Slope stability analysis due to extreme precipitation

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Abstract. Slope stability analysis due to extreme weather, i.e. precipitation is an interesting topic to investigate in the high rainfall region. This paper aims to investigate the effect of extreme rainfall on slope stability. A study case at a location inside the highly vulnerable formation in Aceh-Indonesia to failure, which is Tutut Formation, was carried out. Soil samples at the investigated site were collected and tested for further examination. The geometry of the landslide location was measured using Theodolite. Both the soil and surface geometry data were used to develop a computer model from which the slope failure was justified. A failure mechanism due to extreme precipitation is suggested. This finding is consistent with the field observations.

1. Introduction
Landslide is a natural hazard that often poses threats to both the society and economy ([1]; [2]). As one of the natural hazards, this landslide causes infrastructure and property damages, casualties, and severe injuries. This hazard may be attributed to many destabilizing factors [3]. Most of the landslides are caused by natural dynamic processes [3], including significant rainfall seasonal variation [4]; as this rainfall variation causes enormous impacts on soil characteristics and phreatic groundwater conditions [2]. In many cases of a landslide, extreme or prolonged precipitation is the main trigger of the slope instability.

In general concept, the incidence of the landslide is mainly controlled by outside (external) and/or inside (internal) factors ([5]). The external factors consist of the increasing of load due to a wide range of activities such as loads by earth dumping, slope cutting or excavation, vibration (including machine, turbine and seismic vibrations), loads associated with surface and groundwater flow, and rainfall ([6]; [7]; [8]; [9]; [10]). The internal factors are mainly associated with the characteristics of the soil and rocks. These internal factors include the geological conditions (rock types, stratigraphy, geological structures), landforms (slope), soil type, soil thickness, physical and mechanical properties of soil/rock, and pore water pressure ([11]; [12]; [13]; [14]). These many factors as aforementioned above suggest the complexity of the landslide phenomenon.

This paper aims to investigate slope failure due to extreme precipitation. Recently, extreme precipitation is documented as one of the main causes of natural and engineered earth structures instability ([15]; [16]; [17]). Furthermore, this study is also assessing the damage of road infrastructure at the study location to provide information to relevant stakeholders. The results of this investigation can be used for slope stabilization efforts by relevant stakeholders.

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2. Study site
The study site is in the Aceh Singkil district. Figure 2 shows the simplified geological map of the Aceh Singkil district. There are 7 lithology types at Aceh Singkil district, which are Kluet Formation, Sibolga Formation, Barus Formation, Trumon Volcanic Formation, Toba Tuff, Tutut Formation, and Alluvium. The last two lithology types are very dominant in the Aceh Singkil district [18].

It is estimated that there are two rock formations namely Tutut and Alluvium Formations at the study case site. The Tutut Formation consists of conglomerate sandstone, a little siltstone, and mudstone. Tutut Formation is compact to friable. The red mark in Figure 2 is the point of the measured location of this study. The morphology of the study case site, Lae Pinang village, Singkohor sub-district, Aceh Singkil district, is steep- to gently-slope (Figure 3a).

3. Methods
3.1. Data acquisition
The data field acquisition was carried out in early 2019. The weather was generally calm with no strong winds or rain during the data collection. This filed data collection was using several supporting tools such as a theodolite, measurement tools, camera, survey board, tubes for collecting an undisturbed soil sample. Secondary data were also collected during the field trip. Secondly, the process of collecting field data including the two undisturbed samples (UD#1 and UD#2), visual description, and geometric measurement for modeling was carried simultaneously (see Figure 3b). All the field data is important for modeling slope stability.

3.2. Data analysis
Slope stability analysis is performed to assess the stability of a slope. A limit equilibrium condition is used in this analysis. Currently, this limit equilibrium method is mostly used in the slope stability analysis as it involves to most simplicity and accuracy. Generally, the method must search for critical surfaces by using geometry. A slope is stable if the safety factor, computed along any potential sliding surface, is larger than 1. The smallest value of the safety factor is representing the global stability condition of the slope.
3.3. Developed model

The developed model is based on field geometry data and laboratory test results. Two soil types with different physical and mechanical characteristics are used in the developed models (see Figures 4a and...
4. Results and discussion
As aforementioned, the results of the field measurement and laboratory testing data are for developing slope models. An analysis was carried in three different situations, namely: (1) the condition when the soil is dry, (2) the condition at the time of the soil is moist, and (3) the condition when the soil is fully saturated with water. Furthermore, two different models of Model A (based on UD#1) and Model B (based on UD#2) were used in the analysis. The results of the simulation are shown in Figures 5 to Figure 7.

4.1. Results
A summary of the simulation results is detailed in Table 2. The results show that only in dry conditions the both Model A and Model B have more than 1 (one) safety factor (SF) that can be interpreted as ‘SAFE’ or collapse will not occur in this condition. However, when the ground soil is wet or partly saturated from 1-meter depth, the emerging SF is below 1 (one), which is indicating ‘NO SAFE’ condition or collapse will occur.
Figure 5. Simulated model when the soil moisture is dry for (a) model A, and (b) model B

Figure 6. Simulated model when the soil moisture is wet/moist for (a) model A, and (b) model B

Table 2. A summary of the analysis results

| Soil moisture condition | Model A | Model B | Remarks       |
|------------------------|---------|---------|---------------|
| Dry                    | SAFE    | SAFE    | SAFE is SF>1  |
| Wet/moist              | NOT SAFE| NOT SAFE| NOT SAFE is SF<1 |
| Fully saturated        | NOT SAFE| NOT SAFE|               |
Figure 7. Simulated model when the soil is fully saturated with water (a) Model A, and (b) Model B

Figure 5 displays the analysis of slope stability when the soil is dry. The critical safety factor in this condition is more than 1, which suggests a stable slope. Figure 6 illustrates the simulation when the soil is moist. The simulation suggests a safety factor less than 1 for both models A and model B. Figure 7 demonstrates the impact of high rain intensity on the SF. As can be seen, the SF reaches the lowest value when the soil is fully saturated.

4.2. Discussion
A homogenous sandy SILT and clayey SILT soil slopes (Figure 4) are used to illustrate the impact of the precipitation on the behavior of a natural slope. The model includes a 10m high slope with ~40° to ~70° inclination. This typical slope geometry is reported in the literature for landslide modeling [19]. The analysis implements the classic effective shear strength parameters (i.e., cohesion and angle of friction). In general, Figures 5 to 7 demonstrate the decrease in SF under the projected precipitation. As can be seen in Figure 5, the slope is stable under the initial conditions. Once the soil moisture is increasing until moist/wet due to heavy rainfall, localized tension (represented by the red zones in Figures 6) appears in the middle slope boundary, which suggests that the slope's boundary approaches the limit state to failure. As the projected precipitation persists up to the fully saturated soil, the slope's boundary is overestimated the limit state, which is indicative of active sliding. This can be seen in the upper slope boundary of Figure 7. Such a significant surge in the pore-water pressure causes a substantial reduction in the soil shear strength and increment of the overburden load. This failure mechanism is consistent with the field observations. Extreme rainfall was occurring at the study site in November to the beginning of December 2017 as suggested by several official statements of government agencies and institutions located around the scene. Furthermore, a similar slope failure mechanism was suggested by Cruden and Varnes [20]. A further slope stability assessment using the passive seismic method [21] is an interesting subject to explore.

5. Conclusion
Generally, an extreme rainfall intensity can expose a natural slope, engineered slope or earth retaining structure to significant increases in pore pressures and reduce in bearing capacity. These changes can lead to slope destabilization. This study aims to raise awareness regarding the impacts of extreme rain intensity on slope stability. A case study was carried out. The presented models show substantial
impacts of extreme precipitation on the slope stability. It is imperative to consider the extreme precipitation to ensure the stability of geotechnical structures.

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