram (Figure 10). Each segment has different trend characteristics (Table 3).

The result from the rosette diagram shows: (1) Segment A has a trend with N - E and NE - SW relative direction; (2) Segment B has a trend with NNW - SNE relative direction; (3) Segment C has a trend with NE - SW relative direction; (4) Segment D has trend with NW - SE relative direction; (5) Segment E has trend with NW - SE direction; (6) Segment F has trend with NE - SW and ESE - WNW direction; (7) Segment G has NW - SE relative direction; (8) Segment H has W - E and NE - SW relative direction; and (9) Segment I has NNE - SSW and ENE - ESW

relative direction. This result will be our basis for fault interpretation. Fault interpretation will be discussed in the next sub-chapter.

DISCUSSION

Various factors are likely to control the nature of damage zones around faults, including lithology, the dip of bedding relative to the slip direction of the fault, and the stress system. The patterns of damage zones depend on three-dimensional locations around the fault and stress perturbations that are controlled by tip mode, amount of slip, and interaction between segment faults (Kim *et al.*, 2004). Figure 11 shows an example of increased slip on the composite fault zone, which can add to the damage already created by initiating, propagating, interacting, and linking the fault segments (Kim *et al.*, 2001).

Based on segmentation in the previous sub-chapter and aerial orthophotograph analyses, we interpret the boundaries of each segment as faults. The interpretation results show that the study area has eight (8) faults. Each fault has a different geometry and characteristics. The fault interpretation (Figure 12) shows: (1) F1 has a direction of NW - SE; (2) F2 has a direction of NNW - SSE; (3) F3 has a direction of NNE - SSW; (4) F4 has a direction of NNW - SSE; (5) F5 has a direction of NNW - SSE; (6) F6 has a direction of NNE - SSW; (7) F7 has a direction of ENE - WSW; (8) F8 has a direction of ESE - WNW.

Table 3. Segmentation and Trend

Segment	Population	Main Direction	
		I	II
A	53	005 ^o - 185 ^o	055 ^o - 235 ^o
B	13	350 ^o - 355 ^o	-
C	36	055 ^o - 235 ^o	065 ^o - 245 ^o
D	34	145 ^o - 325 ^o	-
E	62	155 ^o - 335 ^o	-
F	86	055 ^o - 235 ^o	095 ^o - 275 ^o
G	33	085 ^o - 265 ^o	155 ^o - 335 ^o
H	46	060 ^o - 240 ^o	090 ^o - 270 ^o
I	71	015 ^o - 195 ^o	070 ^o - 250 ^o

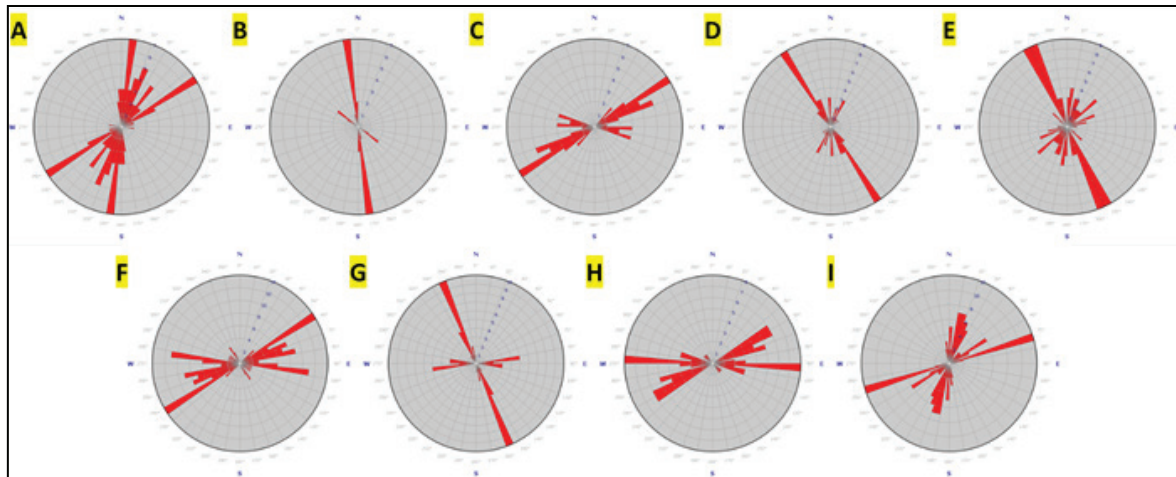


Figure 10. Rosette diagram on a study area showing segment has different trend characteristics.

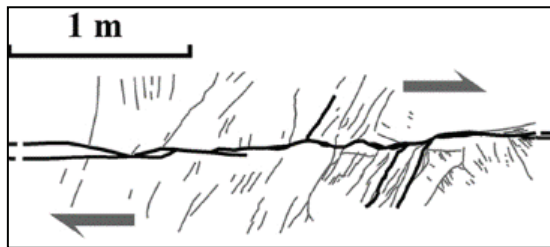


Figure 11. Antithetic fault at Rame Head, UK. An example of a damage zone (Kim et al., 2001).

F6 is the major structure in the study area. F6 has an NNE - SSW direction. Based on the geological map in Figure 2 by Suroño (1992), the F6 fault has the same direction as the main structure on the regional geological map. F6 major fault has a characteristic of a fault with a wide area, weathered and covered by alluvial so that we cannot see the fault plane with the naked eye. The fault plane was unseen because the destruction zone of the F6 major fault is the largest among the other faults. Fault F6 in Figure 12 is drawn based on the elongated valley extending from NNE-SSW. In Figure 12, it can be seen that the author interprets this F6 fault damage zone as passing through Baturagung Reservoir. F6 fault is responsible for the leaking of the Baturagung Reservoir, so the water in the Baturagung Reservoir is never completely filled throughout the year. Further explanation of the geometry of the damaged zone can be seen in the next sub-chapter, in the sub-surface interpretation sub-chapter.

In this section, we use modified ERT (Electrical Resistivity Tomography) in Figure 13a from Zakaria *et al.* (2023) data for sub-surface interpretation to understand how Baturagung Reservoir leaks due to a damaged fault zone of F6. The results of the ERT method are variations in resistivity values along the measurement lines. This resistivity value will be interpreted as the rock and water content type. The 100 m measurement line southwest of the reservoir exhibits a direction of N135°E. Inversion results indicate a range of resistivity values from 4.24 Ωm to 1096 Ωm . Low resistivity values (4.24 Ωm to 45.9 Ωm) dominate the surface, representing the response of subsurface soil (depicted in brown in Figure 13a) up to a depth of 5 m. Between 5 m and 30 m depth, high resistivity values (45.9 Ωm to 1096 Ωm) prevail, corresponding to the Dacite pumice breccia. This breccia, visible on the surface at the line's beginning, is a reference for high resistivity values. At the 70-80th m of the line, a low resistivity value emerges (4.24 Ωm to 20.7 Ωm), interpreted as the impact of reservoir leakage. The leakage is attributed to fractures in the Dacite pumice breccia, serving as conduits for water southwest of the reservoir, resulting in decreased resistivity values.

Fracture density in damage zones increases exponentially when moving closer from the fault cores and decreases exponentially when moving

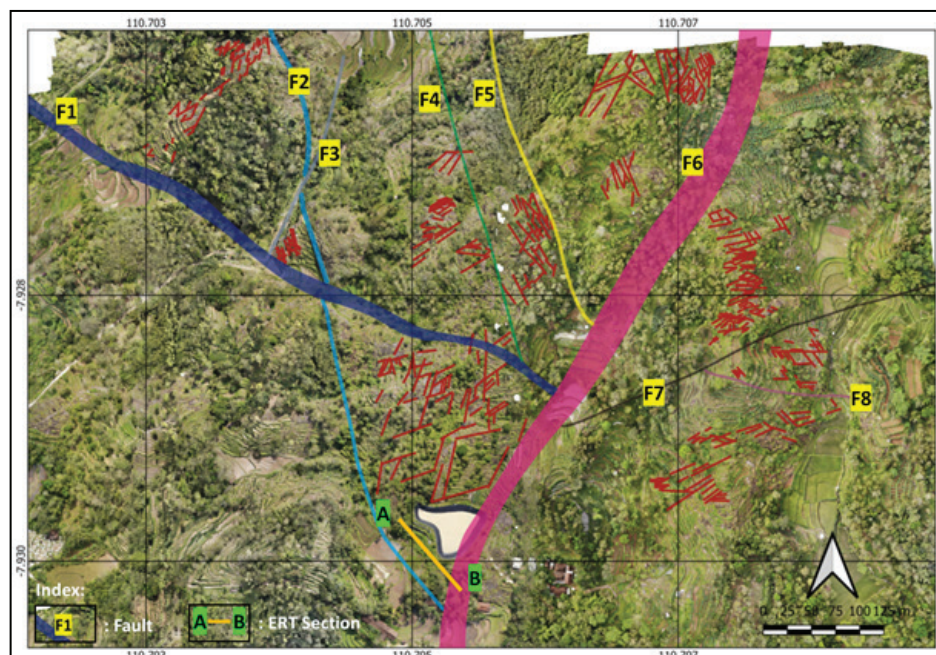


Figure 12. Geological structure map of the research area.

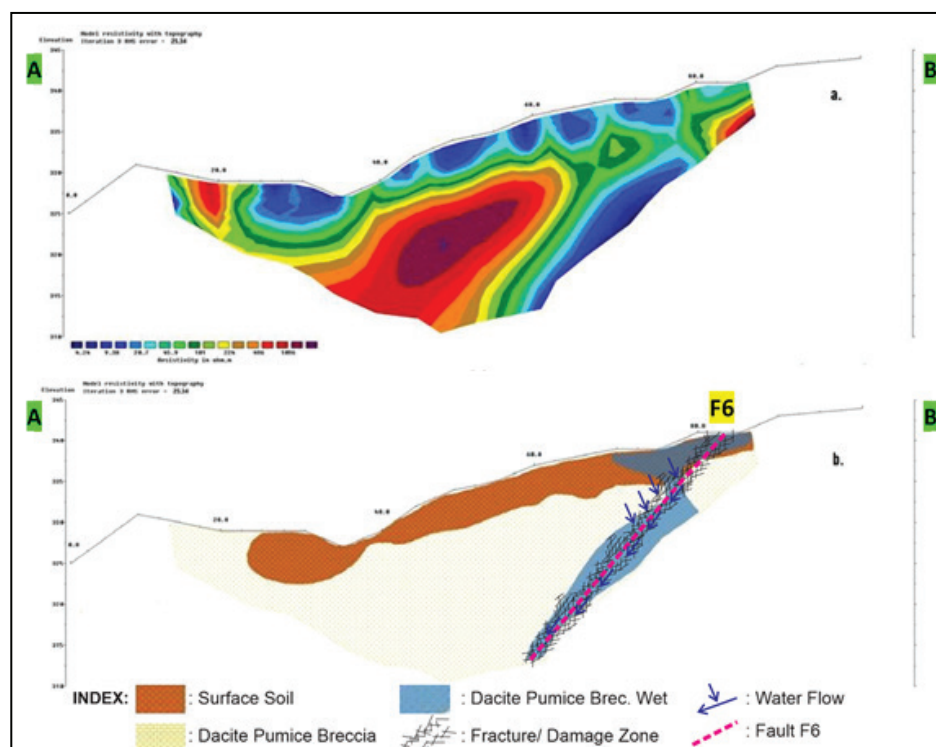


Figure 13. Interpretation of resistivity values on ERT lines A – B (Modified from Zakaria *et al.*, 2023): (a). The result of inversion of field data into actual resistivity; (b). The result of interpretation of resistivity values into rock types and water content. Sub-surface interpretation of Baturagung Reservoir and its surroundings shows that the damage zone of Fault F6 causes the leaking of Baturagung Reservoir.

away from fault cores, while others suggest that deformation intensity unevenly decreases with

fluctuations associated with secondary faults in the damage zone (Balsamo *et al.*, 2019). F6, as the

major fault, has an NNE - SSW direction with a major damage zone. Through line A-B in Figure 12, our interpretation reveals the F6 fault damage zone, leading to leakage in the Baturagung Reservoir (Figure 13b). The analysis highlights that a lack of understanding of geology can contribute to the failure of water storage in the Baturagung Reservoir, which is attributed to the fault.

The research encounters several challenges that can affect its applicability in geological analysis. The limited penetration of vegetation poses a significant hurdle as dense foliage obstructs the view of the ground, making it difficult to capture accurate data beneath the canopy. Additionally, adverse weather conditions, such as heavy cloud cover, rain, or fog, can substantially impact the quality of aerial or satellite imagery, creating a dependency on clear weather for successful photogrammetric analysis. By employing the DOM (Digital Outcrop Model) method, geological structures become challenging to discern in weathered rocks, thereby restricting the interpretation of rocks that remain in a fresh condition.

Another critical factor is the dependency on image quality; the precision of photogrammetric results relies heavily on the quality and resolution of the images used. Low-quality or blurry images can lead to inaccuracies in the generated 3D models. Scale and resolution issues present notable challenges, particularly in capturing small-scale geological features. The images used in the Digital Outcrop Model (DOM) must exhibit a sufficiently high resolution to capture intricate details accurately, and scaling can become problematic in specific instances. The necessity for ground observation is essential for field checking to ensure the reliability and precision of the Digital Outcrop Model (DOM) data.

The limitation of the drone battery is a factor that resulted in 11 sessions for data collection in this study. Merging each session of photogrammetric data acquisition using the drone requires precision in aligning one with another data. A computer with high specifications is necessary to perform this task.

CONCLUSION

The Digital Outcrop Model (DOM) results reveal a dense cloud comprising 118,260,880 points, accompanied by a tiled model featuring 9 levels with a 4.12 cm/pix resolution. Additionally, a Digital Elevation Model (DEM) is generated, consisting of 14,574 x 11,551 points at a resolution of 16.5 cm/pix. The orthomosaic covers 52,216 x 41,264 points with a resolution of 4.12 cm/pix, encompassing an area of 166.16 hectares.

Interpretation of the lineation pattern subdivides the research area into nine segments, revealing the presence of eight faults within the study area. Notably, the major fault (F6) exhibits an NNE - SSW direction, traversing Baturagung Reservoir. The damaged zone associated with this fault is interpreted in the sub-surface as the likely cause of leakage. Consequently, the findings underscore the critical importance of a comprehensive geological understanding in reservoir development to mitigate water conservation failures.

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