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Surface Rupture and Geotechnical Features of The July 2, 2013 Tanah Gayo Earthquake

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Abstract - An assessment of surface rupture and collateral ground failures can help to evaluate the impact of future earthquakes. This paper presents the results of a field survey conducted to map the surface rupture and geotechnical phenomena associated with the ground shaking during the July 2, 2013 earthquakes in Tanah Gayo Highland. The objectives of this survey are to document and to characterize the surface ruptures as well as to identify types of earthquake-induced ground failures. Results of the survey identified four best sites of possible surface rupture. Two locations are obvious surface ruptures that can be traced on primary topographic feature of the active fault segment from the north to the south, crossing Pantan Terong Hill. The fault segment has a total mapped length of 19 km, with WNW trending zone and a dextral rupture offset. The ground shaking also resulted in landslides and liquefaction in areas underlain by very fine-grained tuffaceous sands. Based on the field survey, it can be concluded that the newly defined active fault segment, the Pantan Terong segment, is likely the segment that ruptured at the July 2, 2013 Tanah Gayo earthquake. Due to the soil types and unstable rocky slopes in the hilly Central Aceh region, large-scale landslides are primary risks during an earthquake event in this region.

Keywords: active fault, ground failure, Sumatran Fault, surface rupture, Tanah Gayo earthquake

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Introduction

The Central Aceh main shock (Mw 6.1) occurred at 2:37 p.m. local time, followed by a large aftershock (Mw 5.5) at 8:55 p.m., and a second aftershock (Mw 5.3) at 10:36 p.m. These earthquakes affected an area with the population of about 300,600 people, both in Central Aceh and Bener Meriah Regencies, caused 48 deaths and resulted in significant damages to houses and public buildings. The earthquakes also triggered several landslides in mountain areas, one of which destroyed a village in Ketol Subregency, and claimed lives of 6 inhabitants.

The 2013 earthquake was once believed to be associated with Aceh segment of the Sumatran Fault Zone (Rusydy, 2013). However, the locations of the earthquake epicentre suggests that the earthquake source is about 20 - 30 km NE of Aceh segment. Moreover, previous regional geological and seismic hazard studies did not identify an active fault in this region (*e.g.*, Irsyam *et al*., 2010; Natawidjaja and Triyoso, 2007; Sieh and Natawidjaja, 2000). Thus, the 2013 earthquake event was therefore somewhat unexpected.

A quick field survey to indentify primary evidence of ground surface rupture and secondary effects is important due to the low preservation potential of features in the tropical climate. Thick surficial cover may also hinder the recognition of the surface rupture traces from satellite images. Identification of the ruptured segment of the greater Sumatran Fault system can improve our understanding of the overall fault system as well as local hazards. The July, 2 2013 earthquake provided us with the first opportunity to fully document the surface rupture associated with the earthquake of the unkown segment in the Sumatran Fault. This paper presents the results of a field survey to map surface rupture and geotechnical phenomena associated with the 2013 Tanah Gayo earthquake. The objectives of the survey are (1) to document and to characterize the surface ruptures, (2) to identify the types of earthquake-induced ground failures.

Figure 1 shows the survey location which is located in so called Tanah Gayo at an elevation of 200 to 2,600 m above sea level. The survey focused on the damaged areas in Central Aceh and Bener Meriah Regencies.

Geological Setting

According to the Geological Map of Takengon Quadrangle, Sumatera (Cameron *et al*., 1983), the oldest rock found in Central Aceh region is of Pre-Tertiary. However, the most dominated rock is of volcanic origin of Late Miocene to

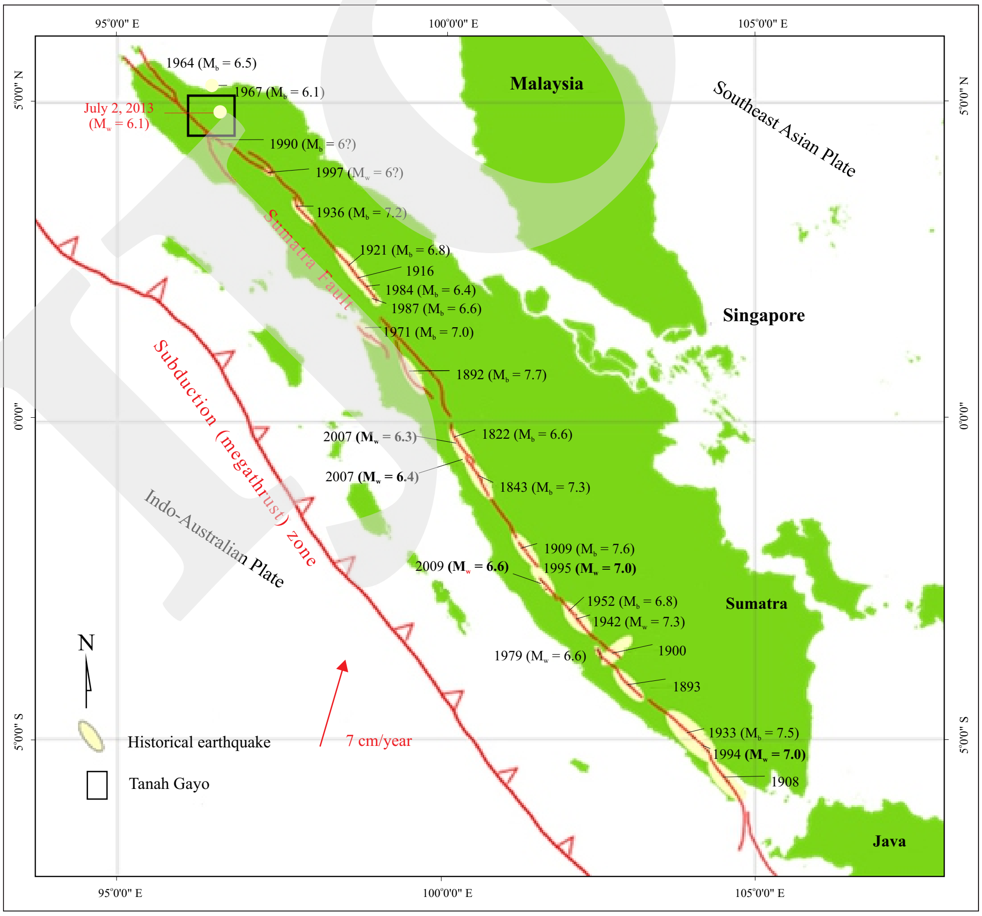

Figure 1. Historical major earthquakes along the Sumatran Fault. The ellipsoidal shapes indicate fault segments that were ruptured. The rectangle shape is Tanah Gayo region (modified from Daryono *et al*., 2012).

Holocene, such as lava, volcanic breccia, and tuff. These volcanic rocks are generally originated from the activity of Bur Ni Telong, Lampahan, Nama Salah, Pepanji, Enang-Enang, and Tuan Volcanos, which belong to the Geureudong Volcanic Complex. The youngest rocks in the region are of Quaternary lake deposits found around Lut Tawar Lake.

Seismo-tectonic Setting

As presented in Figure 1, the Sumatra Island is located in the east of the subduction zone of Southeast Asian and Australian Oceanic Plates that converge obliquely with the rate of movement about 50 to 60 cm/year (Prawirodirdjo *et al.*, 2000). The oblique convergence is partioned into the dip slip and the strike-slip faults. The strike-slip type is accommodated primarily by the Sumatran Fault (McCaffrey, 1994; Sieh and Natawidjaja, 2000), consisting of 19 active major segments separated by extensional and contractional step overs.

Historical records since 1890 indicate that there have been 23 major earthquakes in Sumatra mainland of magnitude 6 or greater. With the exception of the 1967 event (M6.1), these earthquakes ruptured the primary active segments of the Sumatran Fault. Earthquake events in 1990 (mb= 6.0) and in 1997 (Mw= 6?) were believed associated with the activity of Tripa Segment (Sieh and Natawidjaja, 2000).

Characteristics of the July 2, 2013 Earthquake

The main earthquake (Mw 6.1) struck at the depth of 10 km at 2:37 p.m. The National Earthquake Information Center (NEIC) of United States Geological Survey and the Meteorology, Climatology and Geophysics Agency (BMKG) reported focal mechanisms for the main shocks, as compiled in Figure 2. The moment magnitudes and locations of the first, the second, and the third events are summarized in Table 1. The moment tensor of the main earthquake, from USGS, clearly shows a strike-slip movement. According to USGS (2013), the earthquake had a Modified Mercalli Intensity rating of 6 to 7. The focal mechanism from USGS showed two nodal planes. The first nodal plane has a strike of 315^{o},

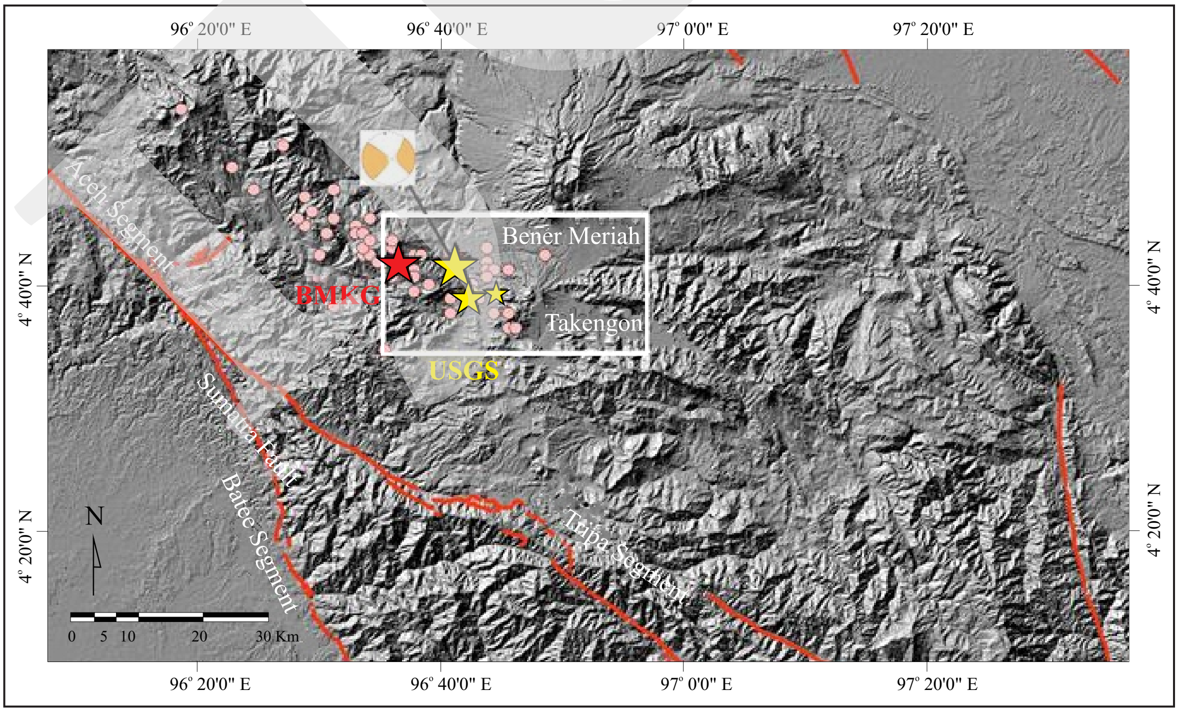

Figure 2. Epicentres of the July 2, 2013 Aceh Tengah main shocks and after shocks. The pink dots are BMKG aftershocks, the yellow stars are USGS main shock epicentre, and the red stars are BMKG main shock epicentre. The primary strand of the Sumatran Fault is shown as a red line.

Table 1. Summary of The Tanah Gayo Earthquakes of July 2, 2013

Earthquake event	Coordinate of epicentre	Moment magnitude (Mw)	Source of data
I	4.698° N, 96.687° E	6.1	NEIC-USGS
	4.7° N, 96.61° E	6.2	BMKG
II	4.654° N, 96.706° E	5.5	NEIC-USGS
	4.7° N, 96.69° E	5.5	BMKG-USGS
III	4.66° N, 96.744° E	5.3	NEIC-USGS
	4.71° N, 96.69° E	5.3	BMKG

a dip of 80°, and a rake of 170°, whilst the latter has a strike of 47°, a dip of 80°, and a rake of 10°, indicating a right-lateral strike-slip fault.

Materials and Methods

The main aim of the field survey is to identify and to map as much of the surface rupture as possible since the survey was conducted two weeks after the earthquake events took place. The survey was focused on the worst damaged area between Takengon and Bener Meriah Regencies. Eighty-six sites with ground cracks were observed. On the site of probable surface rupture, the length of segmentation, the magnitude of lateral and vertical movement, and the orientation of the rupture were documented. The survey at the southern Takengon crossed the probable active fault line. During the field work, the local geotechnical features that controlled ground failures was also studied during the earthquake (Figure 3).

The locations of surface rupture and landslides were mapped using Garmin hand-held GPS. The orientation and magnitude of the rup-

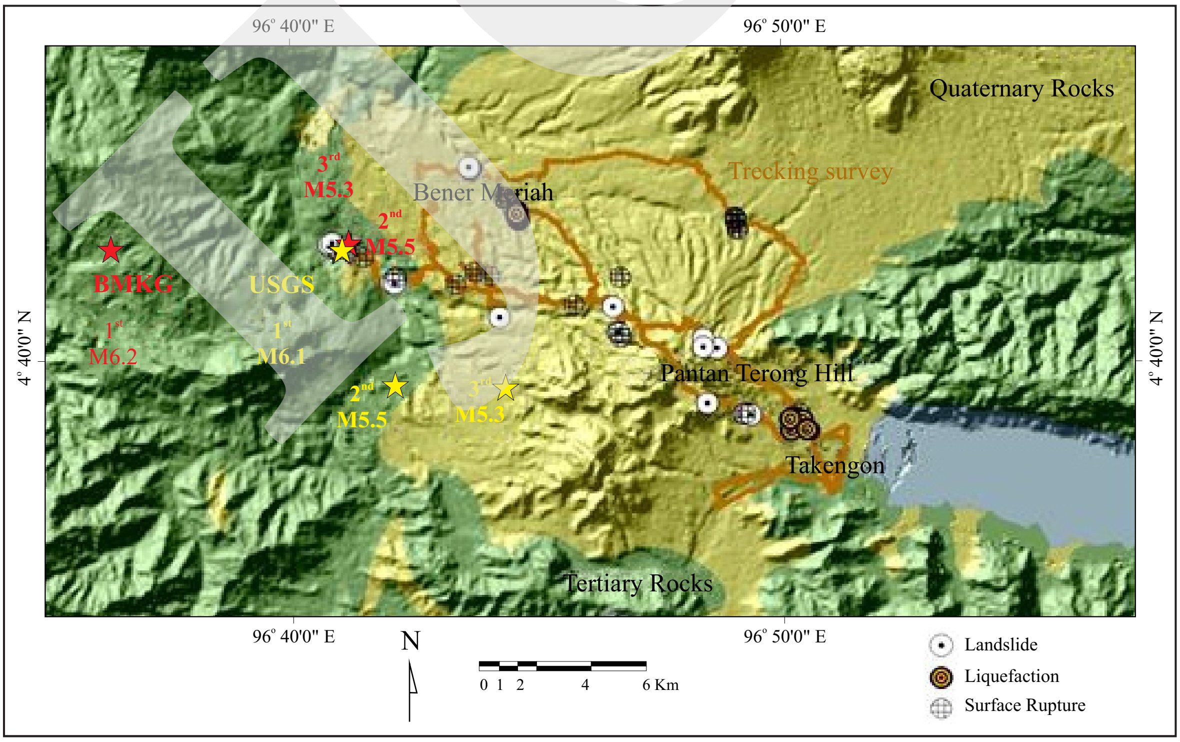

Figure 3. Locality map of surveyed surface ruptures, liquefactions, and landslides due to the July 2, 2013 Tanah Gayo earthquake. Lithologically, the yellow area is Quaternary rocks and the green area is Tertiary rocks (Cameron *et al*., 1983).

ture were measured using compass and measuring tape. Data were overlain onto ASTER GDEM map of 30 m index contours.

Result

Seismicity

Tanah Gayo earthquake event has three strong shocks that were felt differently by interviewed eyewitnesses. Our respondents felt three strong earthquakes at 02:37 p.m., 08:55 p.m. and 10:36 p.m., but people who live in Bener Meriah and north of Takengon gave different accounts about which one the stronger earthquake was. These locations are separated by Pantan Terong Hill. People in Bener Meriah, north of Pantan Terong Hill, felt the strongest shocks at 02:37 p.m. and 08:55 p.m. People in the north of Takengon, south of Pantan Terong Hill, felt that the third shock at 10:36 p.m. was the strongest. People located in the north of Takengon mostly agreed that most of damaged houses collapsed during the third shock. Thus, this finding suggests at least one of earthquake sources was located in the north of Takengon.

Surface Ruptures

Surface rupture surveying in Tanah Gayo is impeded by the hilly morphology and the widespread landsliding. Surface ruptures with less than 5 cm of apparent offset look doubtful. These small offset ruptures (82 sites) were mainly produced by gravity movements. Only four sites exhibited surface ruptures without gravity and spreading movement. The four segments are described here from the northwest to southeast.

Site 1 - Kute Geulimai Surface Rupture

This surface rupture site is located on a steep hillslope, along the road between Kute Geulimai and Seurempah Villages. The surface rupture crosses the road with an orientation of 315°E exhibiting 24 cm of dextral offset and 20 cm of vertical offset with the eastern side moving down (Figure 4).

Figure 4. A photograph showing the surface rupture crossing the road between Kute Geulimai and Seurempah Villages. The rupture right-laterally displaced the road about 24 cm with a vertical displacement of about 20 cm, east side down.

Site 2 - Kuta Malaka Surface Rupture

The surface rupture crosses a flat area at an elevation of about 940 m in Kuta Malaka Village. The group rupture is about 11 m long with an azimuthal trend of 300°, exhibiting a 14 cm-dextral offset and a significant component of vertical displacement of 12 cm with the western side moving down (Figure 5).

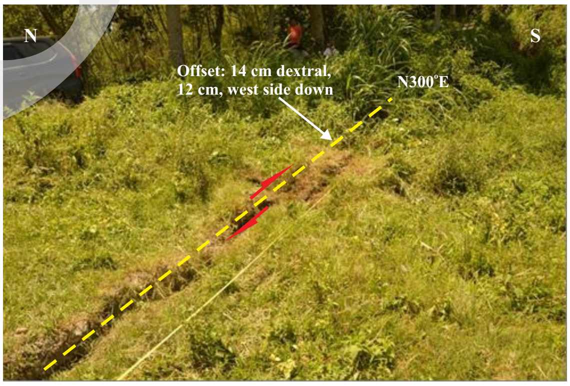

Figure 5. A photograph showing the surface rupture at Kota Melaka Village with a 14 cm dextral diplacement and vertical diplacement of 12 cm, west side down.

Site 3 - Jamur Ujung Surface Rupture

The ground surface rupture is located at Jamur Ujung Village. The rupture begins with an azimuth of 300°E, exhibiting 15 cm-dextral offset (Figure 6), then crosses the road with an azimuth of 85°, and cuts a brick fence (Figure 7). The rupture continues with the orientation of 320°, exhibiting 30 cm-dextral offset and 54 cm-normal displacement with the western side

Figure 6. A photograph showing the ground surface rupture at Site 3, Jamur Ujung Village. There are two ruptures with azimuthal trends of 85° and 300°. The inferred dextral offset is 15 cm.

Figure 8. A photograph showing the change of Site 3 surface rupture orientation to 320°, exhibiting 30 cm dextral offset and 54 cm normal offset with west side moving down.

Figure 7. A photograph showing the Site 3 surface rupture continues through a bent brick fence with 16 cm dextral offset. The black circle indicates the centre of deflection of the brick fence. The inset photo shows the lateral offset of the brick fence wall, indicated by a red arrow.

Figure 9. A photograph showing the small pond dried out due to the ground surface rupture at Jamur Ujung Village. The surface rupture track is indicated by a yellow dashed line.

moving down of 54 cm (Figure 8). The surface rupture also caused the water in small pond to drain out shortly after the earthquake (Figure 9).

Site 4 - Mongal Surface Rupture

This surface rupture site is located in a flat area within Mongal Village, north of Takengon Town. A ground rupture crosses an asphalt road with an azimuthal trend of 300° (Figure 10a) and caused the road to right-laterally displaced about 6 cm without vertical displacement (Figure 10b). This rupture is associated with a 6 m-wide depression as observed on the road surface (Figure 10c).

Geotechnical Aspects

The July 2, 2013 earthquake events not only caused a significant destruction of buildings but also triggered ground failures associated with liquefaction and landslide. Liquefactions, such as lateral spreading and sand boiling, were mainly found in flat areas within Central Aceh Regency. The lateral spreadings were commonly oberved to occur in many road embankments constructed in soft soil ground. Some good examples of lateral spreading were evident in the road embankments in the vicinity of Takengon Town (Figure 11). This type of ground failures is influenced by the geological condition of Takengon flat area / lowland. According to the geological map of Cameron *et al*. (1983), the lowland is underlain by Quaternary lake deposits, especially in the areas around the Lut Tawar Lake. These young soil deposits have obviously low strength to withstand the ground shaking.

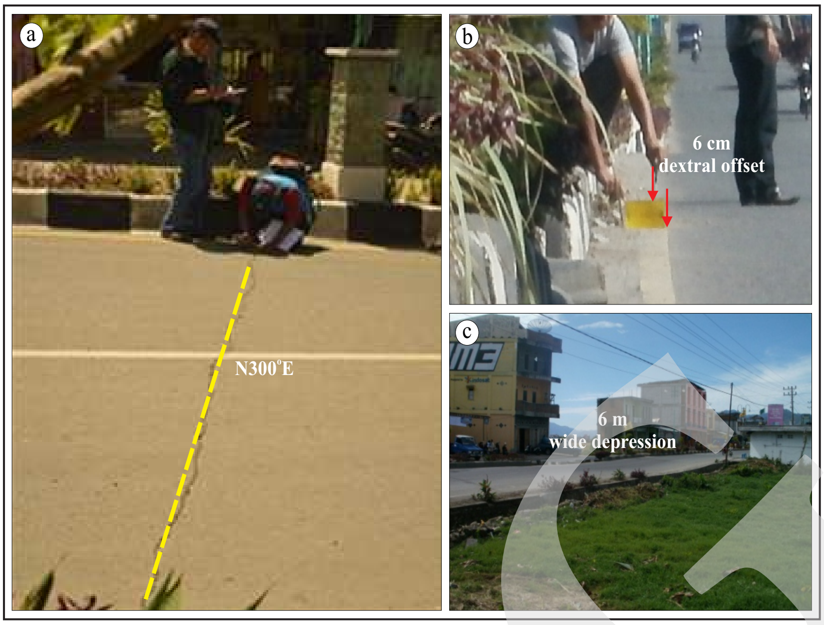

Figure 10. Photographs showing the geometry and kinematics of the surface rupture in Mongal Village. (a) A rupture cut through the road with an azimuthal orientation 300o; (b) A 6 cm- dextral offset measured from the deformed roadside marker; (c) A 6 m-wide depression observed on the road surface.

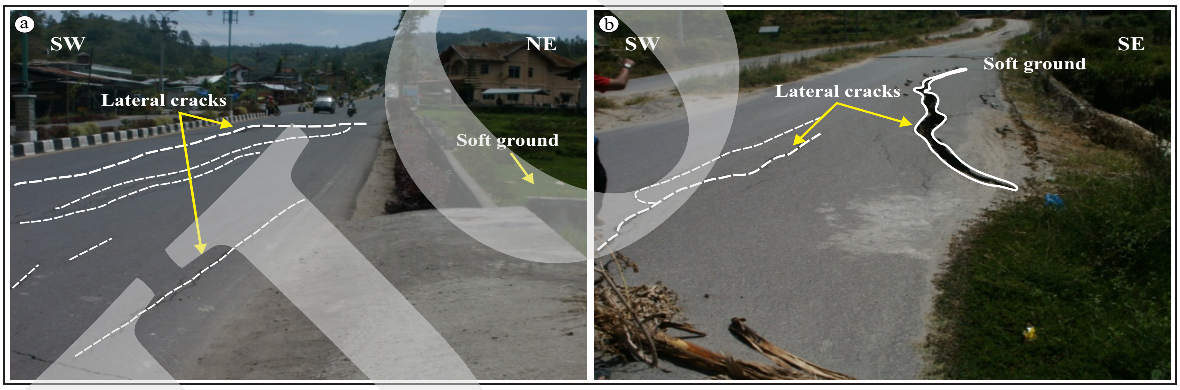

Figure 11. Photographs showing ground failures associated with lateral spreadings of road embankment around Takengon Town. (a) On the main road connecting Takengon Town and Bireun, (b) A lateral spreading on a new road connecting Takengon Town and Kute Panang.

Another type of ground failure was associated with liquefaction as observed in Kuta Malaka Village at an elevation of 950 m above sea level (Figure 12). Numerous sand boilings were found in a flat area where the Kuta Malaka surface rupture is located. The local groundwater level is about 5 m below the ground surface. According to an eyewitness, the occurrences of sand boiling was seen to commence from the first earthquake event (Mw6.1) for two days. As seen in Figure 12, greyish white fine-grained sands spouted of the ground cracks in several locations in a flat area surrounded by hills, probably associated with Quaternary tuffaceous sand-filled lake. The occurrences of liquefaction indicate the intensity of earthquake event of at least MMI 6 in this area. According to the Shake Map produced by USGS soon after the event, the earthquake intensity in the Central Aceh area ranged between MMI 6 and 7 (Anonymous, 2013).

Landslides were widespread after the Tanah Gayo earthquake (Figures 3 and 13). The abundance of these phenomena was due primarily to the hilly morphology and steep surface slopes

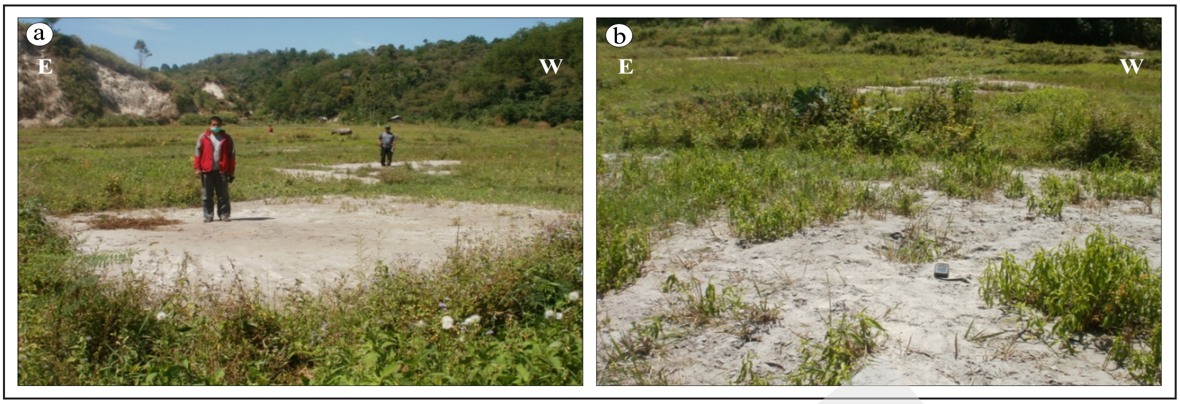

Figure 12. Photographs showing the liquefaction induced sand boilings due to the July 2, 2013 earthquake (Mw 6.1) in Kuta Malaka Village. The white fine-grained sands were spouted out the ground cracks.

Figure 13. Photographs showing types of landslide triggered by the July 2, 2013 earthquake in a Gayo Highland area. (a) Rock fall of intrusive outcrop along the road to Kuta Panang, (b) A larger-scale landslide in Seurempah Village, (c) A dry earth flow triggered in the tuffaceous sand slope, (d) A surficial cut-slope failure along the roadside from Takengon to Blang Mancung.

of the surrounding area in Gayo Highland. According to the geological map of Cameron *et al*. (1983), the Gayo Highland is underlain by thick Quaternary volcanic deposits, consisting of fine-grained tuffaceous sands. Outcrops of igneous rocks are also present in some areas.

Based on field observations, earthquake-induced landslides in this area can be categorized into four basic types. The first type is rock falls of igneous rock. This type of landslides occurred within a narrow area, controlled by the main rock fractures. Figure 13a shows the example of rock fall of igneous outcrop with strike orientation of N60°E and dip direction of 48°.

The second one is large-scale slope failures that commonly occur in steep slopes (>45°) of loose tuffaceous sands. This type of landslides involves a large volume of soil masses. One of which occurred in Seurempah Village in Ketol Subregency, claiming eleven lives and destroying a twelve houses (Figure 13b). The landslide materials temporarily blocked and changed the flow of Air Pesangan River. As seen in Figure 13b, the tuffaceous sand deposits are horizontally layered; thus, the occurrences of the large scale landslide are mainly controlled by the slope morphologic factor. Other large-scale slope failure can also be seen in steep slopes along the Air Pesangan River such as in Bah Village located in the south of Seurempah Village. It is interesting to note that this type of landslides forms steep slopes.

Earth flows are also common throughout the surveyed area and are very well observed on the hillslope of tuffaceous sands. The occurrence of the earth flow is controlled not only by the slope geomorphologic condition but also by the looseness of the earth materials. The tuffaceous sands are evident to travel to a distance of tens to hundreds meters from the landslide sources in a dry state condition (Figure 13c). The fourth type of landslides is surficial slope failures, involving a thin surface soil material (Figure 13d). This type of landslide commonly occurs in unprotected steep cut-slopes along a road side. The mode of failure is a nonrotational slide and the soil materials are not travelled far from the failed slope. This type is capable of blocking the road, and triggering a hazard to down-slope areas.

Discussion

Pantan Terong Segment - An Unidentified Active Fault Segment

The surface rupture survey documented four best surface rupture sites. Sites 1 and 3 are located within a relatively hilly terrain and do not have the appearance of a fault surface rupture, and therefore might not represent surface displacements along the trace of the fault. Moreover, both sites do not show any topographic feature of active fault segment. In contrast, Sites 2 and 4 are more likely surface ruptures. Numerous occurences of sand boiling in Site 2 and the presence of zone of depression in Site 4 are the strong indication of the presence of a fault movement zone in the vicinity of these rupture sites.

The comparison of these mapped rupture locations to geomorphic features visible on ASTER GDEM (Team, 2010) and World30m DEM topographic data, is visualized using a Swiss hillshade technique (Anonymous, 2010). An active fault line can be traced from Site 2 to Site 4, crossing Pantan Terong Hill. Based on the surface mapping, Pantan Terong fault is proposed to rupture during the July 2, 2013 Tanah Gayo earthquake (Figure 14). This fault has a total mapped length of about 19 km. This length is close to the segment length of the Sumatran Fault that ruptured during the 2007 West Sumatra doublet strike-slip earthquake sequence, which ruptured about 22.5 km of fault length (Daryono *et al.*, 2012). This also correlates with the minimum segment length of about 20 - 30 km proposed by Klinger (2010).

The Tanah Gayo earthquake is similar to the M6 Christchurch 2011 earthquake event, both events are caused by faults hidden by alluvial deposits. Based on field surveys within the damaged area, the Tanah Gayo earthquake is inferred to cause surface rupture over a distance of ~6 km, with measured total offsets of about 50cm, of which normal motion is a large component.

Landslide Hazard

The numerous landslide occurrences during the July 2, 2013 Tanah Gayo earthquake indicate that soil and rock slopes within the Gayo Highland are very susceptible to instability during earthquake events. Thus, hillslopes subjected to the July 2, 2013 earthquake are likely to have a low stability, and therefore, prone to landsliding during rainfall events. This hazard can cause risk to the people living beneath the slope areas. Public awareness is, therefore, important to reduce the riks of landslide disasters.

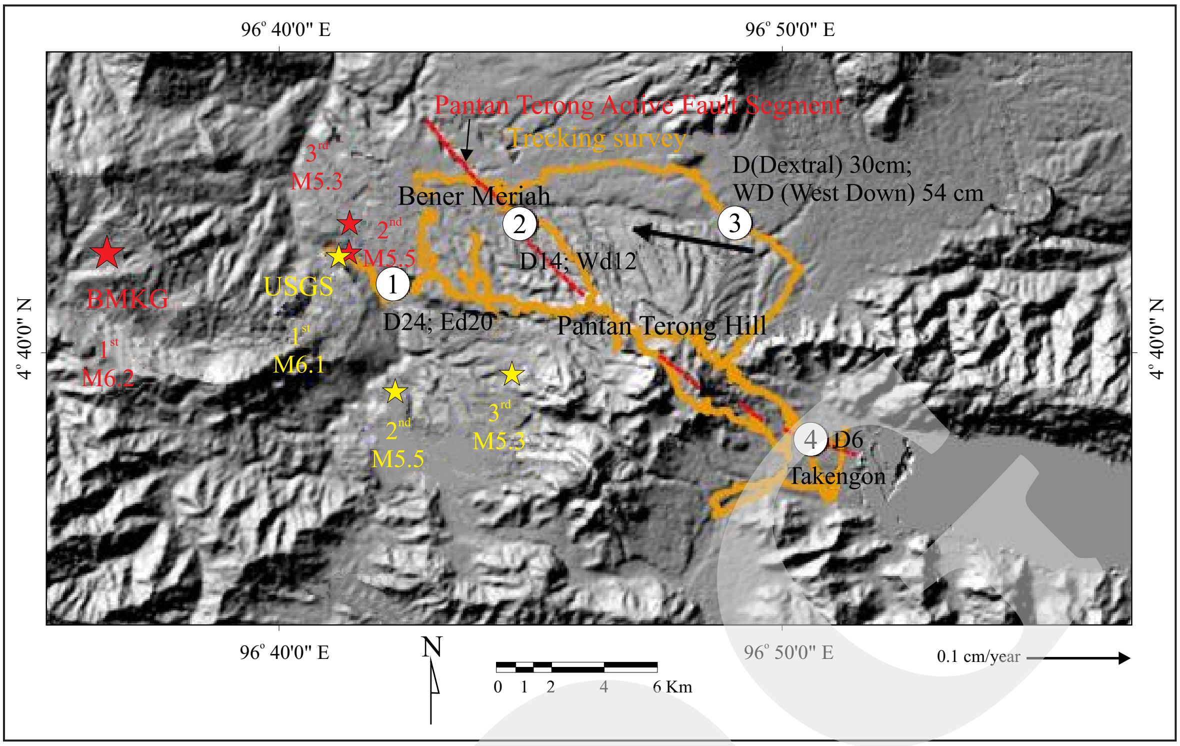

Figure 14. Geological and seismological setting of the previously unidentified Pantan Terong segment. The brown lines show the surveyed path. The red stars indicate earthquake epicentres from BMKG, and the yellow stars indicate earthquake epicentres from NEIC-USGS. The blue circles indicate the best surface rupture sites. The black arrows indicate the GPS results of Ito et al. (2012).

Conclusion

The hilly morphology of the region and the prevalence of tuff sands in the subsurface make surface rupture identification difficult. The four best candidate sites of tectonic surface ruptures do not show a clear association with a linear fault, except two sites that appear to coincide with morphologically a fault line identified using 30-m ASTER GDEM and WORLD 30-m DEMs. This fault line crosses Pantan Terong Hill, after which the fault is named. This fault has a total mapped length up 19 km and a dextral surface rupture offset of 6 to 14 cm.

Due to the soil type and slope morphological condition, many hillslopes in Gayo Highland are obviously prone to landsliding during an earthquake event. Large-scale landslides is the most disasterous hazard in the region.

Further researches are needed to characterize the offset history and seismic potential of this newly identified segment, as well as other thus far unidentified but potentially hazardous faults in the region. The use of combined geophysical techniques is recommended to map this unidentified active fault segment in order to understand the nature of the fault segment.

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