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A retrospective view on liquefaction-induced flowslide and lessons learned - an example of Petobo failure incident during 2018 Palu-Donggala Indonesia earthquake

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ABSTRACT

Soil liquefaction is an important issue in the field of environmental geotechnics where level ground loses its bearing, causing failure or settlement of structures. In cases of river bank or mildly sloping ground, however, liquefaction-induced lateral spreading or flowsliding would be more devastating, where structures on the ground would be ripped or drifted away for distance. One of the striking events was the series of liquefaction-induced flowslides in Balaroa, Petobo, Jono Oge, and South Sibalaya, triggered by the 2018 Palu-Donggala Indonesia earthquake, resulting in ground movements of more than 1000m and causing significant damages and casualties. Post-failure investigations indicated the sliding areas were generally situated on a sloping ground of minor relief ($<5\%$ or $<3°$), with crests bordered a main irrigation waterway, Gumbasa canal. In addition, extensive wet-rice cultivation of the ground, in association with Gumbasa irrigation system, would appear to have had elevated the local groundwater tables. With these findings, the potential causes of the failures could therefore be envisaged. This paper will discuss the causes of the liquefaction-induced flowslide failures, with a particular interest on the Petobo sliding. Relevant evidences from our site reconnaissance and subsurface investigations will be adopted as supports to the causes of failure. We also conduct a series of engineering analysis and try to verify the potential effects of various influence factors on the consequence of the flowslide. In summary, this paper will address retrospectively the lessons that we could learn from the extensive and long-distance flowslides induced by soil liquefaction.

Keywords: soil liquefaction, flowslide, causes, mechanism, lesson learned

1 INTRODUCTION

Liquefaction is a phenomenon where soil transforms its semi-solid phase into fluid phase due to the increased pore pressure that reduces the effective stress and stiffness, and eventually turns the soil into a liquid-like material. As a result, the soil loses its bearing and structures on the ground may settle, ripped, or even be drifted away. Consequently, damages and/or casualties would be involved.

Soil liquefaction would be imminent under a set of conditions when they are jointly met. These conditions include a cohesionless and loosely-packed soil mass, a high groundwater table that saturates soils, and a generated excess pore pressure high enough and substantially reducing the effective stress and stiffness of soils. Another condition that would also be vital in triggering the momentum of liquefaction sliding is the static shears in sloping ground. When the static shears are greater than the residual strength of liquefied soils, the ground would be dragging and moving for distance until the momentum being equalized or overcome.

The above circumstances were identified in the case of 1938 Fort Peck Dam when a significant failure occurred in its upstream slope during the final stage of dam construction. The failure had resulted in sliding of the slope of 300~500m and covered a footprint with a size of about 65ha, which was attributed to the insufficient residual strength of foundation shale, the liquefaction of hydraulic fill sands, as well as the attainment of the slope height (Redlinger et al., 2018). Another case was identified in the failure of Lower San Fernando Dam during the earthquake of 1971. The failure had led to a sliding in the upstream slope of about 21m and vertical settlements up to 9m. Causes of the failure were due to the liquefaction of hydraulic fill near the base of embankment and relatively high static shears in the slope (Seed et al., 1975; Castro et al., 1985).

It is apparent that the conditions for prompting soil liquefaction and flowsliding, as mentioned, could be formed by nature or as a result of human activities. For instance, loosely-placed cohesionless soils, locally-raised groundwater levels, machinery vibrations or impacts, or attainment of slope heights, etc., are due to human's efforts and would increase the likelihood of liquefaction or flowsliding. In view of the mitigation of liquefaction disasters, it would be important to understand the causes and mechanism of the failure; where the involvements of human activities would probably be the ones we need to pay more attention to and try to modify or prevent. In this paper, we will discuss a significant and unique liquefaction-induced flowslide incident that occurred in Palu, Indonesia, in 2018. The discussions will include our verifications of the human involvements in the failure as well as the lessons to be learned.

2 LIQUEFACTION-INDUCED FLOWSLIDES IN PALU, SULAWESI, INDONESIA

On September 28, 2018, a severe earthquake (M_w7.5) hit Palu city, Sulawesi island of Indonesia, triggering tsunamis along the bay of Palu as well as significant landslides inland of Palu valley (PuSGeN, 2018). The incident had resulted in estimated 4,340 fatalities, 4,440 injured, 68,450 home damages, and more than 200,000 people dislocated, according to the Governor of Central Sulawesi; which was considered as the deadliest earthquake disaster worldwide in 2018 (GEER, 2019).

Four major landslides occurred in the areas of Balaroa, Petobo, Jono Oge, and South Sibalaya of Palu valley, with distances approximately 3~30Km south of the bay, or 65~90Km from the epicenter of the earthquake. All of these landslides were triggered by soil liquefaction during the shaking and resulted in long-distance sliding of ground of several hundreds of meters. The Petobo sliding, as shown in Figure 1(a), was the most severe one in terms of its casualty, damage and sliding distance (>1,000m). Figure 1(b) illustrates the moving ground during the course of sliding in Jono Oge area, as indicated by relative movements of the houses and the nearby trees.

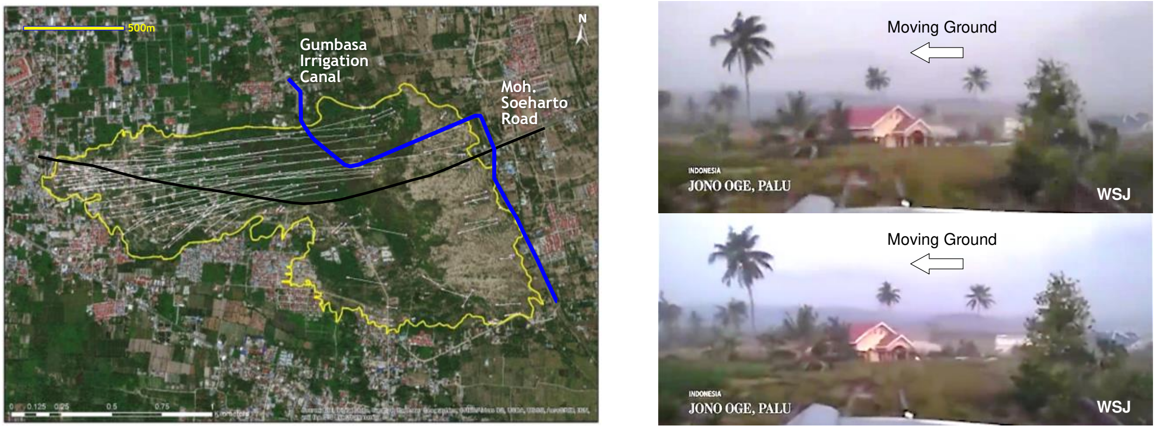

Figure 1. *(a) Displacement vectors of the 2018 Petobo slide (left; Kusumawardani et al., 2021). (b) Snapshots of moving ground from the videos taken at Jono Oge (right; WSJ, 2018).*

Reconnaissance of the landslide failures were conducted shortly after the earthquake by several parties worldwide (PuSGeN, 2018; Cummins, 2019; Bradley et al., 2019; Watkinson & Hall, 2019; GEER, 2019; Kiyota et al., 2020; Okamura et al., 2020). Preliminary findings generally agreed the liquefaction-induced sliding with the observed sand boils and ponds at or near the landslide sites. All of the landslide areas were situated on the sloping flanks of Palu valley with minor reliefs of less than 5% (<3°); facing eastwards (Balaroa) and westwards (Petobo, Jono Oge, South Sibalaya) to Palu river running south to north through the valley. Except Balaroa site, all of the landslide areas bordered their crests to the Gumbasa canal, a major irrigation channel constructed during 1910s by Dutch that extended more than 30km from south to north along eastern flank of the valley. The Gumbasa canal was mostly unlined and constantly filled with water throughout the years based on witness accounts. It was also observed that widespread wet paddy fields existed on the downslope side of Gumbasa canal prior to the earthquake.

These findings would suggest a close relationship of the landslides with the unlined Gumbasa canal and the widespread wet paddy fields. Constant infiltrations of water through the unlined irrigation system and wet paddies would probably have had saturated the ground and hence raised the local groundwater table of the site. In addition, the mildly sloping surface that provided static (driving) shears would probably have had triggered the movement once the ground was liquefied by the shaking. While these arguments seem to be plausible, more precise verifications would be warranted to assure the causes and mechanism of the sliding; and hence the associated results will be addressed below.

3 VERIFICATIONS ON CAUSES AND MECHANISM OF PETOBO SLIDING

As mentioned previously, four conditions would be essential for triggering soil liquefaction and flowsliding. These conditions include: (1) liquefiable soils distributed with a large extent; (2) a high groundwater table substantially saturated the soils; (3) a strong seismic motion sufficiently agitating the excess pore pressures in soils; and (4) static shears in sloping ground high enough for driving the liquefied soils. To verify the above, we have carried out a series of study in Petobo sliding area since mid-2019, including site reconnaissance, subsurface drilling and probing, geo-resistivity surveying, groundwater monitoring, laboratory testing, and various kinds of engineering analysis. Results of the verifications are discussed separately in the following sections.

3.1 Verification of groundwater levels

Ample evidences had revealed ponds, springs and sand boils were extensive near the toe and crest of sliding area soon after the failure (GEER, 2019; Kiyota et al., 2020). Based on our site reconnaissance and witness interviews in 02/2020, victims reported water with sands erupted from the ground during the sliding, and then ponded the softened surface after the slide (Kusumawardani et al., 2021). The phenomena might have been due to the originally high groundwater levels of the area and the pore water being squeezed out of the liquefied ground. Local victims also indicated the constantly-full unlined Gumbasa canal and its irrigation system, as well as the extensive wet-paddy fields that were filled with irrigation water, during Feb-May and Aug-Nov of the year (Kusumawardani et al., 2021); suggesting the groundwater levels prior to the 2018 slide should have been very close to the ground surface.

Figure 2. *Gumbasa canal at the crest of Petobo slide footprint, before (left) and after (right) the 2018 earthquake (Kusumawardani et al., 2021).*

Figure 3. *Surface ponding (left) and artesian waters (right) in the middle of Petobo slide footprint during 02/2020 site reconnaissance (Kusumawardani et al., 2021).*

Our 02/2022 reconnaissance, 1.5-year after slide, also revealed Gumbasa canal, irrigation system, and paddy fields, located in the upper portion (higher elevations) of the sliding footprint, were destroyed, abandoned and completely dried for a period of time, as shown in Figure 2. In the mid-portion (lower elevations), however, surface ponding and artesian waters were found, as seen in Figure 3; implying the groundwater levels in the upper portion of sliding area should have substantially dropped after the slide due to the termination of water supply from the Gumbasa irrigation system and wet-paddies.

We also carried out subsurface exploration, geo-resistivity surveying, and groundwater monitoring along the EW main road (Moh. Soeharto Rd.; location shown in Figure 1) of the Petobo area, and results are summarized in Figure 4. The post-slide investigations indicated the groundwater level in the upper portion near the sliding crest had substantially dropped by 10~15m, as compared with its pre-slide situation. In the mid-upper portion, the groundwater level was close to its post-slide surface; while in the mid-lower portion, the groundwater level was approximately parallel to the pre-slide geometry.

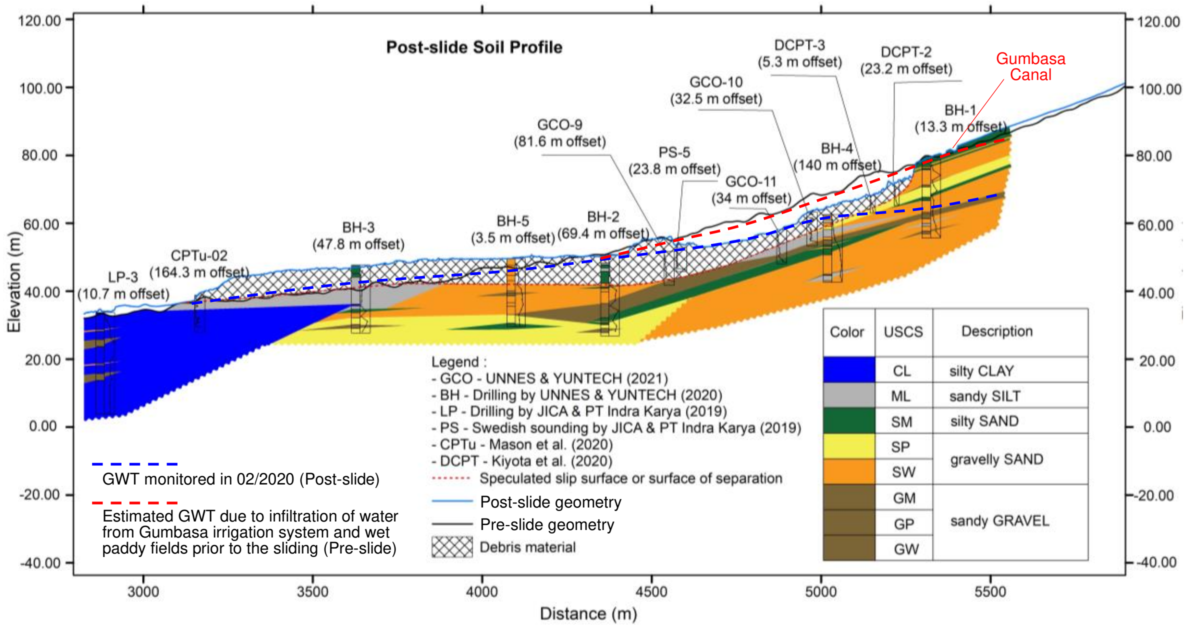

Figure 4. *Post-slide material profile along EW cross-section (Moh. Soeharto Rd.) of Petobo area with monitored / estimated groundwater tables (GWTs), respectively, after / before the 2018 earthquake.*

In accordance, the evidences observed soon after the failure by other parties, as well as the additional information obtained during our investigation of 02/2022 suggest the original groundwater table in the upper portion of slide footprint had been substantially raised prior to the earthquake shaking, as shown by "**Blue**" and "**Red**" dashed lines in Figure 4, which appeared to be the results of constant infiltration of water by Gumbasa irrigation system and wet paddy fields of the area.

3.2 Verification of liquefiable soils

Our site reconnaissance revealed widespread liquefied soils on the surface of upper and middle portions of the sliding area. As shown in Figure 5, the exposed liquefied soils on surface were generally fine to medium sands, with inclusions of some earthen chunks or gravels which might have been carried and drifted by the flowslide. Based on results of borehole logging and geo-resistivity surveying, as shown in Figures 4 & 6, the shallower material profile along the EW cross-section of Petobo area could approximately be divided into three portions. In the upper portion of the sliding area, the earthen materials are generally gravelly sands or sandy gravels. The middle portion consists of mostly silty sands; while the lower portion comprises silty sands, sandy silts and silty clays. Laboratory classification tests, as illustrated in Figure 7, also indicate the grain-size distributions of soils within sliding mass fall in the range of liquefiable zone. It is certain that the in-situ soils are prone to liquefaction.

3.3 Verification of seismic actions

It is noticed that one large foreshock and several aftershocks were involved in this failure incident. As indicated in Figure 8, a foreshock (M_w6.1) occurred approximately 3-hr before the main shock, some

60Km north of Palu city, did terrify the local residents with severe shaking. However, no serious damages of casualties were apparent, based on available reports or witness testimonies (PuSGeN, 2018; Kusumawardani et al., 2021).

Figure 5. *Wide-spread liquefied soils on the surface of Petobo slide: (up) general view, (down) close view; during 02/2020 site reconnaissance (Kusumawardani et al., 2021).*

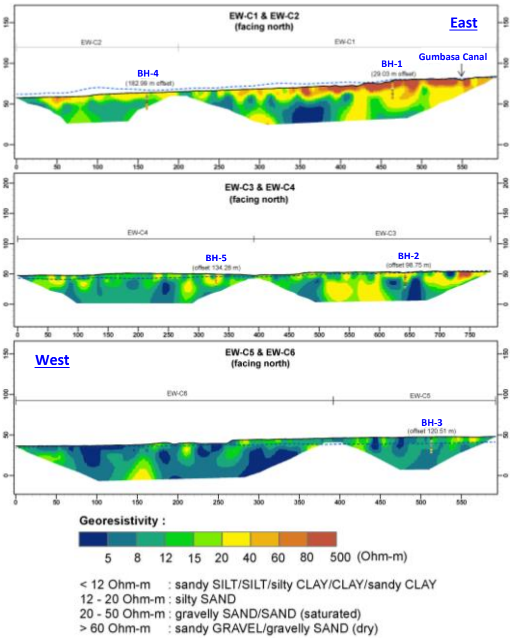

Figure 6. *Results of geo-resistivity surveying along EW cross-section (Moh. Soeharto Rd.) of Petobo area during 02/2020; (up) E-segments, (middle) middle-segments, (down) W-segments.*

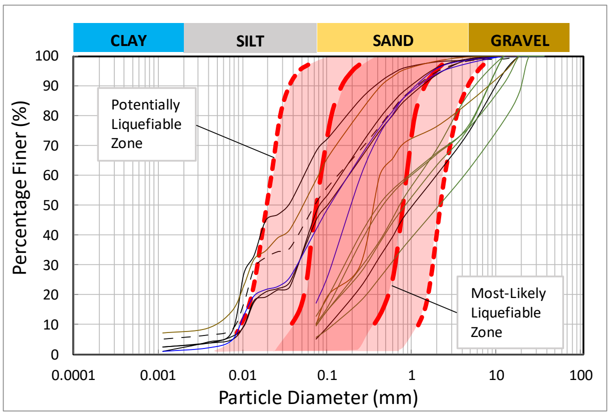

Figure 7. *Grain-size distributions of SPT soil samples within Petobo sliding area.*

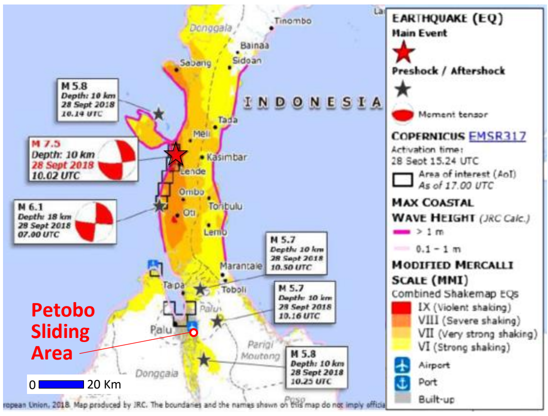

Figure 8. *Foreshock, mainshock, aftershocks of 2018 Palu-Donggala EQ (GEER, 2019).*

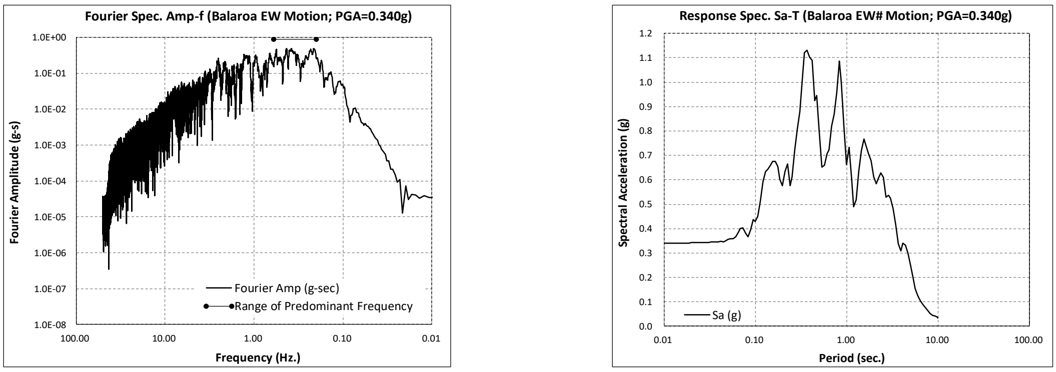

Figure 9. *Fourier spectrum and response spectrum of 2018.9.28 Palu-Donggala mainshock motion (EW component amplified to a PGA of 0.340g) recorded at Balaroa station.*

On 18:02:44 (local time) of September 28, 2018, the main shock with a magnitude M_w7.5 struck the Palu area. The focal depth of shaking was 10Km and the epicenter was around 85Km north of Palu. The shaking was so great with estimated intensities MMI IX-X (0.75~1.39g) in the city of Palu (PuSGeN, 2018). The ground motion was recorded at few seismic stations; where Balaroa station is the closest in Palu area, with a distance to Petobo site of around 8Km. Accordingly, Balaroa data is considered in our subsequent engineering analyses and simulations. In view of the major direction of sliding and the geometric average of horizontal motions (PGA=0.340g) as suggested by Kiyota et al. (2020), we adopted the EW component of Balaroa record and amplified its a_{max} to the estimated geometric average as our input motion for the analyses.

Figure 9 shows the Fourier spectrum and the acceleration response spectrum of this input motion. As seen, Fourier spectrum indicates the predominant frequency of this motion is around 0.2~0.6Hz, or a predominant period of 1.6~5s. The acceleration response spectrum indicates a maximum spectra acceleration of more than 1.1g and the corresponding natural period of 0.35~0.85s. In view of average thickness and shear wave velocity of soil deposit, the estimated site period in Petobo area would be approximately 0.4~0.5s. In accordance, this earthquake motion would have been very severe and destructive to the Petobo site and the Palu valley as well.

3.4 Verification of static driving forces

For the liquefied soils to slide with a large distance, it requires additional gravitational dragging, or static shear, greater than the residual strength of the soils. The static shears would be existing in the sloping ground. To verify the lateral sliding with respect to the static shear or the inclination of slope, we conducted a numerical simulation by OpenSees, an open-source software developed by the Pacific Earthquake Engineering Research (PEER) Center (http://opensees.berkeley.edu).

The software is capable of modelling the coupling response between the soil skeleton and the pore fluid, as well as the redistribution of pore pressure during shaking, either in two or three dimensions. OpenSeesPL is a graphical user interface for facilitating the ground-structure response analysis. Multi-yield surface models are available for cohesionless soils. The coupled solid-fluid analysis option allows for conducting liquefaction studies (http://cyclic.ucsd.edu/openseespl/).

As a preliminary assessment of the influence of ground inclination on lateral deformation, an arbitrary soil deposit profile and an earthquake input motion were selected, as indicated in Hamzah et al. (2022). The inclination of the ground (i) varies from 0 to 6 degrees, and the results are shown in Figure 10.

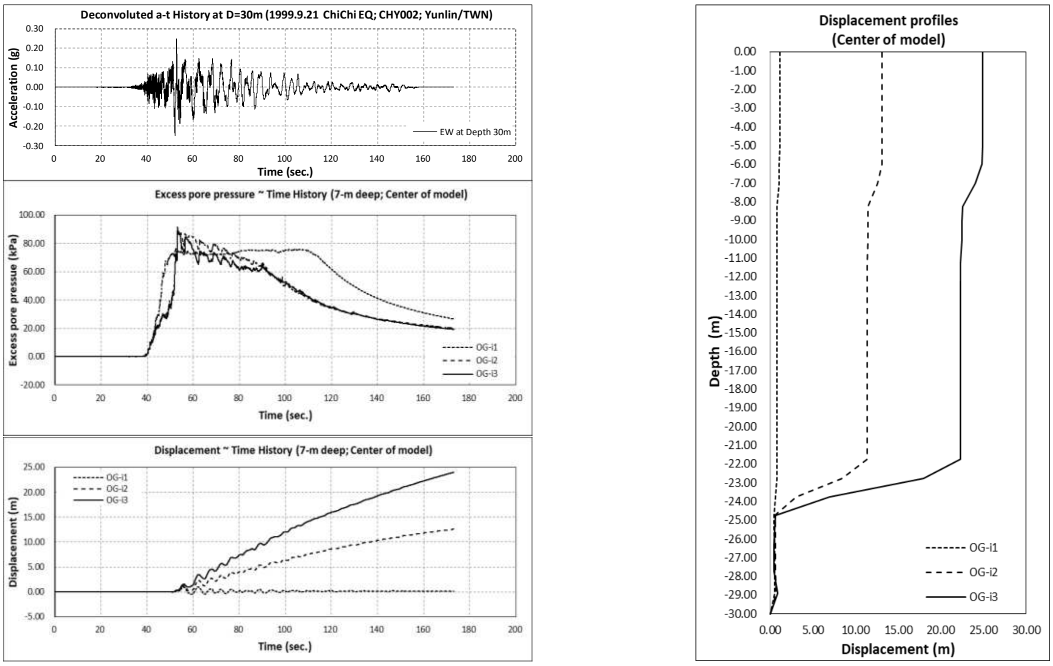

Figure 10. *Verifications of liquefaction-induced flowslide behavior with different ground inclinations by OpenSeesPL (Ground surface inclination: i1=0 / level ground, i2=3deg., and i3=6deg.).*

The soil deposit adopted in this exercise is 30m in depth, where the top 24.75m consists of very-loose to medium sands and the bottom 5.25m is loose to medium silt and clay. For the very-loose to medium sands, the assigned material data includes: ϕ' =29°~33°, c' =0.2~0.4kPa, G_{max} =55~75MPa, B_{max}=150~200MPa, and K_h=6.6x10^{-5}m/s. For the loose to medium silts, the assigned material data includes: ϕ'=29°~33°, c'=0.35kPa, G_{max}=55~75MPa, B_{max}=150~200MPa, and K_h=1x10^{-7}m/s. For the medium clay, the assigned material data includes: ϕ'=0, c'=43kPa, G_{max}=60MPa, B_{max}=300MPa, and K_h=1x10^{-9}m/s. The groundwater table is 3.84m below the ground. The input motion is based on the 1999 Chi-Chi earthquake of Taiwan recorded at Station CHY002, with a_{max} = 0.250g as illustrated in the upper left of Figure 10. Results of time histories in excess pore pressure generation as well as lateral displacement at a depth of 7m are shown in the two lower left graphs. The displacement profile of entire deposit at the end of shaking is shown on the right of this figure.

It's obvious that a slight inclination of the ground would be sufficient to trigger significant lateral displacements once the ground is agitated with excess pore pressure and liquefied. The displacement would appear to last for a period of time even if the excess pore pressure has substantially reduced. The slip surface of this exercise coincides with the boundary between liquefied and non-liquefied zones of the deposit, signifying the sliding triggered by gravitational shear on the liquefied soils. Finally, a slight inclination of ground of 3° could considerably displace the deposit by about 13m at the end of computation (~175s). If the ground is inclined further (6°), the lateral displacement of deposit would appear to increase proportionally (25m), indicating static shears of the inclined ground would be critical in triggering the long-distance sliding of liquefied ground.

4 SUMMARY AND CONCLUSIONS

The verifications discussed previously confirm the essential conditions of soil liquefaction and flowsliding exist at the Petobo site. It is not conclusive, however, whether the Petobo slope would actually liquefy and trigger the sliding when all of the conditions meet. Doubts also remain as to if one of the conditions does not exist would the liquefaction or flowsliding be prohibited at the site. To answer these queries, we start another type of analysis that would be enable for simulation of a flow-type failure. The flowslide simulation is performed by using LS-Rapid, which is a numerical tool developed to assess the initiation and motion of landslides triggered by earthquakes, rainfalls, or the combination of both (Sassa et al., 2018).

Three simulations are considered herein, with the conditions including: (a) pre-slide geometry & high groundwater table; (b) post-slide geometry & high groundwater table; and (c) pre-slide geometry & low groundwater level. Simulation (a) is for the case of Petobo slope at the time of 2018 earthquake, to verify if a liquefaction flowslide is likely under the pre-slide slope geometry and high groundwater table. Simulation (b) is a fictitious case for examining the potential of flowsliding if the slope geometry becomes flatter (i.e., in the post-slide geometry) while the groundwater table remains high. Simulation (c) is also a fictitious case for inspecting the influence of groundwater-table lowering (i.e., a low groundwater table condition due to lacking of water infiltration by the irrigation system and wet paddies) on the potential of flowsliding in the pre-slide slope geometry.

All of the simulations are performed on the EW cross-section of the Petobo slope (i.e., Moh. Soeharto Rd., location shown in Figure 1). The input motion, as mentioned previously, adopts the EW component of Balaroa record during the 2018.9.28 earthquake, with its a_{max} amplified to the horizontal geometric average of 0.340g as suggested by Kiyota et al. (2020). Rest of input data as required by the simulations, including the material parameters for liquefied soils and groundwater table conditions, are detailed in Chang et al. (2022).

Figure 11 indicates the results of Simulation (a) for the conditions of Petobo slope at the time of 2018 earthquake. The slope was in its pre-slide geometry and the groundwater table was high as due to a constant infiltration of water from Gumbasa irrigation system and wet paddies on upper portion of the slope. As illustrated by the "**Red**" dashed line of Figure 4, the high groundwater table was expected to be close to the pre-slide surface of the slope. As shown in Figure 11, results of the simulation clearly demonstrate a significant slide by the 2018 shaking, with a total displacement of the slope up to 569m; which is in resemblance to the post-slide slope geometry of the EW cross-section.

As for the details of sliding process of the simulation, the slide initiates at approximately 3 seconds after the shaking start, and then keeps sliding for around 223 seconds (3.72 minutes) before ceasing. Maximum speed during the course of sliding is 18.3 m/s and the average sliding speed is around 7 m/s (25 Km/h). This simulation validates the Petobo slope would be failing and sliding for distance when all of the conditions are met, including liquefiable soils, high groundwater levels, strong shaking, and the inclined ground that provides sufficient driving forces.

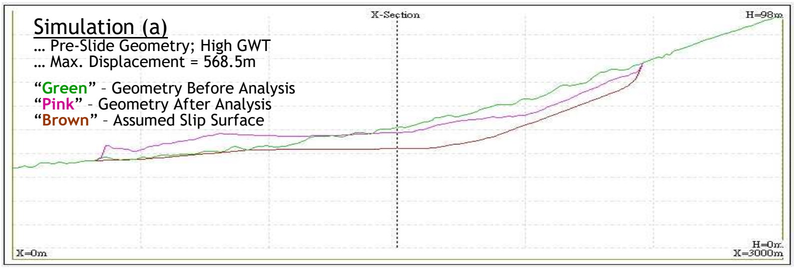

Figure 11. *Verification of Petobo sliding subjected to 2018.9.28 Palu-Donggala earthquake shaking; Simulation (a) - EW cross-section (Moh. Soeharto Rd.), pre-slide geometry, high groundwater table.*

Figure 12 shows the results of Simulation (b), for the case of post-slide geometry of the Petobo slope right after sliding, and then subjected to a second strike of the same earthquake. It would be of interest to know if the post-slide slope geometry, which has become much flatter than its pre-slide one, would still be able to provide sufficient static/driving shears and re-trigger a slide in the slope. The simulation is performed under a condition of high groundwater table since the timing considered is for the "right after pre-slide", where the groundwater level is close to the post-slide surface.

Results of the simulation apparently show the much flatter post-slide geometry would not be able to restart a significant flowsliding in the slope, even if the groundwater table remains high, the slope mass is still liquefied, and the same earthquake is striking at the slope. Details of the simulation also show a slight movement of the slope is noticed at about 3 seconds after the shaking start. The movements last for 56 seconds (<1 minute) then cease, ending up a total displacement of around 13m, which is very small as compared with the length of slope of more than 2000m.

Although the entire slope appears to be "stable", a small amount of the computed displacement within one minute indicates the post-slide slope right after the first strike of earthquake would still be in a quasi-state, given the facts that the groundwater table remains high and the slope mass is still liquefied. The reason why the slide in slope is not re-triggered would probably be due to the geometry of the post-slide surface which is much less inclined than the pre-slide slope. If the slope surface becomes steeper, a significant flowsliding would then be anticipated. This simulation demonstrates the importance of ground inclination, which provides static/driving shears, in triggering a long-distance slide of liquefied slopes.

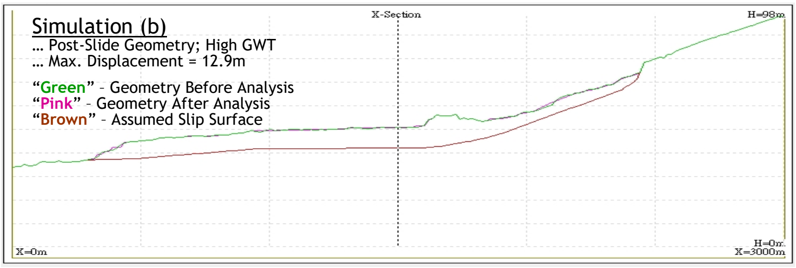

Figure 12. *Verification on the potential of re-initiation of sliding in the failed (flatten) slope subjected to the second striking of the same earthquake; Simulation (b) - EW cross-section (Moh. Soeharto Rd.), post-slide geometry, high groundwater table.*

Figure 13 illustrates the results of Simulation (c), an assumed case of low groundwater table prior to the 2018 shaking, as a result of no water infiltration by Gumbasa irrigation system and wet-paddy fields. This simulation would like to focus on the influence of localized-raised groundwater level due to human activities on the potential of soil liquefaction and flowsliding of the slope. As seen in Figure 4, the groundwater table is expected to have raised by 0~15m in the upper portion of the slope, as a result of the irrigation system and wet paddies, prior to the 2018 earthquake. It would be of interest to see If without rise in groundwater table the Petobo slope would still be experiencing the flowslide as it was during the 2018 shaking.

The simulation is conducted with a low groundwater condition as observed in the 02/2020 investigation and a pre-slide slope geometry of EW cross-section of Petobo area. The Balaroa EW record of the 2018 earthquake, as mentioned previously, is adopted as the input motion for the simulation. As shown in Figure 13, results of the simulation indicate no major liquefaction or flowsliding in the slope is likely. The computed overall displacement of the slope is around 12m, very small as compared with the slope length. The slope movement occurs within the beginning 20 seconds of the shaking and then no further deformation is noticed. This simulation, associated with Simulation (a), clearly demonstrate the importance of the localized-raised groundwater table, as a result of human activities, would have a detrimental effect on the stability of slopes.

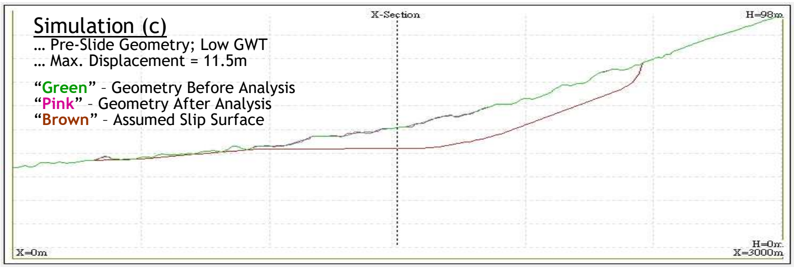

Figure 13. *Verification on the potential of sliding of Petobo slope if no infiltration of water from Gumbasa irrigation system and wet paddy fields; Simulation (c) - EW cross-section (Moh. Soeharto Rd.), pre-slide geometry, low groundwater table.*

This paper discusses potential causes and mechanism of liquefaction-induced flowslides that occurred in Palu valley, Sulawesi island, Indonesia, due to 2018.9.28 Palu-Donggala earthquake; with a particular interest on the incident of Petobo slide. Retrospectively, findings of this study can be summarized as the following:

- For soil liquefaction and the associated flowsliding to be possible, four conditions would appear to be necessary. These conditions include: (1) liquefiable soils distributed with a large extent; (2) a high groundwater table substantially saturated the soils; (3) a strong seismic motion sufficiently agitating the excess pore pressures in soils; and (4) static shears in sloping ground high enough for driving the liquefied soils.
- Our site reconnaissance and subsurface investigations verified the four conditions for contributing to soil liquefaction and flowsliding were existed at the Petobo site at the time of 2018.9.28 earthquake.
- Numerical simulation on the Petobo slope during the 2018.9.28 earthquake (Simulation (a); pre-slide geometry & high groundwater table) confirms the significant slide by the 2018 shaking, with its final configuration resembles the post-slide geometry of the in-situ slope. It also validates the liquefaction and long-distance of Petobo slope when all of four conditions are met.
- Numerical simulation on the post-slide geometry of Petobo slope, with high groundwater table right after slide and then subjected to a second strike of the same earthquake, i.e., Simulation (b), shows insignificant movement of the slope. The simulation demonstrates a much flatter geometry of the post-slide slope would not be able to restart a significant slide.
- Numerical simulation on the pre-slide geometry of Petobo slope with an assumed low groundwater table, i.e., Simulation (c), as expected for the case of no influence of water infiltration by the Gumbasa irrigation system and wet-paddy fields on the upper portion of the slope, shows insignificant movement of the slope and no major liquefaction or flowsliding in the slope is likely.
- Results of Simulations (a) & (b) verify the importance of ground inclination on the potential of flowsliding after soil liquefaction. The static/driving shears as exited in the inclined ground would likely trigger a long-distance sliding in liquefied soils.
- Results of Simulations (a) & (c) demonstrate the importance of localized-raised groundwater table, as a result of human activities, would have a seriously adverse effect on the stability of slopes.
- The primary lesson that we could learn from the 2018 incidents of liquefaction-induced flowsliding in Palu, Indonesia, would probably the avoidance of human activities in raising the local groundwater table, in areas that are prone to strong seismic shaking, covered with large extent of liquefiable soils, and inclined on the ground surface.

Nonetheless, uncertainties still remain as regard to the maintenance of undrained condition of liquefied soils during the course of sliding. Based on witness accounts and numerical simulations, the flowsliding has had lasted for a period of time before ceasing. The way that liquefied soils could have sustained an undrained condition and kept at a “critical void ratio” state, as pointed out by Casagrande (1936) in describing a continuing deformation of sands under undrained loading, would be an important issue needed for further explanations.

Kiyota et al. (2020) have proposed a theory of confined aquifer, though yet to be confirmed, that would release groundwater inflow to the slope and hence help the sliding. Another consideration would be the foreshock and several aftershocks of this earthquake series. The foreshock that occurred 3hr before the main shock would probably have had disturbed or weaken, to some degrees, the “structure” of slope materials; and the aftershocks or tremors that occurred several minutes after the main shock would probably cause a “re-generation” of excess pore pressure and hence sustain a liquefied state of soils during the course of sliding.

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