Development of Web-based Mapping Program for Spatially Distributed Slope Stability Analysis

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Abstract. Rainfall-induced landslide is considered as the deadliest disaster in Indonesia. Many efforts have been made to mitigate the landslide, such as landslide hazard mapping in the landslide-prone area. The traditional landslide mapping is commonly conducted using scoring method which is based on field investigation and data collection. The underlying mechanical theory of this method is vague. In this study, a web based slope instability mapping program was developed using well established geotechnical theory in slope stability. This program is based on infinite slope method. To calculate the infiltration depth, Green-Ampt model was employed. In order to investigate performance of the program, a case study is conducted in Gerdu, Karanganyar, Central Java, Indonesia. The result shows that the program can map the spatial distribution of the safety factor nicely. The program also works well with the raster and vector data.

1. Introduction

Landslide is considered as the deadliest hazard in Indonesia. The Indonesian National Disaster Management Agency (BNPB) recorded 3924 landslides disasters in Indonesia within ten years (2008-2017) \cite{1}. The locations of the events spread across various regions in Indonesia, mostly in Central Java, West Java, and East Java. There are several notable landslide events in recent years, i.e. 2017 Ponorogo Landslide, 2006 and 2014 Banjarnegara Landslides, etc. On 1st April 2017, landslide taken place in Banaran, Ponorogo, East Java. Around 25 people died due to the catastrophe. In 2006 and 2014, two deadly landslide hit Banjarnegeara, Central Java. While the 2006 landslide caused at least 76 death, the 2014 landslide buried 108 people within five minutes. Moreover, at least there are a thing in common within these catastrophes, the landslide was preceded by heavy rainfall.

Another devastating landslide is 2007 Karanganyar Landslide. In this event, landslides hit nine sub-districts in Karanganyar at the same time on 26\textsuperscript{th} December 2007, i.e. Tawangmangu, Ngargoyoso, Kerjo, Jenawi, Jumapolo, Jaten, Metesih, Jatyiyo, and Karanganyar City. The landslides killed 71 people and destroyed dozens of houses after overnight torrential rain. Thus, landslide-prone area mapping is needed.

In this research a web-based landslide application was developed to analyse the stability of the slope. There are plenty methods for mapping landslide-prone area, such as scoring, statistics, physics method, etc. Geotechnical mapping method which is belong to physics method was utilized. The infinite slope method was employed to assess the stability of the slope. In this paper, safety factor ($SF$) measures degree of landslide susceptibility. Moreover, the values of $SF$ were plotted in a map to construct slope failure susceptibility map.
2. Landslide hazard mapping

Broadly speaking, landslide hazard map can be created using two methods: qualitative [2-3] and quantitative [4] method [2,5]. In qualitative method, judgment from field observation plays an important role [6]. Throughout the field observation and data collection, several factors affecting slope instability are listed. The next step is to weight and score the slope instability factors. It means different results may arise from different persons. Thus, the method tends to be subjective [6]. The quantitative method comes to overcome this problem.

In quantitative landslide hazard mapping, there are two well-known methods can be used: statistical [4] and geotechnical method [6-7]. Statistical method uses statistical analysis to obtain the relationship between influencing factors and the degree of stability [6]. Geotechnical method can employ both deterministic and probabilistic analysis [6]. Deterministic analysis relies on mechanic analysis that considers both strength parameters and mechanical equilibrium. Thus, this method is more reasonable than statistical method [8]. This study used geotechnical method for slope instability mapping.

3. Infiltration model

The Green-Ampt model [9] is 1D infiltration model and assumes the water content and suction are distributed uniformly in both saturated and unsaturated part. At the interface between saturated and unsaturated part there is sudden abrupt change in the water content and the suction called wetting front. In order to make the concept applicable in both before and after ponding, [10] modified the equation to determine ponding time under steady rain. Later, [11] proposed modified Green-Ampt model to take account of surface inclination. According to [11], cumulative infiltration at ponding time $F_p'$ (cm) and time of ponding $t_p$ (hours) can be obtained using equation (1) and (2):

$$ F_p' = \left[ \psi \left| \theta_s - \theta_i \right| \right] \left( \frac{p \cos \alpha}{K_s} - \cos \alpha \right) $$

$$ t_p = \frac{F_p'}{p \cos \alpha} $$

with $p$, $\psi$, $K_s$, $\alpha$, $\theta_s$, and $\theta_i$ are hourly precipitation (cm), suction (cm), saturated hydraulic conductivity (cm/hour), inclination angle (degree), saturated water content, and initial water content, respectively. The cumulative infiltration $F'$ at time $t$ can be estimated using equation (3):

$$ t = t_p + \frac{1}{K_s \cos \alpha} \left[ F' - F_p' - \frac{\psi \left| \theta_s - \theta_i \right|}{\cos \alpha} \ln \left( \frac{F' \cos \alpha + \psi \left| \theta_s - \theta_i \right|}{F_p' \cos \alpha + \psi \left| \theta_s - \theta_i \right|} \right) \right] $$

4. Slope stability

In geotechnical engineering, the slope failure susceptibility is measured by safety factor. In this study, we use the infinite slope method which considers that the sliding plane is parallel with surface plane. Another assumption is that the depth of the sliding plane is very small compared with the length of the slope. In this method, the failure plane can be any discontinue, such as wetting front, interfaces of layered soil, crack, etc. We only considered wetting front as potential failure plane in this paper and neglected layer interface, crack, etc. We also assumed that the pore water pressure in saturated layer is proportional to the depth. Thus, the safety factor of the slope under infiltrated water is estimated using equation (4):
\[
SF = \frac{c'}{\gamma_{sat} z_w \sin \alpha \cos \alpha} + \frac{\gamma' \tan \gamma_{sat} \tan \alpha}
\]

with \( c, \phi, z_w, \gamma', \gamma_{sat}, \) and \( \alpha \) are cohesion (kN/m\(^2\)), internal friction angle (degrees), depth of wetting front (m), effective soil density (kN/m\(^3\)), saturated soil density (kN/m\(^3\)), slope angle (degrees), respectively.

5. Programming

In order to developed web-based application for slope instability analysis and mapping, we used HTML markup, CSS, and Javascript as language. The HTML markup was used as a container of the displayed data. A pure HTML web is relatively ugly. To beautify the web, CSS is needed. CSS helped us to control the display. Finally, the Javascript was devoted to compute and display the data. There are many libraries in Javascript which can be used to solve various problems. In our case, Javascript was used to develop a module to compute the stability of slope.

Figure 1 shows the flowchart of the program we developed in this study. Our program consists of three different parts. First part is mapping library and the second part is input library. The last part is stability module to compute safety factor. There are another files outside the program which is required, i.e. the input data. We stored the input data of the stability module in a grid format file, i.e. ASCII grid file. Input data consist of several maps, i.e. gradient, cohesion, internal friction angle, and wetting front map. The input data are prepared outside the program. The gradient map can be prepared using a self-developed code or a popular GIS program. Although coding the gradient module is very easy, we utilized the GRASS GIS to prepare the gradient map. The rest of the input maps are also prepared using GRASS GIS.

To display the data in the map, we need a Javascript library having capability to present the output onto map interactively. Due to its simplicity, Leaflet was utilized in this study (see Figure 1). Leaflet is Javascript library to develop an interactive map. In addition, leaflet is cross-platform, thus application developed using this library is work well in many platform, such as mobile and desktop platform. Leaflet is a small size library, but very powerful. There are plenty of plugins in leaflet which make our work easier.

Before we can present the data in a map using leaflet library, we have to read the ASCII grid file first. This job is handled by the second part of the program, i.e. L.CanvasLayer.DEM (see Figure 1). L.CanvasLayer is a Leaflet’s plugin developed by the first author to work with the ASCII grid data.
This plugin is derived from another Leaflet’s plugin called L.CanvasLayer. L.CanvasLayer provides canvas to draw on top of the Leaflet map. Built on top of L.CanvasLayer plugin, L.CanvasLayer.DEM extends its functionalities, such as reading ASCII grid file, presenting DEM data in the map, displaying graticules, etc. There are two distinct ASCII grid formats, ESRII and GRASS GIS ASCII grid format. The difference of those two formats is laid on the header of the stored data. The L.CanvasLayer.DEM can read both of ESRII and GRASS GIS ASCII grid file. After reading the file, the data are presented in the map and sent to the stability module to compute the SF. This time the SFs are not stored in a file, but directly redirected to the L.CanvasLayer.DEM plugin to be displayed in the map. We can choose the color scheme of the raster map using L.CanvasLayer.DEM plugin. Most of the time, we also want to add graticules in our map. Fortunately, L.CanvasLayer.DEM comes with the ability to generate graticules.

The SF module was developed to compute the degree of stability of the slope. We implemented infinite slope stability model in this module. Other slope stability methods, such as depth average and finite slope stability, can be implemented as well. In GIS-based implementation, infinite slope stability method mostly is implemented in 3D. The idea is to model each cells of the raster/grid data as 3D-column. The depth average method is based on Shallow Water Equation (SWE). To implement depth average slope stability method, we need to solve the equation using numerical method, such as finite difference method and finite volume method. We reserved those methods for the further study.

Unlike finite slope stability and depth average method, infinite slope stability method is relatively easy to be implemented. To implement the method, we need to iterate through all the cells in the grid data. In each cell, we compute the SF using equation (4). The rest of the process is to display data which is handled by L.CanvasLayer.DEM plugin.

In addition to the three main components shown in the figure 1, there are several helper modules and plugins to decorate the map. The legend module comes to display the information of the map as map legend. Here we can display the information of the raster data as well as vector data. We also included layer control to decide which layer should be displayed. North Arrow and scale are inserted in the new developed program as well.

Figure 2. The case study area mapped in the developed program.

6. Case study
The study area is Gerdu which is located within 7°38’28.626”S - 7°38’43.370”S and 111°05’30.120”E - 111°05:13.4E. It covers around 22.95 ha area. Gerdu is belong to Karangpandan sub-district, Karanganyar Regency, where in this location there are several major problems, such as slope failure, soil creep, etc. Based on [12], Karanganyar Regency is situated at an average altitude of
511 m above sea level (MASL) and in tropical region having temperature ranges from 22 – 31°C. In Karangppandan sub-district, the average altitude is around 517 m above sea level. Figure 2 shows the case study area for slope failure susceptibility mapping which is mapped using the program developed in this study. From now on, all the maps shown in this paper were generated from our program.

According to figure 2, the study area is composed of dense vegetation, field crop and residential area. Dense vegetation and field crop dominate almost the whole study area. The residential areas are mostly located in the toe of the slope in the left and right of the street. Due to slope failure, most people lived in the right of street had moved to the upper hill. In term of the topography and geomorphology, most part of the study area is classified as steep slope having inclination of 30% - 70%. Very steep slope composes around 6.15% of the total area. The inclination is observed in range of 2.349° (4.103%) to 41.328° (87.938%) and the average inclination is around 36.01%. The soil is composed of brown Mediteran.

A series of data collection was conducted to gather the required data. There are many factors influencing the stability of the slope, such as inclination, soil properties, rainfall intensity, infiltrated water, etc. All of these data were collected as primary data as well as secondary data. The primary data consist of physical and mechanical properties of soil. The primary data of mechanical properties of soil are combined with secondary data collected from the previous study. Other secondary data collected in this work are topographic data and rainfall storm data.

![Figure 3. Elevation map.](image)

The topographic were collected in form of grid data format. The topographic data consist of elevation and gradient data. The grid data format stores z-values in rectangular grid (cells). The z-value can be arbitrary data value, such as elevation, inclination angle, safety factor, etc. In this study, elevation data used was ASTER GDEM which is developed by the Ministry Eco the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA).

In order to analyze stability of the slope using spatially distributed method, we have to create map which contains the distribution of certain parameters across study area, such as inclination, mechanical and hydraulic properties, etc. Thus, it is essential to generate map containing such parameters. Some maps are obtained from primary investigation, secondary data as well as generated from another map. The elevation data was obtained from ASTER GDEM which has cell size of around 30 m × 30 m (see figure 3). According to this map, the highest spot has altitude of 853 m above sea level, while the lowest is around 714 m above sea level. The average altitude is 773.756 m above sea level.

The next step was to process elevation map, thus slope map was obtained. Another data needed is mechanical properties of the soil, such as internal friction angle and cohesion. The mechanical properties were collected from 10 spots which spread across the area. The spots where the data
collected are shown as blue circles in figure 2. Using direct shear test the strength properties were examined. Both of internal friction angle and cohesion data were interpolated, so that we obtained the spatial distribution of such parameters across study area in form of raster maps. Figure 4 shows the spatial distribution of the mechanical properties of the soil in the study area.

![Figure 4](image1)

![Figure 4](image2)

**Figure 4.** Spatial distribution of mechanical properties: (a) cohesion (b) internal friction angle.

Another data needed is the hourly rainfall. Based on the rainfall intensity, the depth of infiltrated water in the soil is calculated. There are many method to estimated the infiltration depth, we used Green-Ampt method [9] as explained in the previous section. The hourly rainfall intensity of 17.219 mm/hour were obtained from [13] which is from the nearest station, i.e. Metesih and Kranganyar station. From the stations, data were in form of daily rainfall intensity which is not suitable for our study. Hourly rainfall intensity was obtained by means of Mononobe method [13]. In this study we assumed the rainfall is constant both spatially and temporally across study area, thus we need not to generate the spatial distribution of rainfall data.

Besides the storm event, in order to estimate the amount of infiltrated water, the suction and the hydraulic conductivity are necessary. These data were obtained by means of correlating the soil texture in table 1. From grain size distribution, the soil texture in the study area can be classified as
silty clay loam. Thus, the suction and hydraulic conductivity are 53.83 cm and 0.2 cm/hour, respectively. However, we didn’t use porosity from the table, but from primary data. The physical properties of soil were assumed constant as well. Based on those data, the spatial distribution of the depths of infiltrated water in the soil were calculated using Green-Ampt method.

### Table 1. Green-Ampt infiltration parameters from various types of soil texture [14-15].

| Texture          | Porosity η | Residual Porosity Θr | Effective Porosity θe | Suction Head Ψ (cm) | Conductivity k (cm/hr) |
|------------------|------------|-----------------------|------------------------|---------------------|------------------------|
| Sand             | 0.437      | 0.020                 | 0.417                  | 9.62                | 23.56                  |
| Loamy Sand       | 0.437      | 0.036                 | 0.401                  | 11.96               | 5.98                   |
| Sandy Loam       | 0.453      | 0.041                 | 0.412                  | 21.53               | 2.18                   |
| Loam             | 0.463      | 0.029                 | 0.434                  | 17.50               | 1.32                   |
| Silt Loam        | 0.501      | 0.015                 | 0.486                  | 32.96               | 0.68                   |
| Sandy Clay Loam  | 0.398      | 0.068                 | 0.330                  | 42.43               | 0.30                   |
| Clay Loam        | 0.464      | 0.155                 | 0.390                  | 40.89               | 0.20                   |
| Silty Clay Loam  | 0.471      | 0.039                 | 0.432                  | 53.83               | 0.20                   |
| Sandy Clay       | 0.430      | 0.109                 | 0.321                  | 46.65               | 0.12                   |
| Silty Clay       | 0.470      | 0.047                 | 0.423                  | 57.77               | 0.10                   |
| Clay             | 0.475      | 0.090                 | 0.385                  | 62.25               | 0.06                   |

After we prepare all the input data needed, we are ready to the next step. These input data are spatial distribution of inclination, cohesion, internal friction angle, and wetting front map (see figure 1). The next step is to compile all of these maps in our new developed program. We used our program to analyze and generate landslide susceptibility map. As we mentioned earlier, the degree of instability of the slope in this study is denoted by safety factor (SF). Thus we mapped the SF as shown in figure 5. We clustered the SF map in three categories as suggested by [16], i.e. stable (SF < 1.07), critical (1.07 < SF < 1.25), and unstable (SF > 1.25). The stable slope means the landslide rarely takes place in the slope, while critical and unstable mean the landslide has ever happen and commonly happened in that place, respectively. However, another stability clustering system can be adopted.

![Figure 5. Safety factor map.](image_url)
According to figure 5, most parts of the study area are stable slope. The Average factor of safety is 3.154. However, in certain locations, there are several regions classified as critical and unstable slope. The critical and unstable region compose around 4.615% of the total study area. Although these regions are relatively small, all of these regions are located in the important area, i.e. road and residential area. Moreover, we can identify that these regions are located in three distinct areas, i.e. north west uphill residential area, south east uphill residential area and east toe slope residential area. For the shake of simplicity, we call these problematic spots as Area A, B, and C, respectively (see figure 5). In Area B and C, there are an opportunity for landslide to destruct the residential area and the road. While in Area A, slope failure can threaten both of uphill and toe slope residential areas.

7. Conclusion
The web-based development of spatially distributed slope stability program is very promising to mitigate landslide in real time. This technology has ability to provide the location of the critical area in a spatial map in opposite to the traditional geotechnical slope stability analysis which offers only the degree of stability of the slope without its location. The developed program is not only able to compute slope instability, it’s also able to present the data in a map nicely. Not only for raster data, the program can display vector data, particularly shapefile data. Furthermore, several features are added, such as graticules, legend, etc. Due to in early stage of development, the program has several drawbacks. Currently the program only offers one method to analyze slope stability, i.e infinite slope method. It means that program is only suitable for limited cases, such as erosion, shallow landslide, soil movement on the interface between two layers, etc. The deep seated and rotational landslide are not supported yet. The 3D slope analysis using finite slope method is reserved for the further study.

Another drawback of the program is its slow run time. For huge area which is include thousands of cells, the calculation time is very long in comparison with program developed with another language such as C++. The slow run time is inherited by the program from the Javascript language. Although Javascript is an attractive language, its run time is relatively slow. Another strategy to speed up the calculation time is necessary. Several options are available to overcome this drawback, i.e. to combine the program written in javascript with C, C++ or python modules. This strategy is also reserved for the further study.

8. References
[1] BNPB 2019 Disaster Data and Information Database (DIBI) Retrieved on January 7, 2019 from http://dibi.bnpb.go.id.
[2] Wati S E, Hastuti T, Widjojo S and Pinem F 2010 Landslide susceptibility mapping with heuristic approach in mountainous area: A case study in Tawangmangu sub district Central Java, Indonesia, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 38(8) 249–252
[3] Sartohadi J 2010 Landslide susceptibility assessment using heuristic statistically method in Kayangan Catchment Kulon Progo Yogyakarta-Indonesia, Int. J. Geoinformatics 6(3) 23-28
[4] Oh H J, Lee S and Soedradjat G M 2010 Quantitative landslide susceptibility mapping at Pemalang area, Indonesia, Environ. Earth Sci. 60(6) 1317–1328
[5] Fell R, Corominas J, Bonnard C, Cascini L, Leroi E and Savage W Z 2008 Guidelines for landslide susceptibility, hazard and risk zoning for land use planning, Eng. Geol. 102(3), 85-98
[6] Xie M, Esaki T and Cai M 2004 A time-space based approach for mapping rainfall-induced shallow landslide hazard, Environ. Geol 46(6–7) 840–850
[7] Xie M, Esaki T and Zhou G 2004 GIS-based probabilistic mapping of landslide hazard using a three-dimensional deterministic model, Nat. Hazards 33(2) 265–282
[8] Zhou G, Esaki T, Mitani Y, Xie M and Mori J 2003 Spatial probabilistic modeling of slope failure using an integrated GIS Monte Carlo simulation approach, Eng. Geol. 68(3) 373–386
[9] Green W H and Amt G A 1911 Studies on Soil Phyics, J. Agric. Sci. 4(1) 1–24
[10] Mein R G and Larson C L 1973 Modeling infiltration during a steady rain, Water Resour. Res. 9(2) 384–394
[11] Chen L and Young M H 2006 Green-Ampt infiltration model for sloping surfaces, Water Resour. Res. 42(7) 1-9
[12] BPS-statistics of Karanganyar Regency 2019 Karanganyar Regency in Figures 2019 (Indonesia: BPS-statistics of Karanganyar Regency) pp 5
[13] Natanhia B R, Hesti R H D and Hadiani R R R 2018 Pemetaan Angka Keamanan Lereng dengan Script Python sebagai Mitigasi Bencana Alam Tanah Longsor Bukit Ganoman, Matriks Tek. Sipil 6(1) 195-204
[14] Rawls W J, Brakensiek D L and Miller N 1983 Green-Ampt infiltration parameters from soils data, J. Hydraul. Eng. 109(1) 62–70
[15] Ogden F L and Saghafian B 1997 Green and Ampt infiltration with redistribution, J. Irrig. Drain. Eng. 123(5) 386–393
[16] Bowles J E 1979 Physical and Geotechnical Properties of Soils, International Student Edition. (United States: McGraw-Hill International Book Company) pp 448