Effects of Topographic Datasets on Physically Based Landslide Model at a Hyper Local Slope

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ABSTRACT: This study conduct simulation of small (hyper local) rainfall induced landslide event to get a better understanding of the event's mechanism and check its factors for developing more sustainable spatial plan. The issue is important because some report showed that small (hyper local) landslides are insignificant in size, but cause heavy damages and fatalities. This study uses three kinds of topographic data set for simulating the hyper local terrain; 8-meters resolution Digital Elevation Model (arcDEM), GPS-RTK based Digital Terrain Model (rtkDTM), and Unmanned Aerial Vehicle based Digital Surface Model (uavDSM). Accumulated antecedent rainfall intensity also considered as an input beside the physical limits of soil for slope stability modeling (SHALSTAB).

Comparison between all topographic datasets suggest that rtkDTM with 2-meters resolution considered as the best option as an input for simulating the hyper local landslide, compared to other two. The results also suggest that the rainfall threshold for surroundings of the study area should not exceed total accumulated antecedent rainfall intensities, 410 mm in 14 Days. The use of high accuracy and precision three-dimensional ground control points (3D GCPs) are important to increase the aerial mapping quality. Furthermore, the terrain evaluation for more sustainable spatial development plan and better early warning system in the future needs to be done. In short, higher resolutions and quality of topographic data sets are considered valuable investments for landslide hazard prevention in developing areas.

I. Introduction

1.1 Background

Human activity has accelerated the occurrence of landslides by modifying vegetation distribution (i.e., root–soil cohesion), altering the hydrologic regime and disrupting the natural equilibrium (Lepore et al, 2013). A study that compared rainfall thresholds developed for engineered slopes to thresholds for natural slopes on a national scale has been done, resulted that rainfall threshold built for specific engineered slopes can be more conservative than natural slopes (Martinovic et al, 2018). Road networks in mountainous forest landscapes have the potential to increase the susceptibility to shallow land sliding by altering subsurface flow paths. Model results allow quantification of the influence of roads on shallow land sliding hazard across a landscape and generations of hypotheses about the broader geomorphic effect of roads (Borga et al, 2004). In short, earth surface is dynamic, coupled with human activity and environment interactions.

Rainfall is a common trigger for landslides on both natural and engineered slopes (Martinovic et al, 2018). Most users of the engineered slopes, requires the ability to create and maintain their slope stability regardless of the weather. Landslide and other hydro-meteorological disaster are conditions that they have to avoid, urgently, if the rainfall intensity and duration are high and the structures are nearby a communal area. The National Disaster Management Agency of Indonesia noted that during 2017 there are 2,862 disasters, which 80% of them are Hydro-meteorological disasters, and within those events there are facts of small landslide events that can cause fatalities (BNPB, 2018). In short, landslides associated with heavy rainfall cause significant economic losses and may injure several thousand people a year worldwide (Petley, 2012). In addition, the frequency of land sliding increases with the frequency of extreme rainfall events (Kirschbaum et al., 2012), which is expected to be enhanced by global climate change (Gariano and Guzzetti, 2016).

This study aims for analysing the effects of resolution in topography description and try to examine and obtain main factor also better understanding of the rainfall induced landslide through a map simulation. In the process, the rainfall threshold for that specific area needs to be created to support the early warning system development. Good quality, high-resolution topographic data are required to capture the coupled topography and road configuration control on shallow land sliding. Additionally, the study discusses and compare different terrain datasets for their efficiency and cost effectiveness for a detail survey in very small or hyper local area. Previous studies have found that modelling of topographic control of downslope moisture movement is sensitive to the algorithm used for the computation of specific upslope area (Quinn et al., 1995, Wollock and McCabe, 1995).

The importance of hyper local research is related to the current development process in remote areas which prioritizes local wisdom and supports infrastructure development based on the commitment and the need of the local community, along with the support from the central government to decentralize and accelerate the pace of development. Hyper local terms in this study represents the insignificant size of landslide that happen, covering small area, resulted in heavy damage. The mechanism of this hyper local event expected to be more simple than the larger disaster event. However, despite of the event's size, disaster management and mitigation still need to be done along with the development. Sustainable development is expected to be achieved with the ability to evaluate the conditions of the surrounding environment, especially related to spatial planning and land using. In parallel with the innovation of new technology in distance and angle measurement, the use of artificial intelligence (AI) and machine learning in remote sensing science, an effort to make sure a good quality of an input such as topographic dataset is a necessity.

1.2 Slope Stability Model

The Slope stability model used in this paper is derived from SHALSTAB that incorporates a conceptual representation of road interception into a threshold model for slope instability (Dietrich et al, 1993; Montgomery and Dietrich, 1994). In the model equation, *hw* is the thickness of the saturated region above the bedrock, and soil thickness is assumed uniform across the landscape is indicated here by *h*, specified perpendicular to the slope, and. The assumptions above imply that depth integrated sub surface flow (q) per unit contour length is

$$q = \mathrm{R}\left(\frac{A}{b}\right) \;;\quad R = \frac{\mathrm{T.b}\sin\theta}{\mathrm{A}}\left[\frac{Cr+Cs}{\rho_w.gh \quad \cos\theta \quad \tan\Phi} + \left(\frac{\rho_s}{\rho_w} + \frac{W}{\rho_w.gh}\right)\left(1 - \frac{\tan\theta}{\tan\Phi}\right)\right] \tag{1}$$

Where R [m s^{-1}]is the recharge, i.e., rainfall water's infiltration that passes through the unsaturated zone, and become the subsurface runoff, A[m^2] is the upslope area, calculated by the flow algorithm on its terrain data and b[m] is the length across the accounted flow. Soil transmissivity parameter (T) [m^{2}s^{-1}], and the surface's slopes (θ)[°] also affect the subsurface flow occurred along the slope. Thus, from those parameters, relative wetness index for a generic pixel that not influenced by cut slope or road-rerouted subsurface flow (w) might be expressed by

$$w = \left(\frac{hw}{h}\right) \;;\quad w = \mathrm{Min}\left(\frac{R.A}{Tb.\sin\theta} \;;1\right) \tag{2}$$

Under the assumption of infinite slope stability model, one dimensional model for failure of shallow soils that neglect arching and lateral root reinforcement can be provided. Soil parameter such as internal friction angle (Φ)[°], soil cohesion (Cs) [kg m^{-1} s^{-2}], root cohesion (Cr) [kg m^{-1} s^{-2}],, wet soil's density (ρ_s) [kg m^{-3}] were important information for calculating a slope's stability, combined with general parameters, density of water is (ρ_w) [kg m^{-3}] (=1.0), gravitational acceleration (g) [m s^{-2}] and vegetation surcharge (W). The factor of safety (FS) for a vegetated slope with slope parallel seepage, simplified for wet and dry soil density the same, can be expressed as

$$\mathrm{FS} = \left(\frac{Cr+Cs+[\rho s.g(h-hw)\cos\theta+(\rho s.g-\rho w.g)hw\cos\theta+W\cos\theta]\tan\Phi}{h.\rho s.g \quad \sin\theta+W\sin\theta}\right) \tag{3}$$

Inclusion of root cohesion (Cr) and vegetation surcharge (W) into stability analysis allows one to develop a more complete analysis of forest practices, combining cut-slope and vegetation conditions factors into account. Based on this model, critical rainfall concept introduced as the minimum steady state rainfall predicted to cause instability. In SHALSTAB, a slope can be unstable if the recharge (R) that occurred is equal or greater than the critical rainfall threshold for that particular slope. In other word, this instability condition depends on wetness related to contributing area on the slope.

II. Methodology

This study uses a slope stability models to reconstruct landslide events and obtain critical rainfall thresholds for this research area. Several parameters related to the research area are needed as inputs for this model, such as soil's parameters, rainfall intensity data, and digital elevation data. Further study for this hyper local rainfall induced landslide will also need historical land cover and land usage data for related area as an evidence to proof initial assumptions that have been proposed.

2.1 Study area

Study area in this study located at Bendosari Village, Pujon Regency, Malang District, East Java, Indonesia. Major geological formation exists in this area is an *Old Anjasmara Volcanic* formation, which mostly consists of volcanic breccia, lava, Tuff and dikes composition (Santosa, 1992). The surroundings of this study area formed a hill slope type, and the event area located relatively nearby the valley, with elevation ranged from 900 msl up to 1200 msl as shown by DEM data.

2.2 Digital Elevation Data

Three kinds of digital elevation dataset were used for performing simulation in this study. They are; 0.27 arc second resolution Digital Elevation Model (arcDEM), GPS-RTK based Digital Terrain Model (rtkDTM), and Unmanned Aerial Vehicle based Digital Surface Model (uavDSM). Aims for using several different databases are used to show differences in response or results from simulations, and test the effect of quality and descriptions of topographic data sets of simulation results. Schematic illustration for showing the difference response expected from different kinds of dataset (Fig.1).

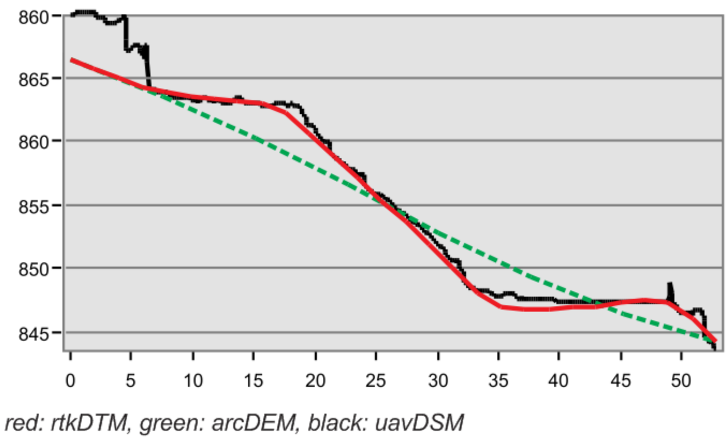

Figure 1. Elevation profile from different topographic data sets

ArcDEM is built from several data sources including IFSAR data (5m resolution), TERRASAR-X (5m resolution) and ALOS PALSAR (resolution 11.25m), by adding stereo-plotting masspoint data. The spatial resolution of the arcDEM is 0.27-arcsecond or 8.25 m, using the vertical datum EGM2008. The method of adding / assimilating masspoint data into Digital Surface Model / arcDSM (IFSAR, TERASAR-X or ALOS-PALSAR) using *GMT-surface* with a tension of 0.32. Details of the assimilation process can be seen on IHO-GEBCO Bathymetry Cookbook (Hell and Jacobson, 2011) and others. Ground Control Point (GCP) and Geodetic Control Net (JKG) measurements were used to validate and test the accuracy of arcDEM data and other high data models. Validation results in Sumatra island show that the accuracy of arcDEM is better than the high data model formed from masspoint, spotheight and breakline (BIG, 2018).

RtkDTM is built from an update field survey, using local base-rover configuration. The correction for elevation value obtained internally after approximately an hour at base receiver. In the real-time kinematic (RTK) method the base station actually transmits correction s to the roving receivers using radio link. The procedure offers high accuracy in real time and the results are not post-processed (Sickle, 2001).

UavDSM obtained from aerial photo points cloud, several ground control points (3D GCP) that obtained using RTK survey, which give relatively high accuracy and precision also recorded. The contour interval, the scale of final map, the positional and elevation that can be achieved using photogrammetric methods are dependent on various interrelated factors. Several factors that mainly affect the aerial mapping results are: The scale and resolution of the aerial photos itself, the flying height when the image was taken, the base-height ratio of the overlapping images, and the accuracy of stereo-plotting equipment used for the measurement (Petrie, 1990).

2.3 Rainfall data

Total rainfall intensity and duration data important to create a specific rainfall threshold in the area and develop an early warning system for land sliding (Martinovic et al, 2018). Daily total rainfall intensity data for this study collected from 10 ground rainfall station nearby the study area within 20 km radius from the event location. Those stations were maintained and operated by Meteorology, Climatology and Geophysics Agency of Indonesia.

III. Results and Discussion

The closest weather station, Kedungrejo was selected to provide the rainfall intensity value. Rainfall data obtained from Station Kedungrejo which located +/- 3 km from the event location. On 2nd February 2018 (event date), the recorded daily rainfall intensity was only 51 mm, it was not the highest intensity recorded during December 2017 - February 2018. Thus, accumulated antecedent rainfall intensity is more likely to induce the landslide event. The 14 days accumulated antecedent rainfall intensity gives better correlation to the landslide event compared with the other trends. This 14-day accumulated antecedent rainfall intensity reaches its peak value at the event date, with total rainfall intensity value 453 mm.

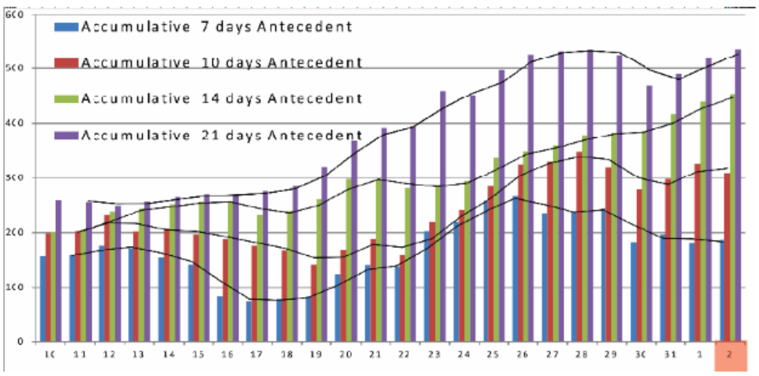

Figure 2. Antecedent rainfall intensities information from Kedungrejo Station.

There are different responses from different kinds of topographic dataset as expected, due to their grid resolution and elevation profile. In this slope stability model, parameter's values used to perform the simulation on each dataset are similar, the map scales are 1:5000. Higher resolution of dataset expected to gives more near actual result, uavDSM can be converted to uavDTM through certain post processing, and need several 3D ground control points to perform corrections. In this study, more than 800 aerial images are used to construct the uavDSM, with and without ground control points (3D GCP). The non- 3D GCP's uavDSM have wider range of elevation compared with the other result that validated using 3D GCP. This issue is obviously important for end users that are willing to create their DTM using aerial images.

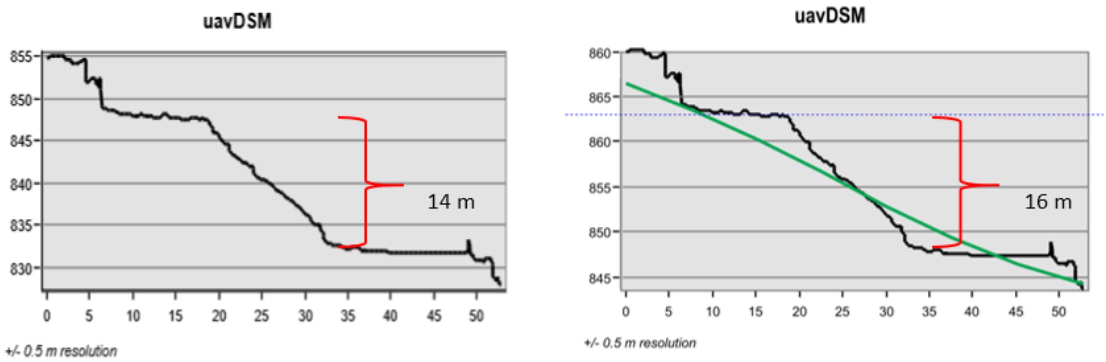

Figure 3. Elevation profile from before(left) and after(right) 3D GCP correction, different elevations range on both profile also show the correction.

IV. Conclusions and Future Work

From several initial result and study literature that have been done, this landslide event on Bendosari village worth for more investigation. Its *volcanics* geological formation have complex characteristic based on their range of process and composition (Del Potro and Hurlimann, 2008). Several input parameters have been used to reconstruct the hyper local rainfall induced landslide event in this study area. Several findings from this study are: a) daily rainfall intensity was not the main factor for this event; b) 14 days accumulated antecedent rainfall intensity more likely to be the main factor; c) Aerial Digital Surface Model (uavDSM) or the highest resolution topographic dataset, expected to gives better response for simulating the hyper local landslide. However, corrections still need to be done using 3D GCPs obtained from additional RTK survey. Although, overall slope surface $(\theta)[°]$ is not change significantly due to the difference in slope's bench height.

In the other hand, for a scientific survey, aerial mapping can be considered promising tools for a topographical survey due to high coverage, their efficiency and cost effective properties. However, improvements are need be done for this method, to obtain better quality terrain data for hyper local spatial planning, deformation or landslide event monitoring. Comparison between 2-meter resolution rtkDTM with 0.5-meter resolution uavDTM for their cost efficiency also has been done, in this study the UAV is not equipped with RTK receiver. Thus, uavDTM still need additional 3D GCP information to provide correction. Results of this study can be used as recommendations for the use of 3D ground control points with good quality to produce high quality maps with efficient and effective efforts in the future, especially involving unmanned aerial vehicle mapping. Furthermore, this information also emphasizes the urgency for updating topographic information with higher quality, in order to create better spatial planning and perform disaster management in the future, since the disaster event are insignificant in size.

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