Influence of low permeability capping layers on liquefaction induced ground failure

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ABSTRACT

This study aims to investigate the effect of low permeability capping layers on the PWP dissipation and deformation of saturated sand deposits under dynamic loading conditions. To evaluate the buildup and dissipation of excess PWP in a simple way, one dimensional (1-D) model tests were conducted by imparting impact loading to a soil column with and without capping layer. The study aims to investigate the probable cause of large-scale flow failure at Juno Oge village in Palu, Indonesia due to 2018, Donggala earthquake.

Keywords: excess pore water pressure, capping layer, flow failure

1 INTRODUCTION

On the 28 September 2018, a magnitude Mw 7.5 earthquake struck the central Sulawesi region of Minahasa Peninsula of Indonesia. The epicenter of earthquake was located at about 80 km north of the provincial capital Palu with a focal depth of 10 km. Extensive damage was occurred to the transportation systems, bridges, earth structures and residential buildings due to the unprecedented and widespread lateral spreading and flow failures in Jono Oge village in central Sulawesi region. Analysis of aerial photographs captured by Unmanned Aerial Vehicles (UAV) and satellite images revealed large scale flow movement of soil from 10 m to 1 Km in some areas with a ground of very gentle slope (less than 2%). This kind of large scale soil movement was also observed in Hakusan District during 1964, Niigata earthquake (Kawakami and Asada, 1966). The lateral flow was triggered during the extreme event and lasted for several minutes after the end of shaking. Similar case of flow failure was reported in past in Lower San Fernando dam during 1971, San Fernando earthquake where the failure occurred after around 1 minute of the cease of ground shaking (Bolton, 1987)

While, inertia force due to earthquake is mainly considered as the cause of such failure, there are many other factors which contribute as well, considering the site conditions and mechanism of 1964, Niigata and 1971, San Fernando earthquake. For example, in Niigata the ground lithology based on bore-logs was found to be stratified with silty sub-layers sandwiched between loose sandy layers (Kishida, 1966). Various studies have been have carried out in the past to study the influence of these low permeability sub-layers on the onset of liquefaction and lateral flow failure. A series of model tests were conducted by Kokusho, 1999 which revealed that if a site with sandwiched lithology liquefies, the excess pore water is trapped below the low permeability layer preventing the rapid dissipation of pore water pressure developed in liquefiable sandy layer below it. This inhibition of excess pore water pressure dissipation will decrease the residual shear strength of the sandy soil layer to less than initial static shear stress. Consequently, gentle slope flows laterally by gravitational forces till the equilibrium is achieved.

In this study, the authors investigate the possible mechanism of the flow failure and contribution of water film formation under low permeability layers after onset of liquefaction in liquefied sandy soil deposits in Juno Oge, Palu. To serve the objective of this study the authors have conducted a series of field investigation and laboratory tests including PDCPT soundings and 1 Dimensional soil model tests for evaluating the liquefaction mechanism of stratified soil.

2 FLOW FAILURE IN JUNO OGE

2.1 Event History

Juno Oge village is located in Palu city in Central Sulawesi Province of Indonesia. With multiple active strike slip faults and subduction zones in the region, Sulawesi tends to be complex seismically active zone. The village was struck by a powerful earthquake of magnitude Mw 7.8 on 28 September 2018 with strong foreshocks and aftershocks. The event caused large scale liquefaction and lateral flow failures across the city. Fig. 1 depicts the intensity contour of Palu city along with the liquefaction susceptibility map for September 28, Donggala Earthquake. It can be seen from the map that the event had maximum intensity in Juno Oge area with the highest liquefaction susceptibility even after being away from the epicenter.

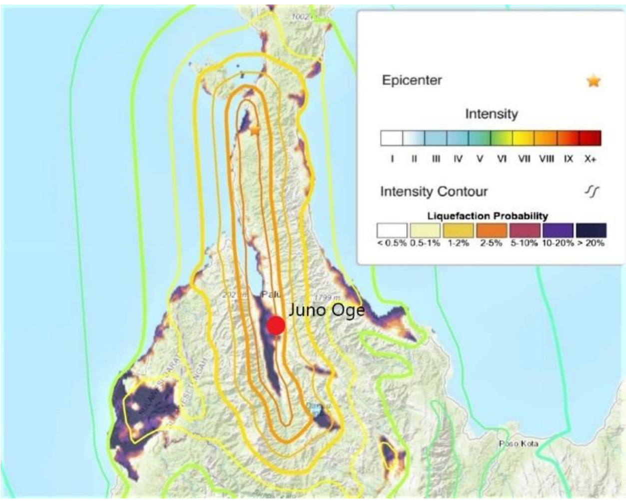

Fig.1. Intensity contour with liquefaction probability map of Palu city for September 28, Donggala Earthquake (USGS, 2018).

2.2 Site Condition

The study area was located in Sigi Regency in Juno Oge village. Fig. 2 shows the condition of the investigated site at Juno Oge before (Fig. 2(a)) and after the event (Fig. 2(b)). The site consisted of agricultural fields with a sparse population and an a very gentle sloping ground of less than 2% (Fig. 2(c)). Furthermore, an irrigation channel was located at the eastern side of failure zone as shown in Fig. 2(b). Due to the presence of irrigation channel, the ground water level was very high (< 5m from ground surface). This also contributed to the flow failure at the site. Earthquake induced liquefaction triggered massive flow slide which breached the water channel discharging a large volume of water into the already failed zone thereby causing massive mudflow as depicted in Fig. 2(b).

2.3 Field Tests

Several large-scale ground failures in the central Sulawesi including flow failure in Jono-Oge was a motivation for researchers of geo-disaster laboratory of Kyushu University to conduct a reconnaissance after earthquake in Palu. Post- event reconnaissance included photographs taken by Unmanned aerial vehicles (UAVs) for damage and geological mapping. Furthermore, in order to evaluate site condition and risk of return of similar cases in the future, site investigation including soil sampling and field tests such as portable dynamic cone penetration tests (PDCPT) was performed at liquefaction sites.

Fig. 3 shows the location of PDCPT tests (PDCPT1 to PDCPT5) and location of soil samples (S1 to S5) collected at depth of 0.5 to 2m. Except PDCPT 1 which was conducted in out of failure zone, the rest of them were conducted within the failure zone.

Ground water level was observed within a meter of ground surface in failed zone which indicates high risk of reliquefication at susceptible areas in the future events. The results of PDCPT 1, 4 and 5 are plotted in Fig. 4(a). Ground water table was seen at depth of 2.3, 0.9 and 0.75 m from ground surface. Results of PDCPT1 (out of flow failure zone) indicates presence of a 2.5 m of layered loose to medium dense sandy soil deposit on top of relatively loose layers (SPT N value<5) of sandy-silt soils.

Comparison between results of field tests at PDCPT1 with that of PDCPT4 and 5 shows similarity between N values for very first 1-2 m of soil below the ground surface at PDCPT 4 and 5 with that of PDCPT1 at depth 2.5m below ground surface. This may explain the possible contribution of underlying loose layer of sandy-silt soil in flow failure of gentle ground. Grain size distribution of soil samples and Scanning Electron Microscopy (SEM) image of sample S2 as representative sample are shown in Fig. 5. All the samples were classified as silt with low liquid limit (ML) according to JGS 0051-2009. Furthermore, specific gravity of samples range between 2.62~2.65.

In order to better understand stratigraphy of soil deposits at the failure zone enclosed by red line, borehole data of a Standard Penetration Test (SPT) performed at location SPT1 (in Fig. 3a) is plotted in Fig.6. As seen from Fig. 4b layers of silt and silty sand are placed over and between the sandy layers which may increase the liquefaction susceptibility of deposit. Therefore, it is necessary to further investigate the effect of low permeable capping layers in liquefaction induced flow failure in Jono-Oge.

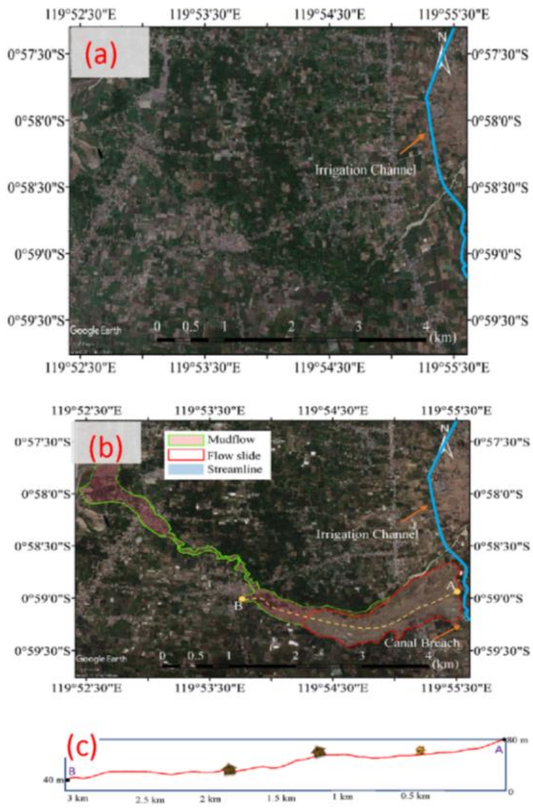

Figure 2: Lateral flow area in Juno Oge due to Donggala Earthquake, (a) before flow failure, (b) after flow failure with mud flow and water channel and (c) slope profile of the flow area (modified from Google Earth).

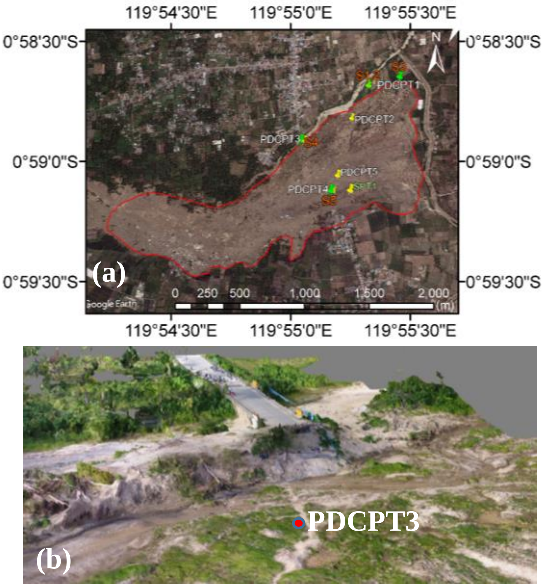

Fig3. (a) Location of PDCPT tests and soil samples (b) UAV3D map of PDCPT3

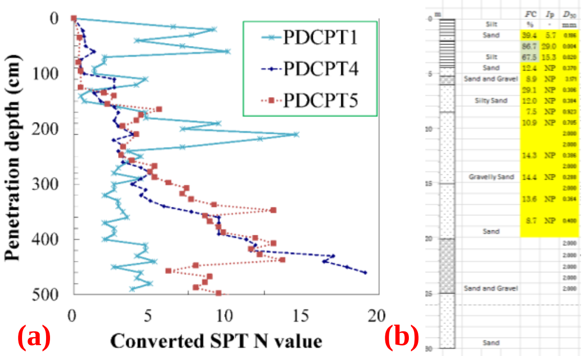

Fig4. (a) PDCPT test results (b) Soil condition at SPT1

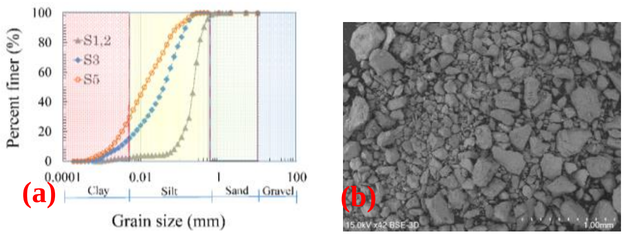

Fig5. (a) grain size distribution of soil samples (b) SEM image of sample S2

2.4 1D Model Tests

To understand the mechanism of lateral flow at Juno Oge, 1D model tests were conducted in lab creating similar soil stratification conditions as observed from field tests. In this study, the 1D model tests were conducted using loose saturated Toyura sand with a layer of Pearl Clay sandwiched between the sand layers. Pearl Clay was used as a capping layer to simulate the presence of a silt seam or clay layer and evaluate it's effect on the dissipation of excess pore water pressure. The grain size distribution of Toyura sand and Pearl clay are given below in Figure 6. The Toyura sand has specific gravity, Gs is 2.65 and emax and emin of 0.977 and 0.615 respectively. For Pearl clay, the Gs is 2.71 and the liquid limit and plasticity index are 49% and 27% respectively (Sun et., al., 2004). The schematic experimental setup is given in Figure 7.

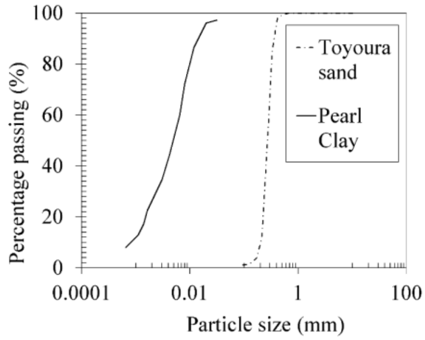

Figure 6: Gradation curve for Toyura sand and Pearl clay.

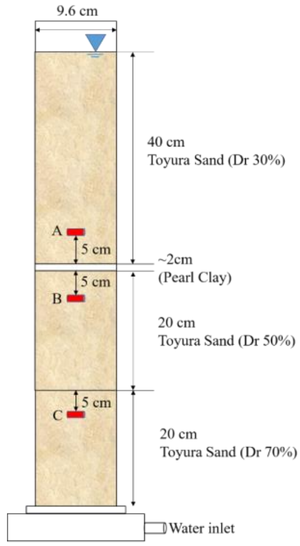

Figure 7: Schematic diagram of experimental setup.

Here in Fig. 7, the Dr is the relative density of the sand layer. A4 and A3 are the accelerometers while P5, NP1 and P2 are the pore water transducers. A condition of liquefaction was generated by providing a shock through a hammer blow to the 1D setup. The resulting excess pore water pressures and accelerations at various points were measured and analyzed for conditions with clay seam and without clay seam.

2.5 RESULTS AND DISCUSSIONS

The results for 1D test after a single impact of hammer have been plotted and shown as a ratio of excess pore water pressure to maximum excess pore water pressure (u/umax). The u/umax value has been plotted against the duration to show the effect of clay seam on development and dissipation of excess pore water pressure in saturated sand under impact loading. Here in Fig. 8, the excess pore water pressure B (1) is for no seam condition while B (2) is for condition with a sandwiched clay seam. The location of pore pressure transducer is just below the clay seam. From the figure it can be observed that ratio u/umax for B (2) takes longer duration to dissipate after reaching peak and still has a higher value while that for B (1) is dissipated. This implies the capping effect of clay seam which inhibits the dissipation of excess pore water pressure in the sand layer below. Further in Fig. 9 the plots for u/umax versus duration for pore pressure transducers A and C are shown, where A is located above the clay seam and C is located at a distance of 15 cm from the bottom of the sand layer with Dr 70%. Here for both the transducers the duration for dissipation of excess pore water pressure for sand with clay seam is higher than the condition without clay seam. This shows that the presence of a low permeability layer can not only hinder the dissipation of pore water pressure in adjacent areas but also in regions at a higher distance from the layer vertically.

Further Fig. 10 depicts the development of water layer below the clay seam. Fig. 10(a) is recorded at T = t seconds when the hammer impact was made. Fig. 10 (b) depicts the maximum thickness of the water film at t + 5 secs while Fig. 10 (c) shows the decreased water film thickness at t + 35 secs. This shows how the water film dissipates slowly in turn influencing the dissipation of excess pore water pressure from the below sand layers by forming an impermeable capping layer.

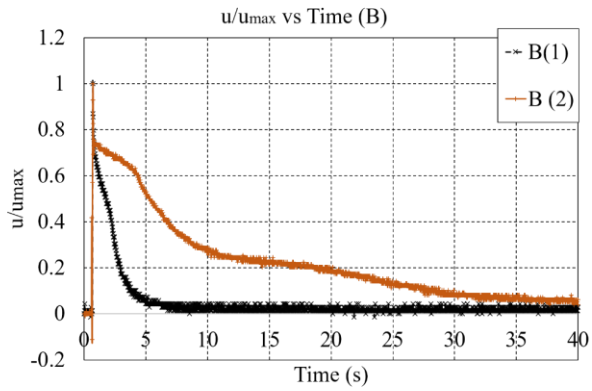

Figure 8: Dissipation of excess pore water pressure versus duration for pore pressure transducer B just below clay layer with/ without clay layer.

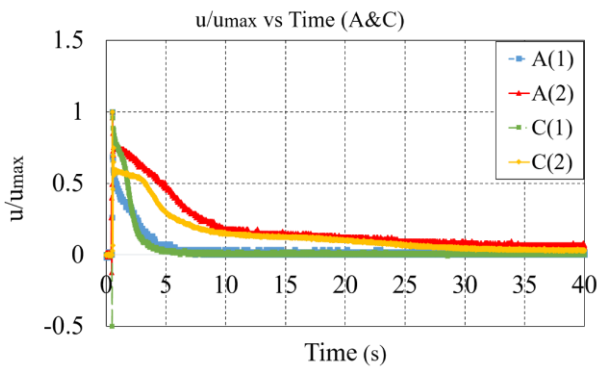

Figure 9: Dissipation of excess pore water pressure versus duration for pore pressure transducers A and C above and far below the clay layer, with and without clay layer.

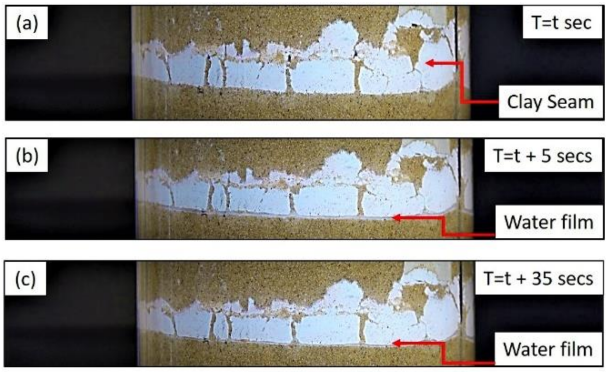

Figure 10: Formation of water layer under the clay seam at different time durations: (a) Time (T) = t secs, (b) T = t + 5 secs and (c) T = t + 35 secs.

Conclusion

The authors conducted site investigation at Juno Oge village in Palu Indonesia after the 2018, Donggala earthquake which caused large loss of life as well as infrastructure. Multiple field tests including PDCPT and aerial drone photography were conducted. From the field tests it was observed that sandy soil consists of silt layers sandwiched in between. 1D model tests were conducted to ascertain the cause of flow failure by simulating the site conditions as per the observations of field investigations. From the results of 1D model tests, it was observed that the presence of a low permeability sub layer sandwiched between saturated sand layers can delay the dissipation of excess pore water pressure due to impact or dynamic loading. This delay in dissipation of excess pore water pressure can reduce the residual strength of soil to the static shear stress. This in turn can cause further instability in the top layer by causing excessive settlements and flow failure.

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