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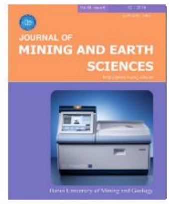

3D slopes stability modeling for landslide early warning design at Halong city area

Ha Viet Nhu [1*], Binh Van Duong [1], Hong Dang Vu [2]

[1] *Faculty of Geosciences and Geoengineering, Hanoi University of Mining and Geology, Vietnam*
[2] *Vietnam Institute of Geosciences and Mineral Resources, Hanoi, Vietnam*

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ABSTRACT

Landslides are a very common form of natural disasters in Vietnam with diverse scales, complex triggers, and mechanisms. The greatest objective of the landslide studies is zoning and predicting, and therefore, a combination of appropriate, modern study methods are needed. This study presents the results of time-variant slope stability analysis by combining the limit equilibrium method with geospatial data. The slope stability analysis was conducted at six times, with the variation of pore water pressure ratio, ru corresponding to the change of rainfall in the study area. The results of the study have helped restore the landslide scenario in Cao Thang, Ha Long, and evaluated the landslide trigger. This model can also be used for slope stability analysis and landslide prediction for early warning, management, and urban planning.

1. Introduction

Landslides are a natural disaster that occurs due to the geodynamic processes, causing instability of the slope, moving material on the slope, destroying everything involved on the way of them (Cruden & Varnes, 1996). Urban landslides are a new trend of natural disasters, growing in scale and complex in the mechanism. Therefore, it is necessary to have identification methods, zoning landslide risks to have early warning solutions and reasonable urban planning. The methods of landslide prediction can be divided into three categories: empirical, statistical, and physical methods (An, Kim, Lee, & Tran, 2016).

For shallow landslide prediction, many studies have built and developed physics-based mathematical models, describing physical processes through mathematical equations. This method integrates the analysis of space-time stability, so it overcomes the disadvantages of empirical and statistical methods. There are some models of shallow landslide prediction such as the Distributed, Physically Based Slope Stability Model (dSLAM), (Wu & Sidle, 1995); the Shallow Landsliding Stability Model (SHALSTAB), (Montgomery & Dietrich, 1994); Stability INdex MAPping (SINMAP), (Pack, Tarboton, & Goodwin,

*Corresponding author
E-mail: nhuvietha@humg.edu.vn

1998); Transient Rainfall Infiltration And Grid-Based Regional Slope Stability (TRIGRS) and Shallow Landslides Instability Prediction (SLIP), (Montrasio & Valentino, 2008); Scoops3D, (E. Reid, Christian, Brien, & Henderson, 2015). Although models of shallow landslide prediction have not been widely applied in Vietnam, there have been studies of Loi et al. (2017), Tran, Alvioli, Lee, and An (2018), Tran, Lee, An, and Kim (2017), Tran, Lee, An, and Thu (2016).

This study used the Scoops3D model to analyze landslide stability for an area in Cao Thang, Ha Long. The analytical results help restore the landslide scenario in the study area. The safety factor distribution map, FS, has a predictive significance for slope stability under the impact of rain, as a basis for designing a landslide early warning system for this area.

2. Study area

Ha Long city (Figure 1) is the economic and political center of Quang Ninh province. The study area has an area of nearly 0.06 km^2, located in hamlet 4, Cao Thang Ward, Ha Long City. This is an area with low mountainous terrain alternating with small, narrow valleys; the terrain elevation ranges from 15.5 m to 92.5 m (Figure 2). The landslide occurred on the night of July 27 to the dawn of July 28 in a mountain of group 44, hamlet 4, Cao Thang ward, Ha Long city, causing very serious consequences. The shape of the sliding surface is shown in Figure 3.

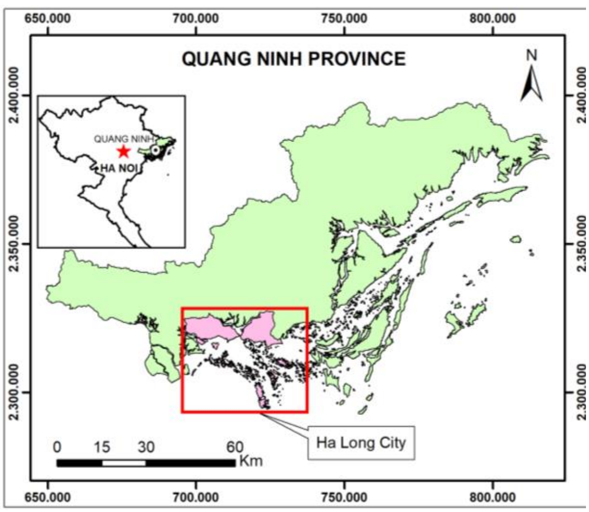

Figure 1. Location of Ha Long city.

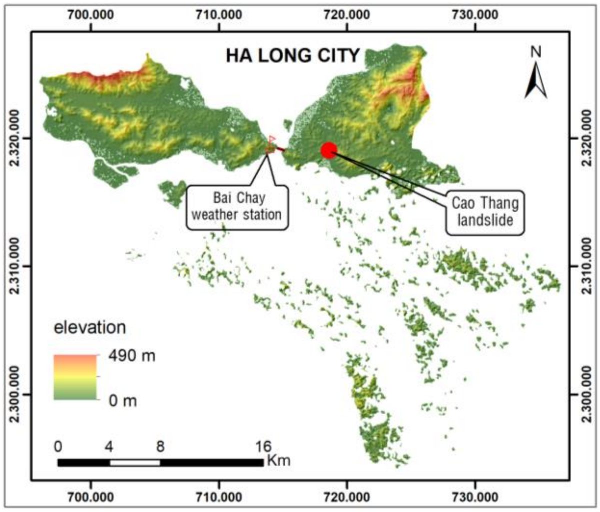

Figure 2. Location of study area on DEM.

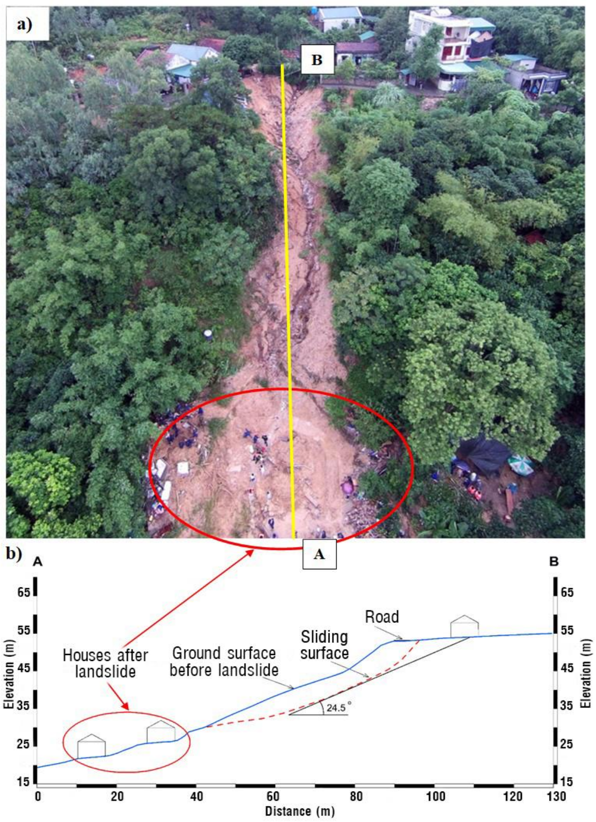

Figure 3. UAV image (modified from Zing) (a) and A-B longitudinal cross-section of Ha Long landslide (b).

This is a shallow landslide in the soil layer, which is weathered product from the bedrock of the Hon Gai formation ($T_{3n-r}hg_1$).

In the study area, there are weathered products from Triassic rocks of Hon Gai formation ($T_{3n-r}hg_1$), such as Sandy clay mixed with grits, stiff to hard, reddish-brown, dark grey (Figure 4). Based on the field survey results, this layer has a thickness of 1.2 m to 5.0 m.

Ha Long has a tropical coastal climate. The average rainfall is about 1849 mm/year, mainly concentrated in July and August (Department of Natural Resources and Environment of Quang Ninh province, 2016). The Bai Chay weather station (Ha Long) recorded a total of 387 mm of rainfall between August 27 and 28, 2015. Especially, the accumulated rainfall for 12 hours from 19:00, July 27 to 07:00, and July 28 was 296 mm (Figure 5).

Figure 4. Engineering geology diagram of the study area (Vu Xuan To et al., 2014) and images of soil and rock in the study area.

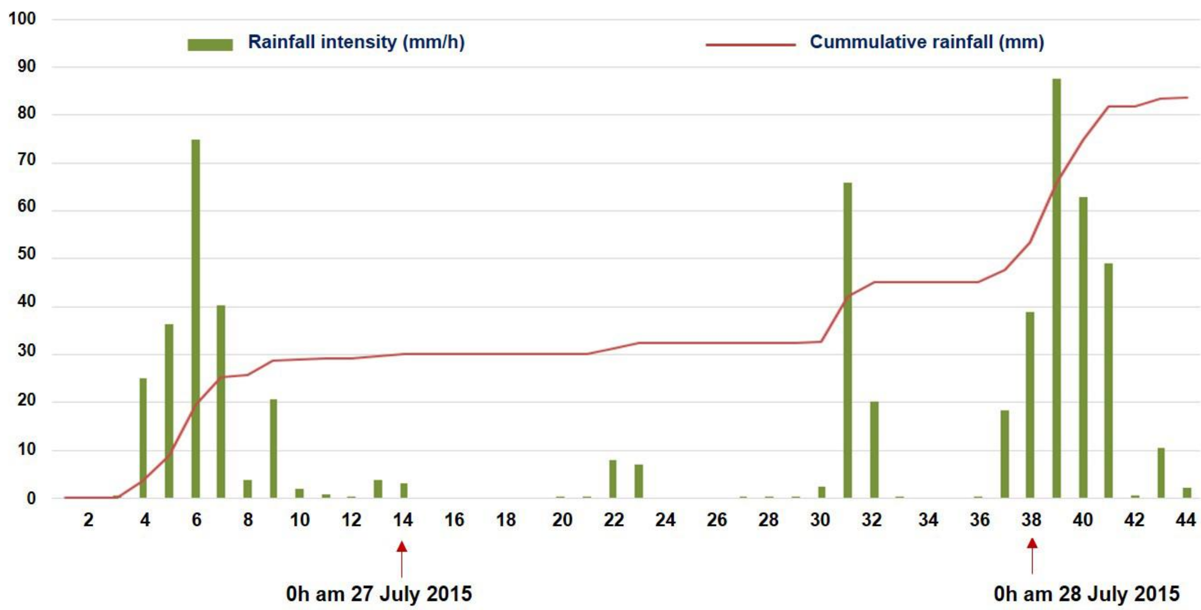

Figure 5. Time series (hourly) of rainfall intensity and cumulative rainfall Bai Chay weather station - Ha Long city.

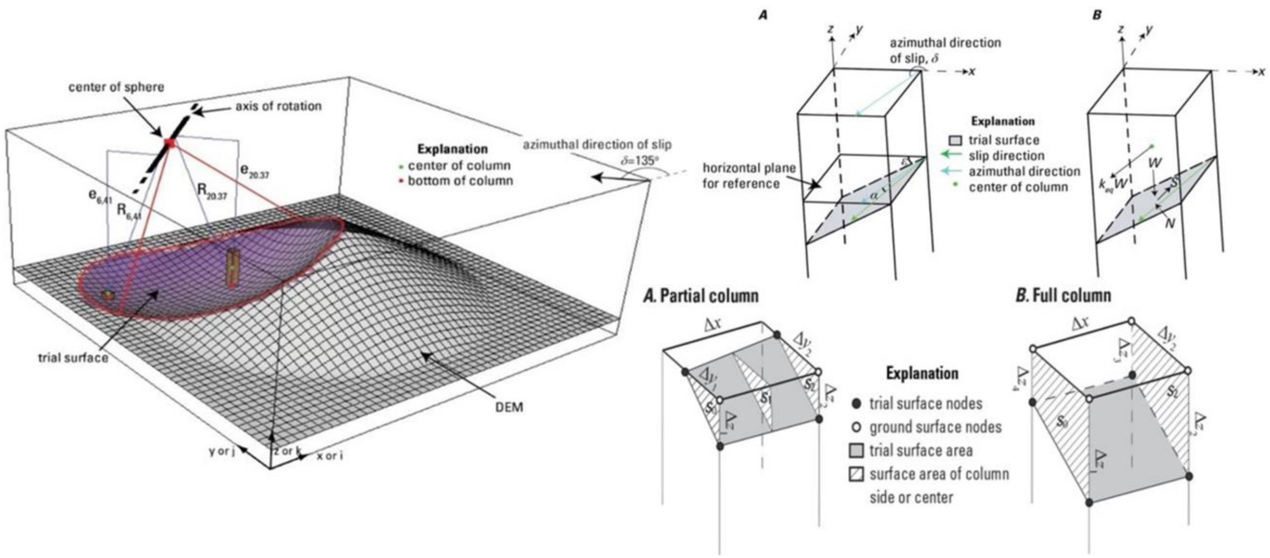

Figure 6. Schematic diagram of the Scoops3D calculation model on DEM grid and 3D "column analysis" method. (E. Reid et al., 2015)

3. Methods

Based on Figure 3 and the results of the field survey, we determined that this is a shallow sliding mass in a homogeneous soil layer above the hard rock layer, and the sliding surface has an arc shape.

On the other hand, in fact, it is not possible to predict the shape of the sliding surface; in addition, the Scoops3D model has been used in many studies of shallow landslides. The Scoops3D model uses a three-dimensional column analysis on the potential spherical sliding surface to predict landslides in any direction on that sphere.

Therefore, to analyze time-dependent slope stability, a simulation model for the study area was created by Scoops3D using the 3D "column analysis" limit equilibrium analysis method.

Scoops3D (E. Reid et al., 2015) uses the 3D "column analysis" limit equilibrium analysis method to compute the stability of potential sliding masses in a digital topography, which is denoted by a digital elevation model (DEM), with a potential spherical sliding surface, the center of the sphere may be any point above the DEM (Figure 6). Scoops3D searches and analyzes slope stability through the calculation of safety factors, FS, of millions of potential three-dimensional (3D) landslides at different depths on the DEM grid (E. Reid et al., 2015). At the base of each DEM column, the slope of a trial surface through the center of each column is calculated by taking partial derivatives ($\frac{\partial z}{\partial x}$ and $\frac{\partial z}{\partial y}$) of the sphere equation:

$$\boldsymbol{R^2 = x^2 + y^2 + z^2} \qquad (1)$$

Where x, y, and z are orthogonal coordinates relative to the spherical center and determined in space by DEM. The true dip of the trial surface, ε, and apparent dip in the direction of slide movement, α is calculated by the following equation:

$$\boldsymbol{\varepsilon = cos^{-1}\left[1/\sqrt{1 + (\partial z/\partial x)^2 + (\partial z/\partial y)^2}\right]} \qquad (2)$$

$$\alpha = tan^{-1}[(\partial z/\partial x)cos\delta + (\partial z/\partial y)sin\delta] \qquad (3)$$

Where δ is the azimuth angle of the sliding direction.

The weight of the columns, W_c, will also be calculated based on the column volume (V_c) and the unit weight of material changes with depth:

$$\boldsymbol{W_c = \int V_c\gamma(z)dz} \qquad (4)$$

Where γ is the unit weight of the material, which can vary with depth, z.

Scoops 3D applies the linear Mohr-Coulomb failure theory to compute the shear strength of soil, s, on trial surfaces:

$$s = c + (\sigma_n - u)tan\varphi \qquad (5)$$

Where c is the cohesion, φ is the internal friction angle, σ_n is the normal stress, and u is the pore water pressure of the soil on the shear surface. This rule may be suitable for many standard geotechnical analyzes, including total stress (where $u = 0$) and effective stress ($u \neq 0$), as well as undrained analyzes ($\varphi = 0$).

The Scoops 3D model computes a safety factor, FS, for trial surfaces, using moment equilibrium, where FS is the ratio of the average shear strength, s, to shear stress, τ:

$$FS = \frac{s}{\tau} \quad (6)$$

In equation 6, FS < 1 represents the instability of the analytical area; when FS ≥ 1, the slope is in limited equilibrium. In general, the safety factor is determined by the equation:

$$F_{s3D} = \frac{\sum R_{i,j}\left[c_{i,j}A_{h_{i,j}} + \left(W_{i,j} - u_{i,j}A_{h_{i,j}}\right)tan\varphi_{i,j}\right]/m_{\alpha_{i,j}}}{\sum W_{i,j}\left(R_{i,j}sin\alpha_{i,j} + k_{eq}e_{i,j}\right)} \quad (7)$$

Scoops 3D analyzes landslide stability using the 3D extension of the Ordinary method (Fellenius) or the Bishop's simplified method.

Ordinary (Fellenius) method: Use moment equilibrium to calculate stability on a 2D slip circle. Scoops3D has developed this method, which analyzes 3D columns that integrate the effects of earthquake loads.

The safety factor, FS, is calculated using the following equation (8). Additional details explain the equation (8) are described in E. Reid et al. (2015).

The Bishop's simplified method: This method has been developed as a 2D slice method (Bishop, 1955). Set up 3D for this method (M. Reid, Christian, & Brien, 2000) makes similar assumptions for columns. To simplify the conditions, the Bishop's safety factor is computed by the equation (9). Additional details explain the equation (9) is described in E. Reid et al. (2015).

$$FS = \frac{\sum R_{i,j}\left[c_{i,j}A_{i,j} + \left(\frac{cos^2\alpha_{i,j}}{cos\varepsilon_{i,j}}\left[W_{i,j} - k_{eq}W_{i,j}tan\alpha_{i,j}\right] - u_{i,j}A_{i,j}\right)tan\varphi_{i,j}\right]}{\sum W_{i,j}\left(R_{i,j}sin\alpha_{i,j} + k_{eq}e_{i,j}\right)} \quad (8)$$

$$FS = \frac{\sum R_{i,j}\left[c_{i,j}A_{h_{i,j}} + \left(W_{i,j} - u_{i,j}A_{h_{i,j}}\right)tan\varphi_{i,j}\right]/m_{\alpha_{i,j}}}{\sum W_{i,j}\left(R_{i,j}sin\alpha_{i,j} + k_{eq}e_{i,j}\right)} \quad (9)$$

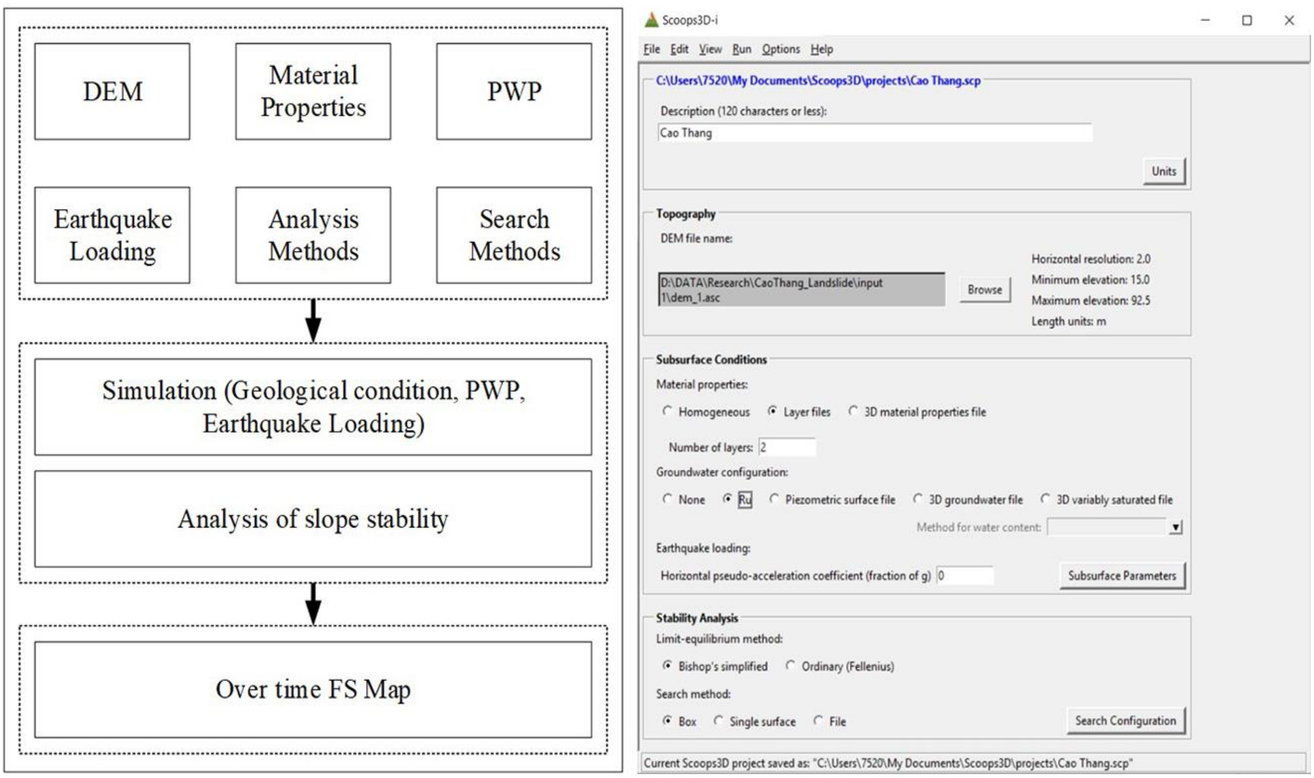

Figure 7. Building analytical model and the interface of Scoops 3D numerical model.

4. Setting analysis model

The model of landslide analysis in Cao Thang and Ha Long areas was built based on topographic settings (DEM), material properties, groundwater configuration, earthquake loading, and search methods. This study uses the Bishop's method to analyze slope stability because of the safety factor, FS analysis by the Bishop's method very closely to the results obtained from the rigorous limited equilibrium methods (LEM) (Hungr, 1987; Lam & Fredlund, 1994; Ugai, 1988). The results of the analysis will give values of FS, areas of potential landslide shown visually on the FS maps.

4.1. Topography

The topography of the ground surface, which denotes the upper boundary of the 3D domain, is represented by the digital elevation model (DEM). The DEM required format of Scoops3D contains an orthogonal array of equal-sized cells, with each raster containing an elevation value. Scoops3D uses a DEM file structured in the Esri ASCII raster format. (E. Reid et al., 2015).

To analyze the stability of landslides in the study area, we selected a 2x2 m digital elevation model (DEM), which was established from data extracted from 1/10,000 topographic map (F-48-83-A-a-2). Raw data from topographic maps are processed by ArcGIS version 10.3 to convert into

4.2. Material Properties

Scoops3D uses 3 types of material properties description for analytical models, such as homogeneous material, layered material properties, and 3D material property distribution (E. Reid et al., 2015).

The analysis model in the study area uses layered material properties, which simulate the displacement of the soil layer on the hard rock layer. Physical - Mechanical properties of the soil layer include unit weight (γ), internal friction angle (φ), cohesion (c). These properties are determined by laboratory tests (Loi et al., 2017). The mechanical and physical properties of the hard rock layer are estimated from our experience.

The soil layer thickness map was created with ArcGIS version 10.3 using a combination of DEM data and a linear interpolation method to determine the thickness of the soil layer according to the slope. DEM data is processed to form a slope map, combining the results of linear interpolation to obtain a soil layer thickness map.

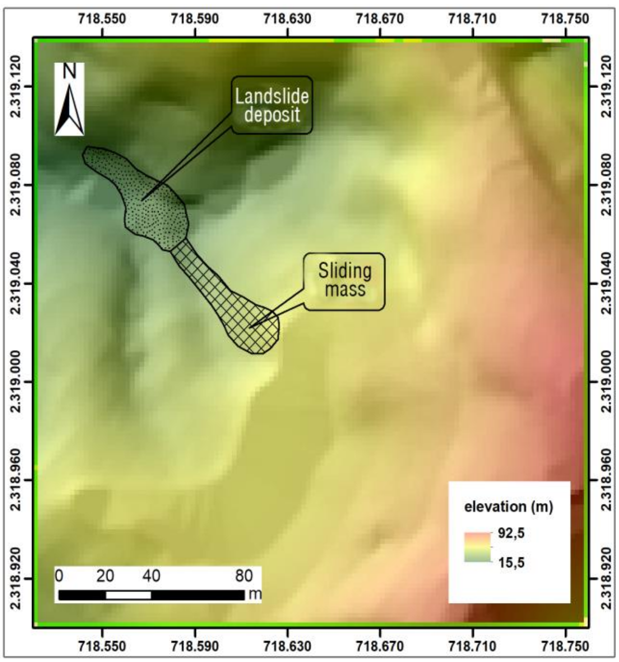

Figure 9. DEM of the study area.

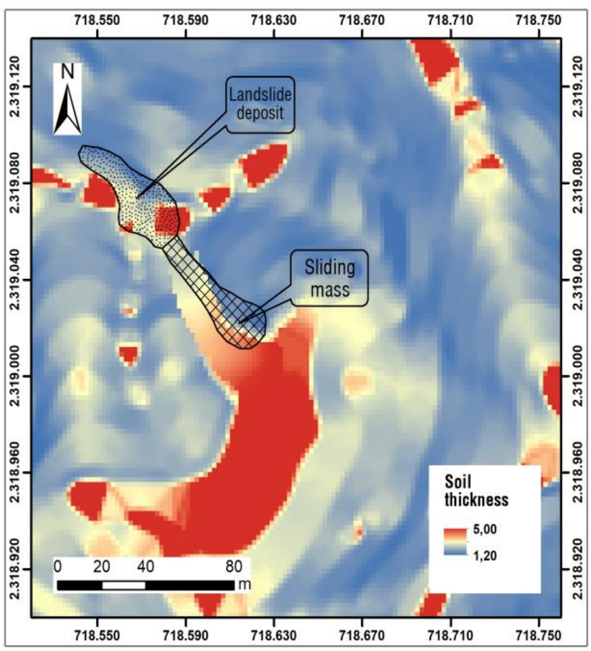

Figure 9. Map of soil thickness of study

Table 1. Material properties for the analytical model (Loi et al., 2017).

No	Property	Symbol	Unit	Layer 1	Layer 2
1	Unit weight	γ	kN/m^3	19.2	24
2	Cohesion	c	kPa	5	150
3	Internal friction angle	φ	Degree	35.6	43

4.3. Groundwater configuration

The PWP is related to the pressure head, h according to the equation:

$$u = h.\gamma_w \quad (10)$$

Scoops3D configures groundwater conditions with options for PWP distribution (E. Reid et al., 2015). Each of these options makes different assumptions in calculating PWP to evaluate slope stability, creating variations in the stability equation used in Scoops3D. In this study, we select "pore water pressure ratio, r_u", to establish groundwater configuration for slope stability analysis. The ratio of PWP, r_u, is defined by Bishop (1955):

$$r_u = \frac{u}{\int \gamma z dz} = \frac{u}{W/A_h} \quad (11)$$

Where γ is the unit weight of the overlaying material. However, since there is no groundwater monitoring station in this area, it is impossible to identify h. On the other hand, in this study, rainfall causes the initial groundwater table to rise, leading to an increase in h. Therefore, we propose to use r_u values based on the calculation results of Loi et al. (2017) using SLIDE model.

4.4. Earthquake Loading

The earthquake or seismic loading was modeled in Scoops3D as a uniform horizontal force ($k_{eq}W$), where k_{eq} is a horizontal pseudo-acceleration coefficient (E. Reid et al., 2015). In this study, because there were no earthquakes before landslides, we set k_{eq} = 0 for the slope analysis model.

4.5. Search in 3D domain

Scoops3D searches on a lot of trial surfaces because the minimum safety factor needs to be determined for each DEM cell, and the variation in topography, material properties, groundwater

Table 2. Time of slope stability analysis and PWP ratio, ru (Loi et al., 2017).

No	Time of slope stability analysis	r_u
1	0h, July 26, 2015	0.00
2	0h, July 27, 2015	0.19
3	18h, July 27, 2015	0.21
4	0h, July 28, 2015	0.23
5	1h, July 28, 2015	0.30
6	3h, July 28, 2015	0.41

affects the safety factor. When the search is complete, Scoops3D creates a 2D map-view grids of the minimum factor of safety values (E. Reid et al., 2015).

The search configuration includes size limits for potential landslide areas and determines the model's search extent. The horizontal search extent of the model is the same as the extent of the study area. The extent of vertical search from 15m to 150m.

5. Results

The safety factor (FS) distribution maps are the results of time-dependent slope stability analysis, shown in Figure 10, Figure 11, and Figure 12. We also compared the analysis results with the actual landslides in the study area.

FS map includes the range of values: FS < 1; 1 ≤ FS < 1.25; 1.25 ≤ FS < 1.5; and FS ≥ 1.5. These ranges are indicated by corresponding colors on the map.

The slope stability analysis was conducted from 0h July 26, 2015 to 03h July 28, 2015 at 6 times. The analysis results show the change of FS over time, corresponding to the change of rainfall.

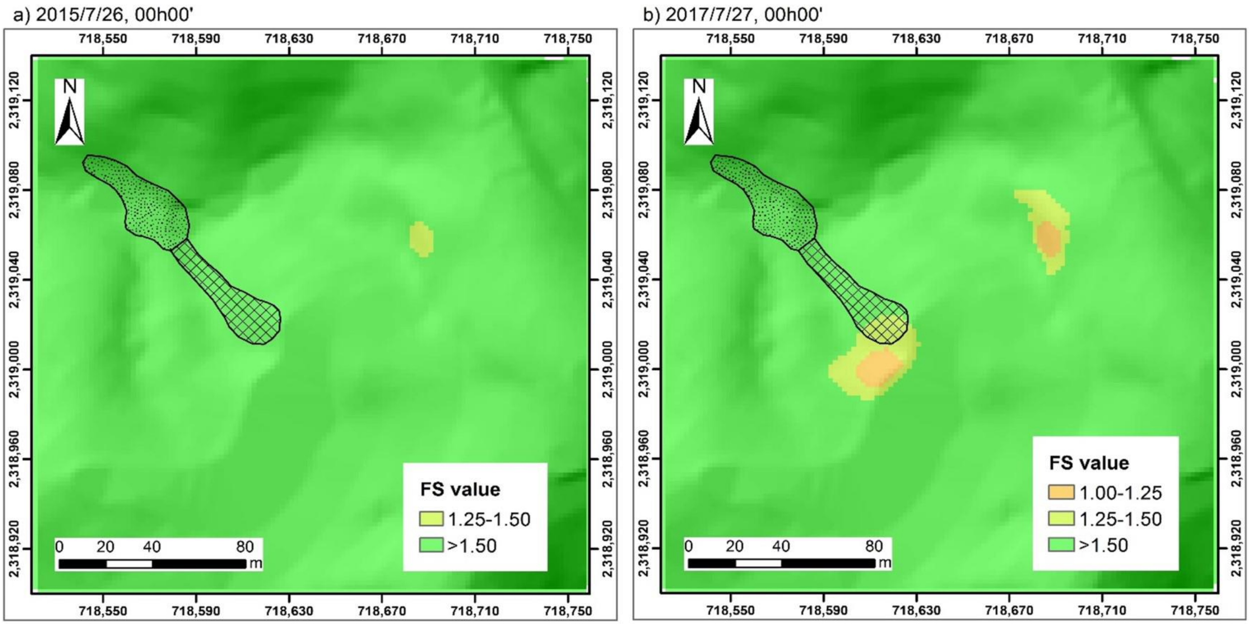

Figure 10. Results of the slope stability analysis from 0h July 26 (a) to 0h July 27 (b).

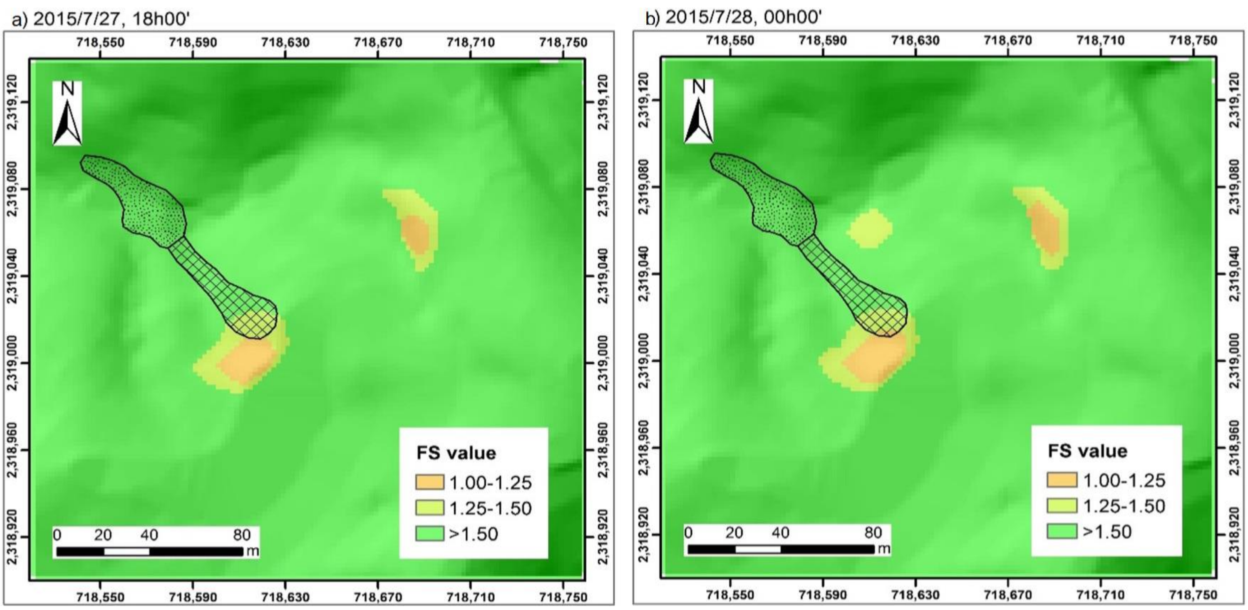

Figure 11. The results of the slope stability analysis from 18h July 27 (a) to 0h July 28 (b).

The FS maps from 0h July 26 to 00h July 27 indicate that no grid cells are in an unstable state. Potential instability points appear on the FS map (Figure 10), corresponding to the increase in rainfall in the study area.

The FS map from 18h July 27 to 00h July 28 still shows stability in grid cells. However, the density of potential instability points increases (Figure 11).

In the short time period from 1h to 3h on July 28, there was a rapid increase in potential instability points. The grid locations with the highest potential for landslides (FS <1) are shown in Figure 12b.

Potential instability locations are mainly in the center, north, and some places in the southeast of the FS map.

The change in the topographic surface of the study area after the landslide is shown in Figure 13. At the same time, we determined the location of the landslide and the influence are of the sliding mass on the GE image.

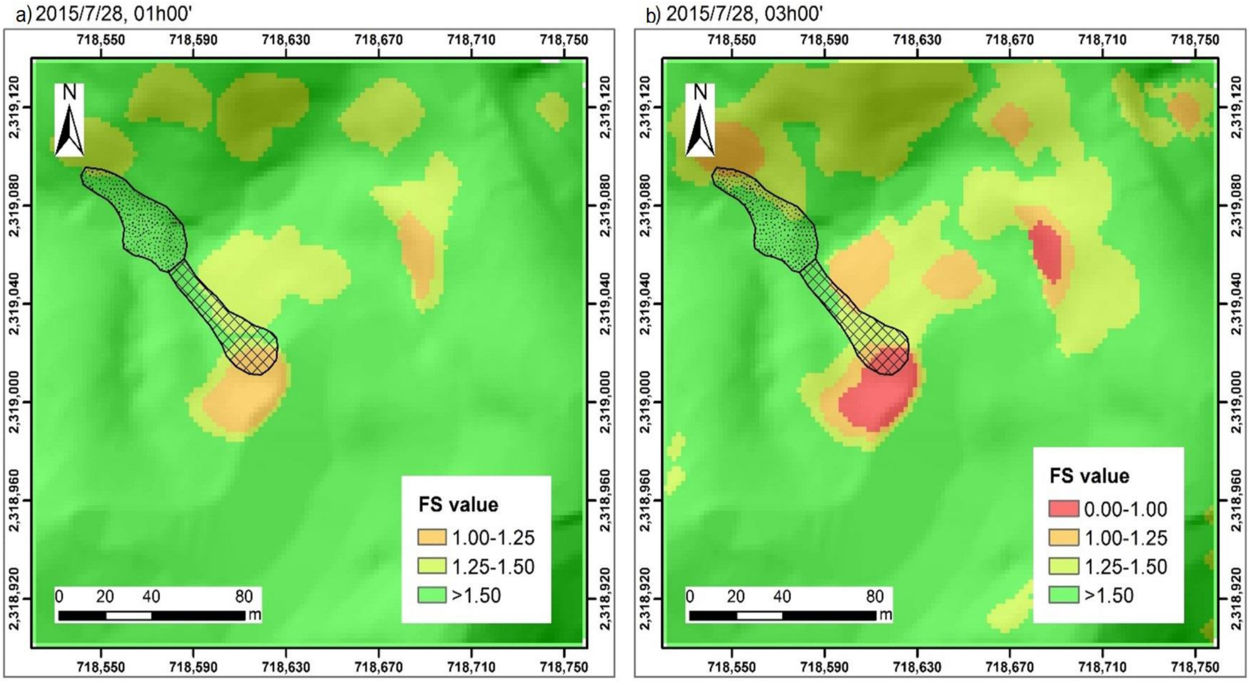

Figure 12. Results of slope stability analysis from 1h on July 28 (a) to 3h on July 28 (b).

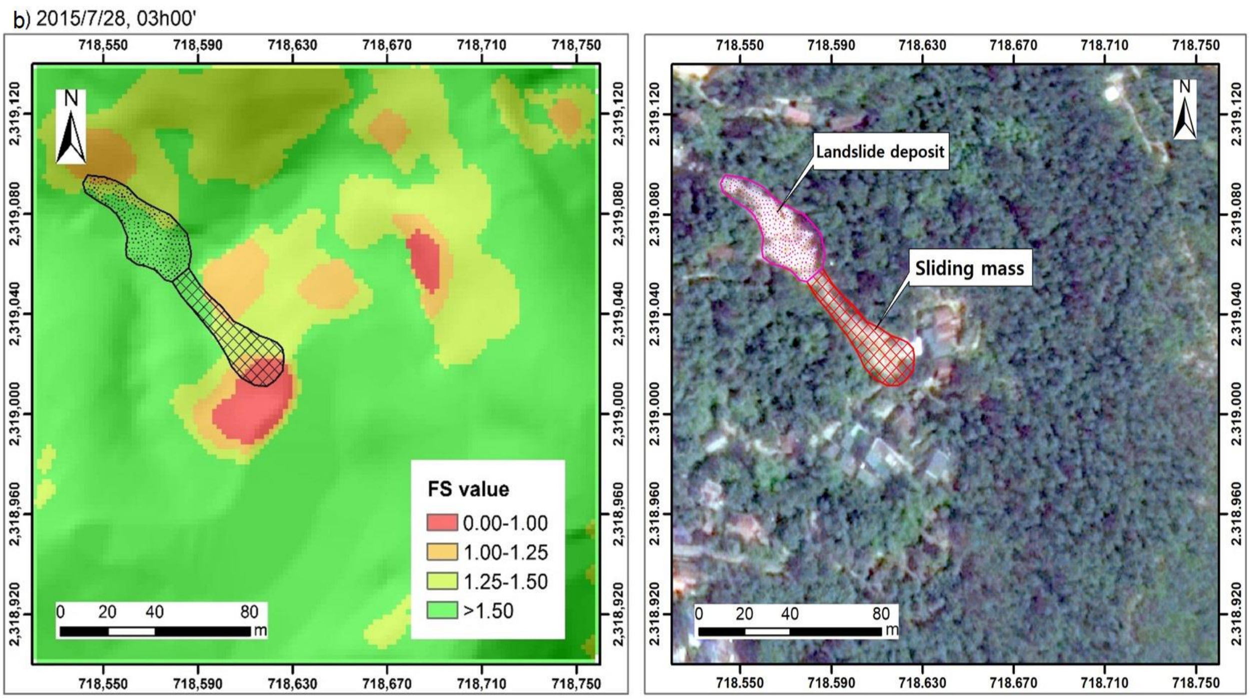

Figure 13. FS map (3h, July 28, 2015), GE image after the landslide (August 22, 2015).

The analysis results show that potential landslides are distributed in densely populated areas close to the slopes, thick weathered soils, high permeability (based on the DEM map of the study area). These results are consistent with the theory of slope stability.

Based on the analysis results, we propose the locations of landslide monitoring system in the study area as follows:

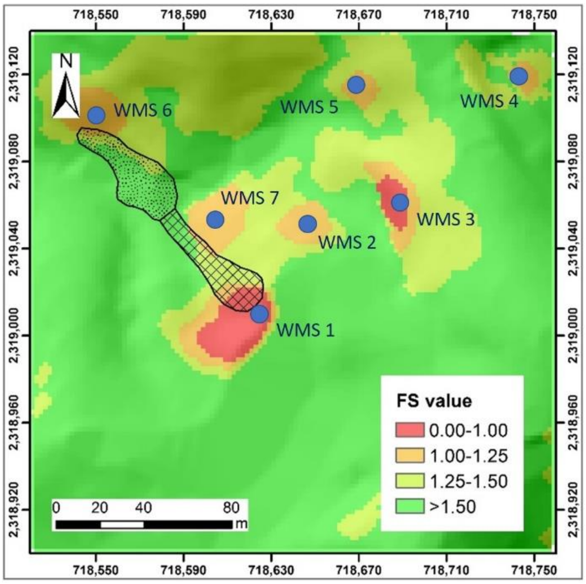

Figure 14. Distribution map of landslide monitoring system locations (WMS).

6. Discussions

The Scoops3D model analyzed slope stability in the study area over time and changes in rainfall based on input data. Research results have shown that the cause of landslides triggered in the study area is due to heavy rain in a short time, increasing the pore water pressure in the soil, reducing shear strength, increasing the weight of soil on the slope. The analysis has proved that by decreasing the safety factor, FS over time.

The analysis results are relatively consistent with the actual landslides in the study area. Therefore, this model can be used in predicting slope stability and orienting the construction of landslide early warning system.

The degree of accuracy of the analytical results depends on the input data. The establishment of the data is complex, requiring users to have meticulous surveys for the research area and apply information technology in the data processing. Especially, rainfall parameters forecasting for the model is very important as this is a factor that triggering landslides.

Because of the use of conventional limited equilibrium analysis methods, Scoops3D has the typical disadvantages of these methods. For example, the assumption of mass is a rigid failure masses with a uniform safety factor along all sections of the pre-defined potential slip surfaces (Duncan, Wright, & Brandon, 2014; Krahn, 2003). Therefore, it is possible to combine this model with other models (e.g., TiVaSS or Trigrs) to increase the predictive efficiency and accuracy of the analysis results.

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