17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

INVESTIGATION AND ANALYSIS OF LIQUEFACTION-INDUCED DEBRIS FLOWS IN PALU, INDONESIA FOLLOWING THE 28TH SEPTEMBER 2018 CENTRAL SULAWESI EARTHQUAKE

R. Lagesse (1), A. Brennan (2), I. Rusydy(3)

(1) *Senior Engineering Geologist, Arup Singapore Pte Ltd., richard.lagesse@arup.com*
(2) *Senior Lecturer, University of Dundee, a.j.brennan@dundee.ac.uk*
32) *Researcher, Tsunami and Disaster Mitigation Research Center, Universitas Syiah Kuala, Indonesia, ibnu@tdmrc.org*

Abstract

On the 28th September 2018, an earthquake with a magnitude of 7.5 M_w occurred on the island of Sulawesi in Indonesia, approximately 80 km north of the city of Palu. The earthquake caused significant damage to buildings and infrastructure in the city and surrounding area as well as triggering a number of extensive ground failures. This paper considers the largest three ground failure occurrences in the city districts of Balaroa and Petobo as well as at the town of Sidera to the southeast of the city. The Balaroa and Petobo ground failures alone are thought to have accounted for over half of the overall human losses from the disaster and therefore a more thorough evaluation of their characteristics is warranted. These failures were initially perceived to be soil liquefaction due to ground shaking alone but findings from the Earthquake Engineering Field Investigation Team (EEFIT) field mission in November 2018 revealed that the failure mechanisms, causal factors and runout characteristics are more complex. This paper presents the findings of the field investigation as well a more detailed analysis of these failures with a view to informing mitigation strategy and planning policy in Palu and elsewhere to reduce potential future losses.

Keywords: liquefaction, landslide, geotechnical, debris flow, Palu

1. Introduction

Following the Central Sulawesi Earthquake on the 28th September 2018 a field reconnaissance mission was carried out, approximately seven weeks after the event, by a joint team from the United Kingdom Earthquake Engineering Field Investigation Team (EEFIT) and the Tsunami and Disaster Mitigation Research Centre (TDMRC) from Syiah Kuala University in Banda Aceh, Sumatra, Indonesia. The aims of the joint EEFIT-TDMRC mission were to assess the impacts of the earthquake ground shaking and secondary hazards on the built environment at Palu and the surrounding area with a view to making recommendations to reduce or prevent future losses.

The team comprised multidisciplinary members from academia and industry focussed on investigating the main aspects of the disaster including the earthquake fault rupture, ground shaking, tsunami, ground failures and performance of structures and infrastructure. This paper documents the findings of the geotechnical team investigating the large-scale ground failures and provides analysis on the perceived failure mechanisms, causal factors and runout characteristics of the three largest failures at Balaroa, Petobo and Sidera.

2. Summary of Earthquake and Landslide Events

The 28th September 2018 sequence of earthquakes occurred due to the rupturing of the Palu-Koro Fault with the epicentre of the main shock located approximately 80 km north of Palu city and an estimated hypocentral depth of approximately 10-15km [1]. The earthquake occurred at 18:03 local time (10:03 UTC) and had a moment magnitude (M_w) of 7.5 with a total fault rupture length of more than 150 km. From measurements in the field, the EEFIT-TDMRC team estimated a mean fault displacement at the surface of approximately 3 to 5m. The total calculated fault rupture area is approximately 150 km by 30 km with most of the rupture occurring to the south of the epicentre. The field investigation conducted detailed mapping of the fault rupture (Fig. 1) and confirmed that the rupture runs along the western side of Palu Valley, where displacements were at their largest. In addition to the large displacements caused by the fault rupture, significant ground shaking occurred in the valley where peak ground accelerations (PGA) are estimated to have reached 0.5 to 0.6 g during the main shock [2] [3].

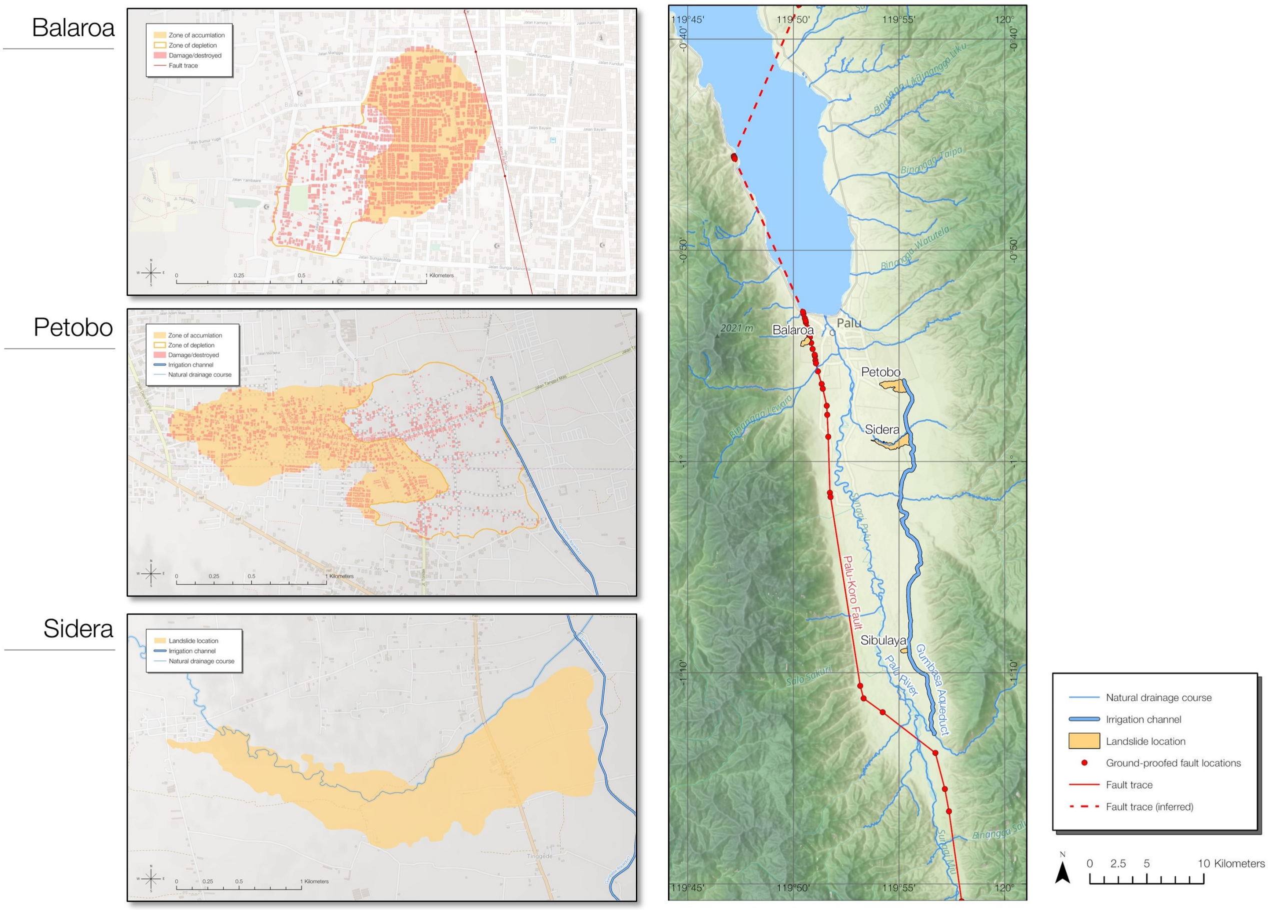

Fig. 1 – Location map of Palu Valley showing Palu-Koro Fault, landslide locations, natural watercourses and the Gumbasa Aqueduct (*right*). Insets for each landslide (*left*).

The main shock was preceded by a number of significant foreshocks including a moment magnitude 6.1 M_w three hours before at around 15:00 local time. An active aftershock sequence occurred including over 40 recorded events of moment magnitude 4.4 M_w or greater in the first five days following the main shock with the largest moment magnitude event of 5.8 M_w occurring at 18:25 local time [1].

Following the main shock, evidence of large-scale ground failure was reported with references to *"liquefaction"* widely described. Anecdotal evidence from interviews during the field investigation suggest the large-scale ground failures were concurrent with the main shock and occurred within *"one to two minutes following the onset of ground shaking"*. Evidence from in-country reports and satellite imagery quickly revealed three main areas with obvious large-scale mass movement occurrences in Palu Valley, including two densely populated parts of the city at Balaroa and Petobo districts and close to the town of Sidera to the southeast of the city. Other smaller failures were also recorded in the valley as well as landslides and rockfalls in more mountainous areas.

3. Observations from the Balaroa Landslide

The Balaroa Landslide occurred in the western district of Balaroa in Palu city. The landslide had a head scarp approximately 0.5 km wide and a runout approximately 1 km long; the head scarp was measured to be approximately 8 to 9 m at its highest. The overall slope angle from the top of the head scarp to the toe is approximately 3.5° although there was local variation in slope angle. It has reasonably well-defined zones of depletion and accumulation with most debris being deposited 0.4 km downslope (east) of the head scarp (Fig. 1). The surface rupture of the Palu-Koro Fault also runs along the toe of the landslide.

Prior to the landslide, Balaroa was a densely populated residential area with historical aerial photos suggesting this was one of the oldest urbanised parts of Palu; as a result, damaged buildings and man-made debris was observed throughout the landslide area. Much of the debris in the lower depositional part of the landslide remained with most of the upper part having been cleared. Some buildings and vegetated areas remained intact but had been transported significant distances from their original location.

Subsurface materials were exposed in the head scarp (Fig. 2) demonstrating the following succession:

- <1 m granular engineering fill, predominantly sandy gravel and cobbles;
- 1-2 m of fluvial deposits comprising sandy gravel, gravelly sand, silty sand, sandy silt; and
- Underlying granitoid subangular to sub-rounded cobbles and boulders in a gravelly medium to coarse sand matrix – suspected colluvium / previous landslide deposit, base not proven.

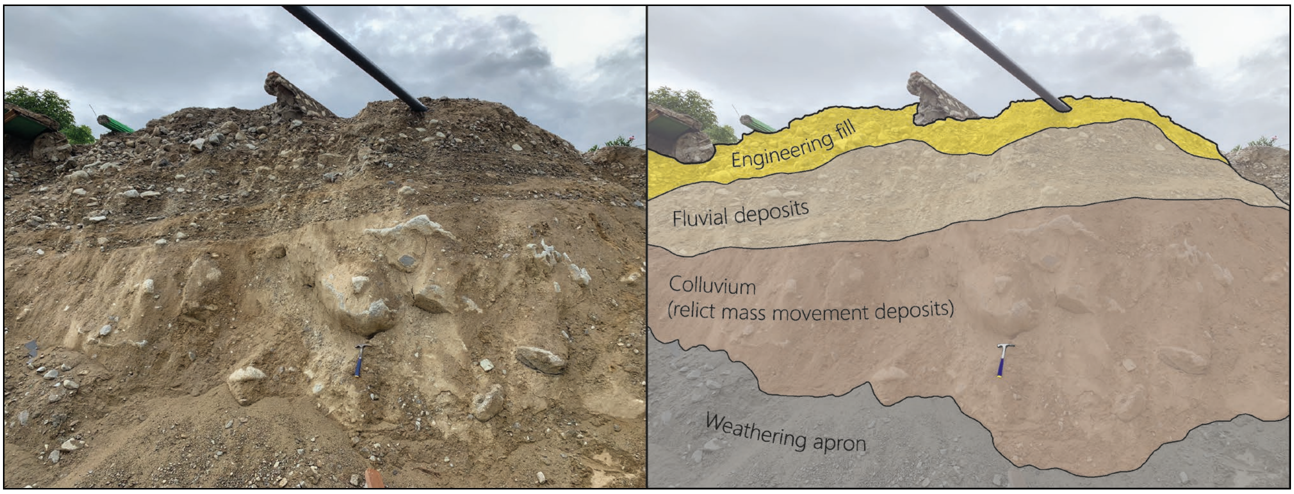

Fig. 2 – Geological profile exposed in Balaroa Landslide head scarp.

Many large boulders, similar to those observed in the colluvium, were also noticed scattered across the zone of depletion across the upper part of the landslide. Accounts from local geologists and engineers suggested colluvial material was widespread in the valley side areas.

Follow-up investigation in the immediate aftermath of the landslide by geotechnical representatives from Tadulako University identified evidence of liquefaction in the underlying soils at Balaroa. A 4 m deep borehole hand-drilled one week after the event revealed localised sand material that has undergone liquefaction. A 20 m deep CPT located at the Anutapura Hospital, 200 m from the toe of the landslide, revealed mostly silty clay and loose sand material with no refusal at 20 m and a highest cone resistance (qc) value of 8MPa.

Accounts from local residents, geologists and engineers suggest the groundwater levels on the western side of Palu Valley are relatively high with springs observed by locals in the slopes above Balaroa. A local resident and representative of the Meteorological, Climatological and Geophysical Agency (BKMG) commented that prior to the earthquake groundwater levels were 4 m below ground level at the location of his house at the toe of the landslide. He also noted that during the landslide his house was raised by 3 to 4 m and travelled 260 m to the north from its original location. Significant ponding was observed during the walkover in the zone of accumulation and debris lobe.

A walkover of the area immediately above the landslide scarp revealed significant tension cracking, however, none were recorded further back than 30 to 40 m from the scarp, with limited evidence of displacement or deformation beyond this distance. One account from a local resident revealed that the area around the central part of landside scarp was previously a football pitch where many local residents migrated to during the earthquake seeking open ground and safety from falling structures. Unfortunately, the ground underlying the pitch failed during the landslide and the group perished.

4. Observations from the Petobo Landslide

The Petobo Landslide occurred in the south-eastern district of Petobo. The landslide had a head scarp of approximately 1 km wide with a runout approximately 2 km long; the head scarp was measured to be approximately 8 to 9 m at its highest. The overall slope angle from the top of the head scarp to the toe was approximately 3°. It has reasonably well-defined zones of depletion and accumulation with most debris being deposited 1 km downslope (west) of the head scarp (Fig. 1). There is also partial back-sloping of the main debris lobe around the central area of the landslide.

In the upper part of the landslide there is a stable area of ground that has been partially inundated with debris but has largely stayed in situ and as a result this has led to a secondary runout, approximately 1 km long, to the south of this area. Much of the lower depositional part of the landslide had been cleared, however, a damaged house situated in a gully formed in the debris with the base at original ground level suggested the deposited debris thickness was approximately 4 m (Fig. 3).

Fig. 3 – Deposited debris thickness in the accumulation zone of the Petobo Landslide.

Prior to the landslide, Petobo was largely a residential area along a main road than ran down what is now the central axis of the main runout path. Similarly to Balaroa, some buildings and vegetated areas remained intact but had been transported significant distances from their original location. Along the flanks of what is now the landslide area, was predominantly open ground and some marshland areas. The upper part of the landslide was mostly agricultural land and rice paddies prior to the ground failure. A map published by Dutch settlers in the early 20th Century [4] suggests that this area, as well as large parts of Palu, were also largely rice paddies during this time, with a network of aqueducts constructed to provide irrigation water. Significant urbanisation in the Palu city area occurred from 1952 onwards.

Subsurface materials were exposed in the head scarp (Fig. 4) demonstrating the following succession:

- <1 m of agriculturally reworked topsoil; and
- Underlying fluvial/alluvial deposits comprising occasionally gravelly fine to medium sand with occasional layers of increased fines content – base not proven.

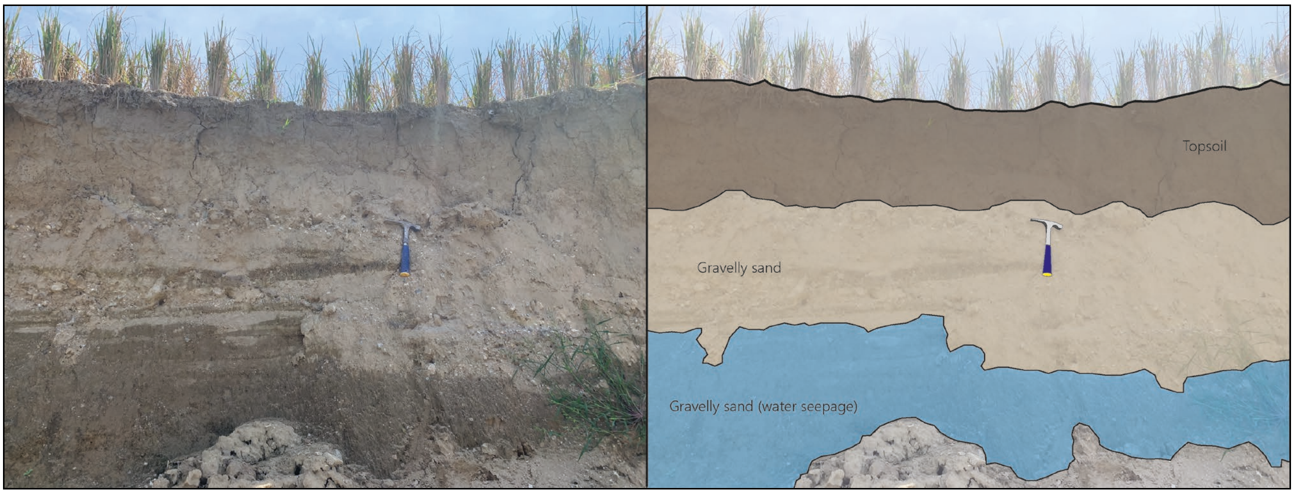

Fig. 4 – Geological profile exposed in Petobo Landslide head scarp.

This succession was confirmed by a 3 m deep borehole hand-drilled prior to the earthquake in the area that is now the upper part of the landslide. Bulk samples of material were collected by EEFIT-TDMRC team from the northern end of the head scarp at depths of 1.6 m and 3.1 m. These were tested for particle size distribution at University of Dundee as shown in Fig. 5. The particle size distribution suggested a profile of silty fine sand. Darker patches of wet/damp material were observed in the exposed head scarp suggesting ongoing seepage of groundwater.

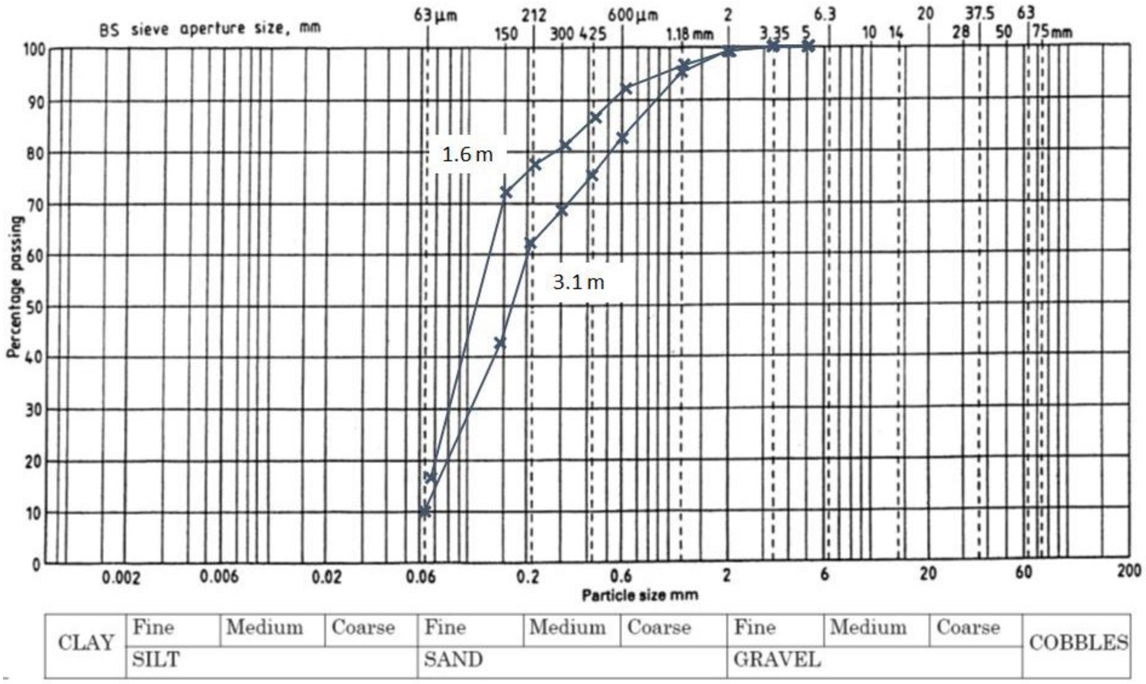

Fig. 5 – Particle size distribution of samples taken from Petobo head scarp

Representatives of the provincial office of the Ministry of Public Works and Public Housing (MoPWPH), suggested in a conversation with the EEFIT-TDMRC Team that the agricultural land was quite permeable and farmers have trouble saturating the ground for agricultural purposes as the water flows away; this suggests permeable granular material underlying the area. However, following a meeting with a geologist and hydrogeologist from the local office of the Department for Energy and Minerals (DfEM), evidence suggests that there is indeed clay material interbedded with the sand deposits with the shallowest significant clay layer occurring at approximately 10 m below ground level in the Petobo area. This interbedding is illustrated on cross-sections of the local geological map provided by the DfEM, which show the dip of interbedded layers run parallel to the ground profile. Further discussion with the DfEM revealed that their drilling showed the clay layer is confining an aquifer that was under artesian water pressures.

Conflicting accounts (by locals and officials) of groundwater depths in the area suggest that the interbedding of clay layers may have resulted in multiple confined aquifers as well as the shallow unconfined groundwater. Accounts suggest that prior to the earthquake groundwater levels in the lower part of Petobo were between 8 and 12 m below ground level, whereas after the earthquake and landslide they had risen to 2 m below ground level. Significant water flow was observed coming from the toe of the landslide into local drainage networks.

As mentioned, the upper part of Petobo area was predominantly rice paddies and other agricultural land prior to the landslide. Rice paddies require inundation of 20 cm of water for a 15-day period during growing phases – this saturates the subsurface. The control of irrigation water is managed via a man-made network of channels and sluice gates which runs along the valley side, approximately at the location of the concave break of slope between steeper mountainous terrain and flatter valley sides. This system requires a large volume of water to always be present in the main irrigation channel such that farmers can syphon off the water via the sluice gate network as required. Over time, as the rice paddies have proliferated, the discharge of water into the ground, rather than local drainage networks, has increased as farmers have diverted more water onto their land. As a result of this dynamic use of irrigation water it is likely that groundwater conditions in the Petobo area are not hydrostatic and there is a flow component.

The main irrigation channel, the Gumbasa Aqueduct, is approximately 32 km long and runs from south to north along the Palu Valley from its confluence with a major tributary of the Palu River in the south of the valley (Fig. 1). The local office of the MoPWPH are responsible for the operation and maintenance of the irrigation channel, which was constructed in 1973. However, on the historical map published by Kruyt (1938), the channel is delineated and labelled ‘waterleiding’ (water pipe in Dutch), which suggests that a man-made channel was also present at that time. The MoPWPH also stated that there is a network of underground water pipes supplying fresh water to residents in the area; and the EEFIT-TDMRC Team observed exposed subsurface pipes in areas of broken ground.

The main irrigation channel terminates in the Petobo area, with two much smaller channels located at the end, presumably to transport water into local man-made and natural drainage networks. However, the dimensions of the smaller channels (2 m width, 1 m depth) are significantly smaller than the main irrigation channel (14.5 m width, 3.5 m depth), and would not be sufficient to discharge significant amounts of water quickly. Instead, as the main channel is predominantly unlined, there is likely significant seepage of irrigation water into the ground in this area.

Anecdotal evidence suggests that groundwater in the area above the irrigation channel, as terrain steepens, is much deeper between 15 and 30 m below ground level. This is reflected in the aerial photography and satellite imagery of the area, with the land above the irrigation channel observed to be brown (no vegetation), whereas below the channel the ground is green in colour, indicating significant vegetation growth and agriculture (Fig. 6). There is also limited urban development upslope of the channel as groundwater extraction is likely more challenging.

It is notable that both the Petobo and Sidera landslides, as well as a much smaller (but still significant) failure in the town of Sibulaya to the south, all initiated along the irrigation channel (Fig. 1). Eyewitnesses remarked that prior to the earthquake the irrigation channel was full of water and rapidly emptied during the ground shaking. Local eyewitnesses at the confluence where the main channel flow control structures are situated reported that flow to the irrigation was stopped in the evening after the earthquake and, at the time of the mission, the entire channel was observed by the EEFIT-TDMRC to be dry except for some localised ponding.

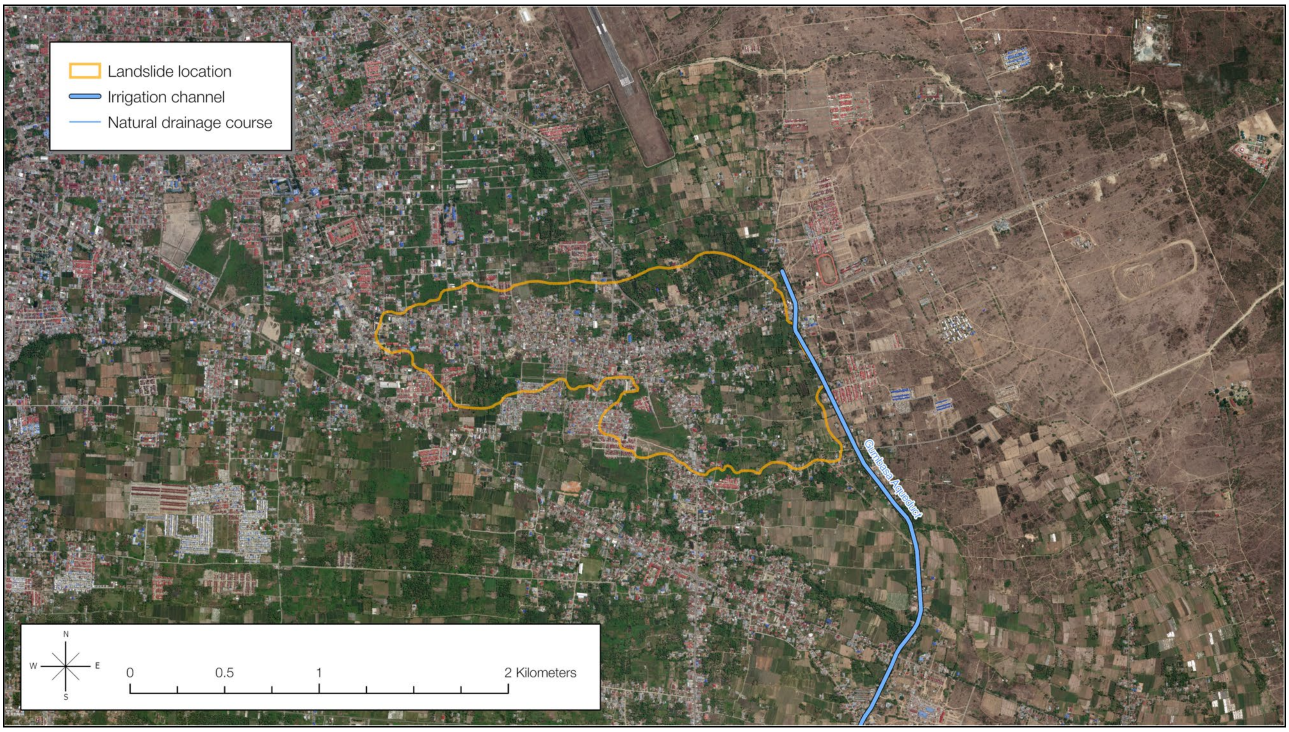

Fig. 6 – Difference in vegetation growth due to groundwater conditions on either side of the Gumbasa Aqueduct in the Petobo area. Green vegetation growth (left) indicates wetter ground conditions as opposed to brown land with lack of vegetation growth (right) indicating mostly dry ground.

Representatives from the MoPWPH suggested that there were plans to restore the irrigation channel following the landslide, adding to it an impermeable geosynthetic clay liner (GCL) as well as upgrade the local drainage network. They also remarked that a new residential area was planned at the southern end of the airport, to the north of the Petobo Landslide. The airport was pre-existing to the development of the main irrigation channel and it is possible the continuation of the channel was restricted by planning restrictions related to the airport.

5. Observations from the Sidera Landslide

The Sidera Landslide occurred to the southeast of Palu city, in a more rural area compared to Balaroa and Petobo. The landslide has a head scarp of approximately 1 km wide with a runout of the main debris lobe of 4.5 km. However, at the toe of the landslide, debris became entrained in a natural drainage channel, and was transported as far as the Palu Bay via the main Palu River.

The exposed part of the head scarp was measured to be 3 to 4 m at its highest, although measurement was partially obstructed back-tilted blocks. Significant minor scarps were observed due to abundant back-tilted blocks remaining intact (Fig. 7). The overall slope angle from the top of the head scarp to the toe was less than 1°. The landslide is bounded to the north by a major drainage line – the same drainage line that it eventually becomes entrained in.

In the head scarp and minor scarps, a maximum of 2 to 3 m of natural material was exposed demonstrating the following succession:

- <0.5 m of agriculturally reworked topsoil;
- <0.5 m of an organic rich relict topsoil layer; and
- Underlying fluvial/alluvial deposits comprising occasionally gravelly silty sand.

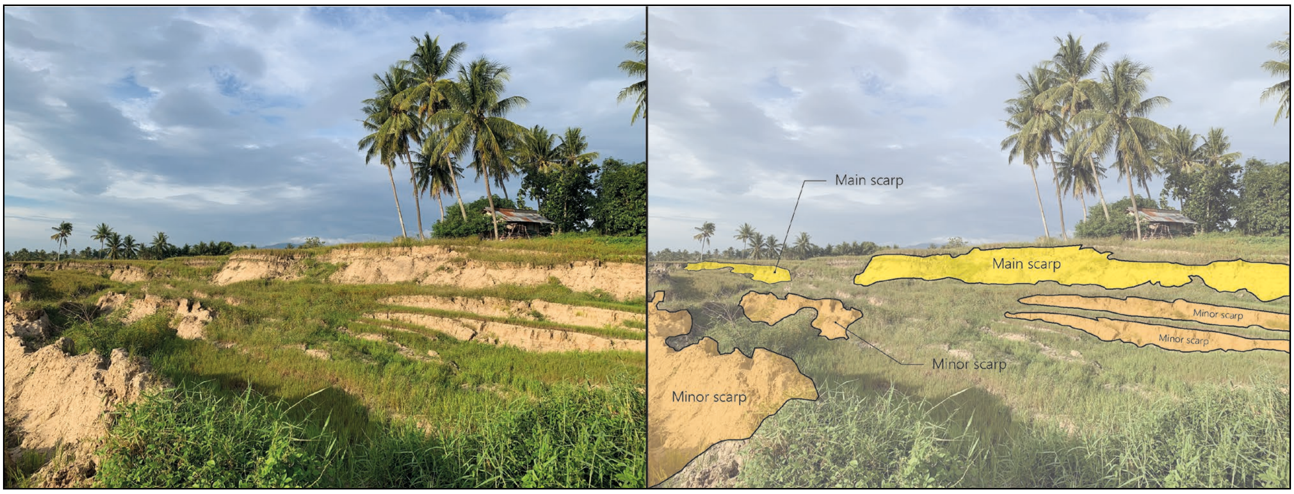

Fig. 7 – Upper part of the Sidera Landslide with the main scarp and minor scarps indicated.

Geotechnical representatives from Tadulako University suggested that the Sidera area had more clay rich soils in comparison to Petobo and Balaroa, with a thick clay layer proved in a hand-drilled borehole. The Sidera landslide also initiated at the Gumbasa Aqueduct, with the channel forming a large graben behind the main head scarp. Lateral spreading liquefaction was observed in the main part of Sidera town to the north of the landslide. Significant differential settlement and tension cracking, along with evidence of sand boils, was observed.

6. Discussion

Prior to the earthquake, the topographic characteristics of the Palu Valley did not suggest landslide hazards were a major concern; certainly in contrast to the mountainous areas bounding the valley where landslides and slope failures would typically be more prevalent. In addition, there is no evidence suggesting major liquefaction had occurred in the valley following previous earthquakes. That said, widespread alluvial soils in an area of high seismic hazard do indicate liquefaction potential, but it was surprising that such large-scale ground failure would be caused by extensive lateral spreading alone. Given the spatial characteristics and geometry of the failures it was clear that there was a 'runout' component and that flow liquefaction must have induced large landslides, manifested as debris flows.

Prior to the field investigation the failure mechanisms and causal factors were not obvious, but early on in the field investigation it became apparent that anthropogenic factors may have contributed. Most notably, the Gumbasa Aqueduct was identified early on as likely causal factor [5] to the Petobo and Sidera landslides, as well as an additional smaller landslide at Sibulaya further south (Fig. 1). Clearly the local hydrogeological regime was influenced by irrigation water from the aqueduct and the ground was saturated over large areas. Given the subsurface materials (predominantly sand, overlying clay) and the hydrogeological conditions in the area, it is likely that flow liquefaction of the sand material occurred. This, coupled with shear stresses induced by the slope angle, (even if the latter is slight), led to a catastrophic failure of the slope, which in turn initiated a highly mobile translational debris flow.

Back-tilted blocks in close proximity to the head scarp suggest that the initial failure mechanism also had a rotational component. Given the height of the back scarp (8 to 9 m) and the reported depth of the shallowest clay layer (10 m) it is also possible that increased pore pressures at the boundary between the sand and clay led to development of a basal shear surface along this horizon. It is further noted that, if the clay layer breached during the landslide this would introduce significant additional groundwater from the underlying confined aquifer, possibly with artesian pressures. Further, if the local water supply pipes ruptured this would, again, introduce additional water into the ground.

The evidence and characteristics of the Sidera Landslide suggest the failure mechanism and causal factors were similar to the Petobo failure, however, with some notable differences. In contrast to Balaroa and Petobo, the Sidera area is much more rural, and the main area of damage was a 700 m long section of the town, comprising one row of houses. There were also some localised developed areas that were partially inundated with debris. However, similarly to in Balaroa and Petobo, some buildings and vegetated areas remained intact but had been transported significant distances from their original location. This suggests an underlying flow transport mechanism with shearing occurring deeper than many structure foundations and vegetation roots. This is supported by video evidence which shows large areas of ground with buildings and vegetation moving as one block. Eyewitnesses also suggested that the landslide had a ‘swirling’ motion.

Given the location of Balaroa on the opposite side of the valley from the Gumbasa Aqueduct, the causal factors are less clear. Similarly to the Petobo and Sidera landslides, the Balaroa failure seems to initiate where the natural terrain conditions and hydrogeological regime form a transition between drier ground upslope and lush vegetated ground. Shallow groundwater had been reported in the area and springs have been noted by locals. The shorter runout along a similar slope angle also indicates that the landslide was less mobile possibly due to lower water content, although the greater urban density may have played a role. The proximity of the Balaroa Landslide to the fault rupture may also have led to stronger ground shaking in this area.

The question remains whether the Petobo and Sidera landslides, as well as the other smaller failures, would have occurred in the absence of the Gumbasa Aqueduct, or in light of the Balaroa Landslide would they have occurred but with shorter runouts or in localised pockets? It is possible that elevated groundwater levels due to irrigation increased the lateral subsurface connectivity of isolated liquefiable pockets causing more extensive liquefaction.

7. Conclusion

The three main landslides that occurred following the earthquake are considered to be low-angle liquefaction-induced debris flows that were extremely mobile due to significant water content. The causal factors are largely thought to be related to the hydrogeological regimes’ interaction with the topography as well as anthropogenic factors. Most notably, a man-made irrigation channel running along the eastern side of the valley (Gumbasa Aqueduct) appears to be the initiation point of the two largest landslides, amongst others, within evidence suggesting the underlying hydrogeological regime is significantly affected by its’ presence. Whether or not the irrigation channel alone directly led to the failures is cause for discussion, but it is likely at the very least that it contributed to the long runouts due to the significant volume of additional water introduced into the ground.

Clearly anthropogenic factors contributed to the landslides following the 2018 Central Sulawesi Earthquake and, given the continuing reliance on agriculture in the region, measures should be taken to assess the effects this has on slope stability and implement actions to reduce the potential risks.

8. References

[1] Valkaniotis, S.; Tsironi, V.; Ganas, A.; Barberopoulou, A. (2018). A preliminary report on the M7.5 Palu earthquake co-seismic ruptures and landslides using image correlation techniques on optical satellite data. Unpublished.

[2] United States Geological Survey (2018) 7.5 Mw 70 km N of Palu, Indonesia.

[3] Worden C. B. et al. (2018) Spatial and spectral interpolation of ground-motion intensity measure observations. Bulletin. Seismological Society. Am. 108, 866–875.

[4] Kruyt, Albert C. (1938): De West-Toradjas op Midden-Celebes. 4 vols. Amsterdam. (Verhandelingen der Koninklijke Nederlandsche Akademie van Wetenschapen te Amsterdam, Afdeeling Letterkunde, Nieuwe Reeks, Deel XL)

[5] Institute of Structural Engineers (2018) EEFIT mission: Indonesia - interesting findings. YouTube video, https://www.youtube.com/watch?v=rBpxfvDKHVg.