Field Identification of Active Fault nearby the Footprint of the Dam

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ABSTRACT: Tigadihaji dam located in the mountain range and have only 18 km from the Komering section of the Sumatra Fault Zone, which known have a high seismic activity, and has already known as an earthquake sources. The seismic hazard assessments reveal that 2 faults located on the downstream of the dam as secondary faults which parallel to the Sumatra Fault Zone. The Pauh and Sukarena faults named after the nearby villages have a distance of 1.85 and 8 km from the dam site respectively. Since the faults were closed to the dam, a further detail investigation was carried to reveal the level of activity of the Pauh fault. An electrical resistivity tomography (geo-electric) method and paleoseismic trenching were carried out to confirm the level of activity. The carbon dating test was also carried out from the samples taken from the fault zone at the depth of 2,00 m from the ground surface. The result indicated that the Pauh fault considered as an active fault with low sliprate, and shall be account in the seismic hazard analysis of the dam.
Keywords: Active fault, electrical resistivity tomography, paleoseismic trenching, carbon dating test.

1. INTRODUCTION

Tigadihaji dam was a rock fill dam which will be built on Selabung river, in the South Sumatra province of Indonesia. The dam was located only 18 km from the Komering segment of the Sumatra Fault Zone, which known have a high seismic avtivity, and has already known as an earthquake sources. The seismic hazard assessment reveal that 2 faults located on the downstream of the dam as secondary faults which parallel to the Sumatra Fault Zone. The Pauh and Sukarena faults named after the nearby villages have a distance of 1.85 and 8 km from the dam site respectively.

A study on Sumatra Fault Zone as a major source of earthquake as well as the slip rate were carried out in order to indentify the possibility of earthquake magnitude. Also the Komering segment of Sumatra Fault Zone as the nearest earthquake source were studied. Two major earthquake on 1933 and 1994 were recorded occured at Komering segment of Sumatra Fault Zone.

Earthquakes have an effects to the dam such as vibration to the dam body, appurtenant structures, dam foundation and rock fall on the reservoir slopes. Fault movement in the dam foundation may causing structural deformation and distortion, while fault movement in the reservoir may caused seiches in the reservoir and loss of freeboard.

Dams shall be designed to resist the maximum credible earthquake (MCE) which defined as the largest reasonably conceiable earthquake magnitude that is considered possible along a recognized fault systems or within a geograpically defined tectonic province, under the presenly known or presumed tectonic framework (ICOLD, 2016).

Seismic hazards assessments is compulsory for dam construction, particularly if the proposed dam is located on and around the known active fault zones. Detailed investigations of active faults occurrences incuding their exact locations, level of activities, earthquake history shall be conducted carrefully since the active faults pose three kind of hazards to the dam constructions, there are: strong-high frequency ground shaking, direct ground deformations related to fault movements during earthquake events and earthquake triggered landslide and liquefaction.

In the vicinity of Tigadihaji dam, detailed geology and active fault studies have been conducted. This includes mapping of the lithology and suspected active fault strands using high-resolution digital topography and latest GIS techniques, documenting geological outcrop data, shallow geophysical imaging using resistivity method, and conducting paleoseismological trenching on suspected active fault strand.

2. SUMATRA FAULT ZONE

The 1900-km long Sumatran fault zone (SFZ) traverses the back-bone of Sumatra, within or near the active volcanic arc (Sieh & Natawidjaja, 2000., Katili & Hehuwat, 1967., Bellier et al, 1997). The substantial portion of the dextral component of the Sumatran oblique convergence is accommodated by SFZ. At its northern terminus, the SFZ transforms into the spreading centers of the Andaman Sea (Curray, 2005). At its southern end, around the Sunda Strait, the fault curves southward toward and possibly intersects the Sunda trench (Hutchon & Pichon, 1984., Diament et al, 1992). Figure 1 shows the complexity of Sumatra fault zone.

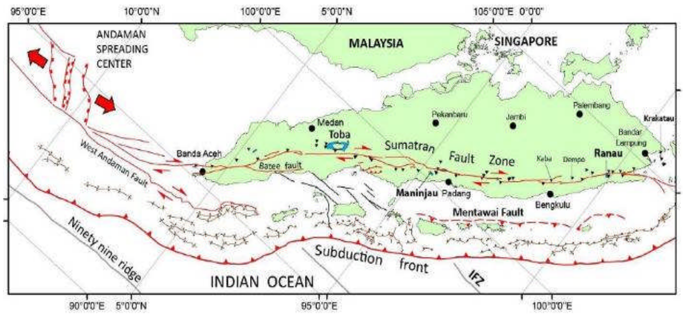


Figure 1. Neotectonics of the Sumatran oblique convergent showing major active tectonic elements

Convergence along Sumatra is highly oblique where tectonics strain is strongly partitioned into a dip-slip on the subduction interface or the megathrust, and a dextral slip component on the Sumatran fault zone that bisect the Sumatra island (Fitch, 1972., McCaffrey, 1991). With this high relative plate motions and all active fault arrays accomodating the movements, Sumatra ranks is considered as one of the most active seismic region on Earth. In the past 12 years seismic activities in Sumatra is unussually highten, both on the megathrust and along the Sumatran fault zone.

The Sumatran fault zone (SFZ) has been mapped using mostly the 1:100,000-scale aerial photographs and the 1:50,000-scale topographic maps (Sieh & Natawidjaja, 2000). The results of their works are digitized and put into a GIS database. Sieh and Natawidjaja's Sumatran fault map has a large-enough scale to enable discrimination of fault segmentations, so it can be used for seismic hazard evaluation. The SFZ is highly segmented, and consists of 20 major geometrically defined segments, which varies in length from about 35 to 200 km, separated by major fault discontinuities, mostly dilational jogs, which are expressed as valleys and lakes. These segment lengths influenced seismic source dimensions and have limited the magnitudes of large historical fault ruptures to between M_w 6.5 and about Mw 7.7.

In the past two years, based on current availability of modern digital elevation maps of SRTM-30m and TERRASAR World-30m data, coupled with high-resolution satellite images, Natawidjaja relocated previously identified active fault strands and identified new fault strands to updated the Sieh and Natawidjaja's map. New fault strands are particularly mapped in the northern and southern parts of SFZ where it runs toward the Andaman spreading center and the Sunda Strait grabens respectively.

The SFZ map that has been significantly revised is In the northern and the southern parts (Natawidjaja, 2017). In the northern part of Sumatra, Renun – Tripa segments of SFZ runs along the west side of Lake Toba toward north and make a compressive bend before it merges with the Batee fault that ascending from the west coast line. Previously, in Sieh and Natawidjaja (2000) as well as in the 2010 Indonesian PSHA map, the Batee fault was not taken into account since it was previously considered not active. Recent data and analysis indicates vice versa (Natawidjaja et al., 2017).

2.1 Slip Rate along the Sumatra Fault Zone

The geological sliprates of the Sumatran fault at three locations have been measured (Sieh & Natawidjaja, 2000). From the southern part, at about 3.6 S on the western flank of Kaba Volcano, they measured ~ 600 meters offset of the Musi River that flows on the ~60,000 years-old lava. The geological sliprates at this latitude, then, is ~10 mm/year. Near the Equator, Sianok Rivers was offset about 720 meters along the fault line that cuts the thick, ~60,000-year-old Maninjau tuff deposits. The geological sliprates here then is about 11 mm/year. On about 2N latitude, Several streams of the Renun River are offset dextrally about 2 km along the Sumatran fault segment that cuts the 70,000 years-old Toba tuff on the western side of the Toba Lake. They use this evidence to determine sliprate at this location, which is about 27 mm/year. These geological sliprates have been published in (Sieh et al, 1991., Sieh et al, 1994., and Natawidjaja & Triyoso, 2007).

Bellier and Sebrier (1995) also estimated sliprates at few locations using the principle that offset stream's age is linearly related to its length upstream from the fault. Then they calibrate this relationship with one location (i.e. Toba) that has good offsets and known age of underlying geological unit, but these values are less reliable.

Genrich et al (2000) and Prawirodirdjo et al (2000) determined the fault sliprates at several locations from their GPS survey-mode study. Their GPS sliprate values at 2.7°N, 2.2°N, 1.3°N, 0.6°N, 0.4°S, 0.8°S are 26 ± 2 mm/yr, 24 ± 1 mm/yr, 24 ± 2 mm/yr, 23 ± 2 mm/yr, 23 ± 3 mm/yr, 23 ± 5 mm/yr. The GPS sliprate at latitude ~2°N is about similar to the geological slip; but at latitude ~0.8°S in Bukit Tinggi area, the slip rate deducted from the GPS measurements is about twice as much as that of geological sliprate. Further study is required to resolve this discrepancy.

Bradley et al (2016) reevaluate slip-rates along SFZ based on multiple offsets of isochronous streams incising Toba tuffs in North Sumatra and Maninjau Tuffs in central/west Sumatra. The results of their measurements yielded that geological slip-rates near Lake Toba and Lake Maninjau are about similar values, 14 – 15 mm/yr. In other word, slip-rate at Sianok valley increase a bit higher, and slip-rate near Toba becomes only half as much as that of the previous study. In south Sumatra, Natawidjaja (2017) conducted a new measurement on geological sliprate of the Kumering segment south of Ranau Lake. Their analysis yields about 8 to 12 mm/year, thus twice as much as that of the previous measurement (Bellier and Sebrier (1995).

Bradley et al (2016) also conducted robust geodetic modelling and sliprate analysis for Sumatra region based on continued GPS data from SuGAr and all available campaign-GPS data as well as coral uplift rate data. Their detail sliprate analysis at Toba and Maninjau area yields geodetic sliprates of ~15 mm/yr. Hence, these new geodetic sliprates are similar with new geologic sliprates.

3. SEISMICITY CONDITION OF TIGADIHAJI DAM

Geological regional survey was carried out within radius of 50 km, to include the extent of the Pauh and Sukarena faults, while detail geological survey was carried out surroundings the Tigadihaji dam site in order to identify the fault strands and the activity of the Sukarena and Pauh faults. The basic data in this survey was digital elevation map (DEM) and then processing using GIS (Geographic Information System) software to obtain detail topographic map which may shows the geologic structures and suspected fault location. Tigadihaji dam was built on the Gumai and Air Benakat geologic formation which covered by thick Ranau tuff as product of mega eruption of ancient Ranau volcano, which at present left Ranau lake as their huge crater. Figure 2 shows the distribution of Ranau tuff as product of mega eruption of ancient Ranau volcano (Natawidjaja, 2017).

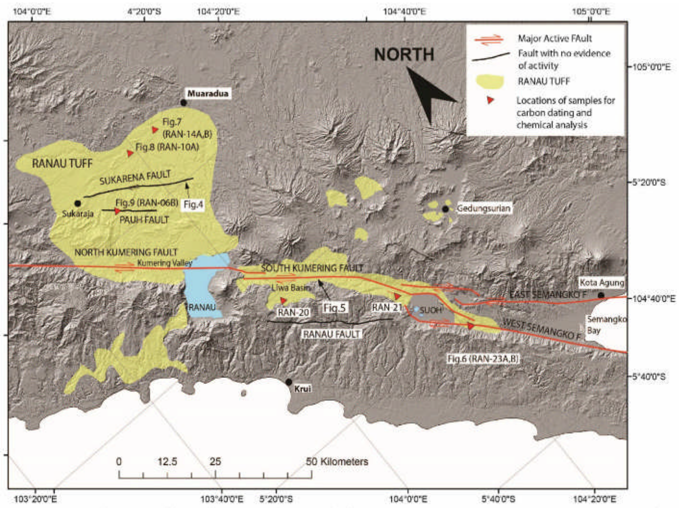


Figure 2. Distribution of Ranau tuff surrounding the present Ranau lake (Natawidjaja, 2017)

The Gumai and Air Benakat formations were tertiary sediment rocks which composed of massive of shale-limestone interbedded with tuff-sandstone and sandy limestone. Outcrop of this tertiary rocks found along the Selabung riverbed. Pauh fault characterized by the straightness of the hills that extends towards the northwest southeast and becomes the limit of surface texture morphology changes that express two different rock formations. Ranau tuff laid unconformity above the tertiary rock formation of Gumai and Air Benakat. Figure 3 shows the rock formation in the surroundings the Tigadihaji dam site. At the northeast of Ranau lake, two secondary fault lines runs parallel to the Kumering fault we obseved, called here as the Sukarena and Pauh faults. These fault line were visible as straight morphological lineaments by inspecting SRTM 30.

Figure 3. Unconformity on the boundary between Gumai rock formation and Ranau tuff

During field survey, we confirmed that these faults are indeed presence, marked by topographical breaks, fault-water falls and lineaments of scarps and streams. We also conducted GPR surveys two ascertain the locations of the faults. Similar to the Ranau fault, however, the geomorphological evidences of fault movements have been subdued and unclear. Luckily, on the main road between Ranau lake and Muaradua town, we found a fresh cut of road cliffs exposing the southern end of Sukarena fault outcrop as shown in Figure 4 (Natawidjaja et al, 2017).

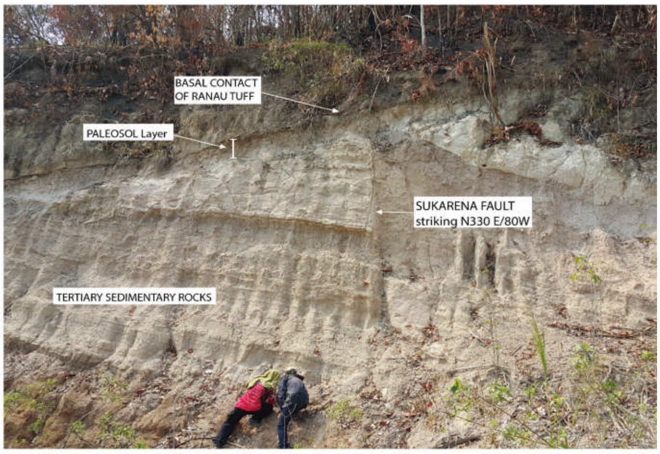


Figure 4. Road cut exposure between Muaradua town to Ranau Lake exposed the Sukarena fault (Natawidjaja et al, 2017)

The outcrop shows the dipping of the tertiary sedimentary rocks that is unconformably overlied by the Ranau tuff. The fault clearly cut the underlying sedimentary rocks, but ends at the Ranau tuff's basal contact. Hence, it clearly proves that the fault has been inactive prior to the Ranau tuff emplacement, 31,000 years. We also observed thin paleosoils on the upperpart of the tertiary rocks, burried by the tuffs, but we do not conduct radiometric dating analysis here since the the paleosoils do not seem to have rich in organics and there are modern plants and roots contaminate it. Figure 4 shows that Sukarena fault which found on the Gumai Formation did not cross the Ranau tuff layer which found on the above the Gumai formation. Since the Ranau tuff was deposited around 31.000 years ago, it means that there was no movement of the Sukarena fault for the last 31.000 years. It can be concluded that the Sukarena fault was inactive at present time.

The remnant of the center of the paroximal eruptions of Ranau tuff is the huge caldera, known as the a rectangular-shaped Ranau lake, 14 km long and 7 km wide. This rectangular-shape was thought to be controlled by inactive SFZ strands that were operating during the development of a hyphothetical Ranau pull-apart basin, and was also suspected to have significant role in facilitating the rise of magma forming giant volcano similar to Toba. The pull-apart bounding faults serve like 'ring structures' in ordinary volcanoes, thus forming rectangular-shape caldera after explosion as seen today.

Ranau tuff blanketed a wide area about 70-km radius around its center of eruption. Clearly the voluminous Ranau ash flows reset the previous landscapes by effectively buried the pre-existing topography upon its emplacement. Then, it was followed by the fast creation of a new network of drainages. In the proximal area, south of the lake, the tuffs filled the Liwa Basin, which then has been incised 40 to 80 meter deep by wide river canyons forming a plateau-like landscape. Away from the center, the Ranau tuff bed becomes thinner and then dissapears.

On the cliff exposures along the main road near Muaradua town , 80 km northeast of Ranau Lake, 4-5 meter-thick Ranau tuff bed lies on the moderately dipping tertiary sedimentary rocks, nicely showing an angular unconformity contact. Along the boundary a few tens of cm organic-rich paleosoils had been developed on the upper surfaces of the tertiary rocks. We carefully digged and selected part of this organic sample for radiocarbon dating to avoid possibilities of any modern-carbon contaminations from nearby modern plants and roots. The AMS analysis of this sample (RAN-014) yields a conventional carbon age of 26,830 ±140 BP, or the corrected calendar-year age of Cal BP 31085 to 30805 (95% probability)(Natawidjaja et al, 2017).

Southeast of Ranau lake, Kumering segment of Sumatra Fault Zone straightly runs through the thick, flat-top Ranau-tuff filling Liwa basin, marked by linear alignment of Way Robok deep canyons and major deflections of major river canyons crossing the fault line. Five major river canyons are right-laterally offset about the same amount along the single major traces of Kumering fault indicating they are formed isochronously or nearly so. Three of the displaced canyons are across the fault at right angle, thus give excellent measures for fault offset of about 320 to 380 meters, as shown in Figure 5. Uncertainty of the amount offset are appoximated by the width of displaced river canyons. We do not include the other two offsets since the river cut at low angle to the fault, so they yield less accurate measure of the offsets. The average of these three river offsets is 350 ± 50 meter, thus yields a sliprate of 10.4 ± 2.4 mm/year for the Kumering fault segment.

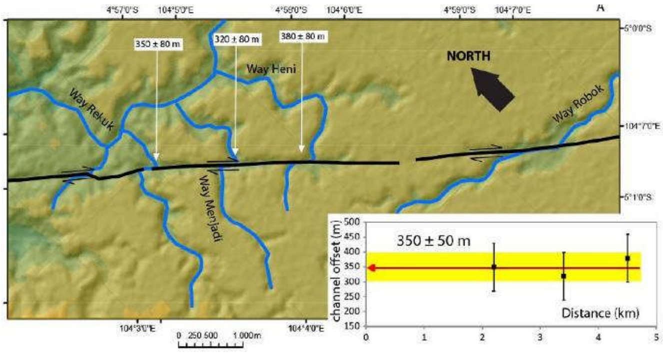


Figure 5. Consistent right lateral offsets of isochronous river channels deeply incised into Ranau tuff near Liwa. The total offset is estimated from three channels that across the fault at high angle

4. INVESTIGATION ACTIVE FAULTS

In this study, the geoelectric survey using SuperSting R8 multichannel equiped with 112 electrodes at 5.00 meter spacing, thus every measurement have around 555 meter in length. Total eight (8) lines, one line across Pauh fault, and seven (7) lines on the dam area were carried out in order to investigate the presence of the faults in dam foundations.

Geoelectric survey on line 1 primarily intended to scan underground structures of the Pauh fault. The result of this scan will be used to pinpoint the location of the trench excavation for palaeoseismology study. Figure 6 shows the geoelectric result of line 1 which across the Pauh fault.

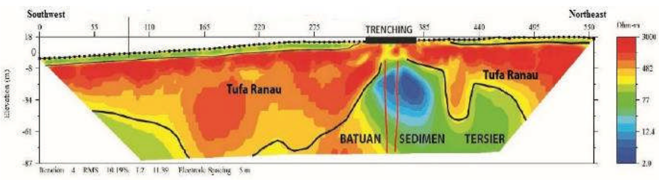


Figure 6. Scanning result of line 1 with indication of Pauh fault

Scanning results indicated that the decomposed top soil have a thickness more than 5 meter, interpreted from the resistivity less than 200 Ohm.m. This soil layer probably young alluvial deposit and decomposed of Ranau tuff. Below the decomposed soils, the Ranau tuff layer with high resistivity found up to 80 meters except at the suspected Pauh fault. Below the Ranau tuff, the tertiary sedimentary rock was found indicated from low resistivity which range from 2 to 100 Ohm.m. The most important from line 1 scan result was the capture of the suspected Pauh fault.

Palaeoseismic trench ussually carried out to prove the existence of a fault structure that has been identified from morphological analyses or geoelectric scanning. It can be use also to evaluate the fault activity and look for traces of past seismicity recorded in the soil layer (Yeats, 1996). Palaeoseismic trench was a method that has widely used in the earthquake research. This method became popular following the successfully study of palaeoseismology in Pallet Creek, California (Sieh et al, 1989., Sieh, K , 1977).

Palaeoseismic trench was carried out on the approximate the Pauh fault line. Trenching was made over the line 1 of the geoelectric survey, cut the Pauh fault perpendicularly. The dimension of the trench are; 20 meter in length, 1.50 in width and 2.00 m in depth. Logging on the both (left and right) walls were made using different colours to identify the soil layers and fault structures. Logging were made to identify colour, texture, type or nomenclatures of soils. Trenching in Pauh faults have five (5) different soil layers and described as follows:

Layer 100 was the first soil layer, identified by black colour was top soil consists of sandy silt soils, dark brown in colour, many roots found.

Layer 200 was the second layer, gravelly sandy silt with some lithic fragment up to 4 cm, brown in colour.

Layer 300 was the third layer, coarse sand from Ranau tuff, with some lithic fragment up to 2 cm, yellowish brown in colour.

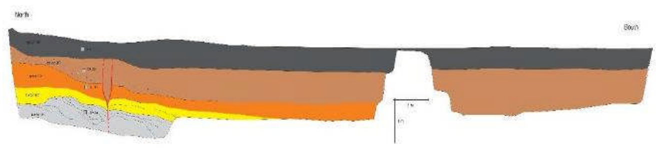
Layer 400 was the fourth layer, coarse sand from Ranau tuff with some sand layers interbedded, greyish brown.

Layer 500 was the bottom layer, coarse sand from Ranau tuff with some sand layers interbedded, grey colour.

On the trench walls there is an indication of fracture and fault plane that shear the soil layers with the parallel direction of the Pauh fault. Although the fault structure did not appear on the surface, indication of Pauh fault found at least on the soil layer 400 that shear the soil layer, so that the existence of possible ttectonic fracture structures deforming this soil layer is classified as an active fault.

Figure 7 shows the logging of the east and west walls of the palaeoseismic trenching, while Figure 8 indicated the Pauh fault in the palaeoseismic trenching wall.

Logging of the left wall



Logging of the right wall

Figure 7. Logging of the palaeoseismic trenching walls

Figure 8. Indication of Pauh fault on the palaeoseismic trench wall

Geological observation, geo-electric survey and data evaluation on the paleoseismic trenching as shown on Figure 8, indicated that Pauh fault was still active, even there was not clearly exposed on the ground surface. The Ranau tuff layer as a product of mega eruption above the Gumai formation indicated a shifting in vertical direction (left lateral normal fault). Carbon dating results on the soil samples taken from the soils on the fault location indicated that the age of the soils was 114 to 249 yaears. This indicated as the last earthquake resulting from the Pauh fault, even there was no historical record was found. The calculation on the Mmax based on the length of the fault based on several GMPE (ground motion prediction equation) resulting the possibility Mmax 6,4 earthquake may occured from the Pauh fault. Based on this result, the earthquake which may occured from Pauh fault shall be included in the Seismic Hazard Analysis for Tigadihaji dam.

This founding will change the Seismic Hazard Analysis which has been made previously. In the previous Seismic Hazard Analysis, the Pauh fault was considered as an inactive fault, and the Seismic Hazard Analysis were made based on the Probabilistic Seismic Hazard Analysis (PSHA). But considering that Pauh fault was an active fault and the distance to the proposed Tigadihaji dam was very closed, and also the length of Pauh fault has already known, the new Seismic Hazard Analysis was made based on the Deterministic Seismic Hazard Analysis (DSHA).

5. CONCLUSION

The identification of active fault nearby the foot print of the Tigadihaji has been presented. The presence of the Sumatra Fault Zone, the sliprates along the fault and paleoseismic on the Pauh fault has been carried out to study the condition of the fault. The conclusions of the investigation are summarized as follows;

i. The Tigadihaji dam location was covered by Ranau tuff as a product of mega eruption of Ranau volcano which have an age of around 31.000 years,
ii. Pauh fault which located at 1.85 km in the downstream of the dam with 14 km in length shall be accounted as an active fault, based on the finding from paleoseismic trenching
iii. The Seismic Hazard Analysis for Tigadihaji dam shall included the Pauh fault in the analysis.
iv. There was a change in Seismic Hazard analysis for proposed Tigadihaji dam, where before Pauh fault was consideren as inactive fault, the Seismic Hazard Analysis was made base on the probabilistic (PSHA), while after the Pauh fault was considered as an active fault, the Seismic Hazard Analysis was re-calculated based on Deterministic (DSHA).

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