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Run-out distribution of debris-flow materials: case study from some Java landslides

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Abstract. Indonesia is a risk prone country from landslide disasters. The occurrence of landslides followed by the debris flow often make a lot of casualties and very terrible destructions. Accordingly, debris flow modeling of some Java landslides has been conducted in this study to determine run-out distribution characteristics of the debris materials. The concept of debris flow modeling is based on the equations of momentum, continuation, riverbed deformation, erosion/deposition and riverbed shearing stress. From this modeling, it has been indicated the best fit simulation results. In this case, run-out distributions of Pacet landslide at Mojokerto, December 12, 2002 has been properly modeled with a scenario of 0.4 viscosity value for around 5 minutes. At Sijeruk landslide, Banjarnegara, January 4, 2006 run-out distributions have been modeled using viscosity value of 0.45 for 14 minutes 51 seconds. Meanwhile, the modeling for Tenjolaya landslide at southern Bandung, February 23, 2010 with viscosity value of 0.38 shows time needed for debris materials to reach depositional area is estimated for around 12 minutes 37 seconds. From this study, debris flow modeling had given better understandings regarding flow track, velocity and distribution of debris materials from some debris flows in Java.

1. Introduction

As one of the countries located in a tectonically active region, Indonesia naturally has various geological hazards which always appear to be potentially disastrous. Landslide is one of the most common geological hazards mostly occurring at areas having steep to very steep slopes, intensive weathering processes and high to very high rainfall intensity. Landslides in whole or in part can develop into debris flows. The occurrence of landslides which followed by the debris flow often make a lot of casualties and very terrible destructions. Some examples of the debris flow in some areas of Java Island, among others are Cililin Landslide on April 21, 2004 has 15 peoples killed [1], Jember Landslide on January 2, 2006 has 98 died victims [2] and Jemblung Landslide on December 12, 2014 has 139 casualties [3].

Debris flow in general can be defined as mass movements consisting of granular solids, water and air moving as a viscous flow (Varnes, 1978 op cit. [4]). Related to its feature, debris flow consists of three parts, which are the source area, flow track and depositional area of debris materials. This study will focus on modeling the run-out distributions of debris materials found mainly in the plains of the foot slopes. Several landslide events in Java Island, in addition to those described earlier, have been selected as case studies.

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2. Method for debris flow modeling

Debris flow modeling was conducted to determine the run-out distributions of debris materials at the depositional area. This modeling will highly relate to the initial volume of moving materials, viscosity and velocity of flowing materials. In this case, numerical simulation technique with a Graphical User Interface (GUI) was applied using a software which called as Kanako Version 2.00 Debris Flow Numerical Simulator (figure 1) [5].

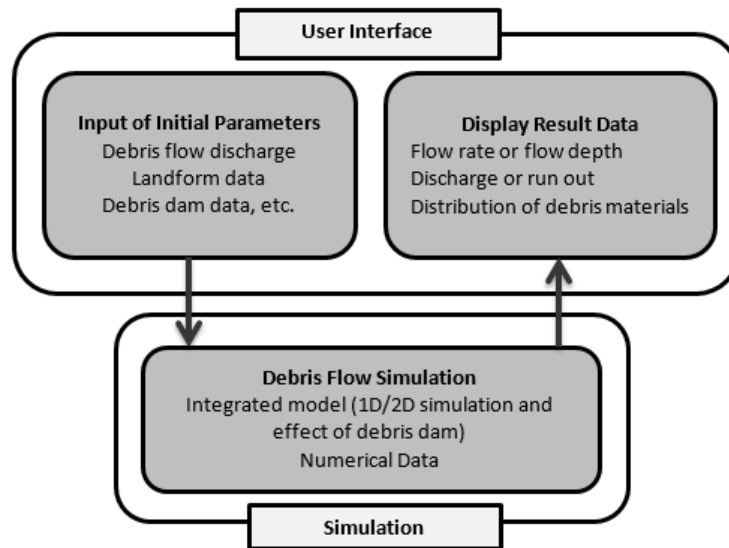


Figure 1. System outline of Kanako Debris Flow Numerical Simulator (after [5]).

The concept of debris flow modeling is based on the equations of momentum, continuation, riverbed deformation, erosion/deposition and riverbed shearing stress developed by Takahashi and Nakagawa [5][6]. As for an example here, the continuation equation for the total volume of debris flow is:

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = \sum_{k=1}^{k=e} i \quad (1)$$

Then, the continuation equation for determining the debris flow of the k-th grade of particle i is:

$$\frac{\partial C_k h}{\partial t} + \frac{\partial C_k hu}{\partial x} + \frac{\partial C_k hv}{\partial y} = \sum_{k=1}^{k=e} i_k C_* \quad (2)$$

where h is flow depth, u is x-axis direction flow velocity, v is y-axis direction flow velocity, C_k is the k-th sediment concentration by volume in debris flow, t is time, i_k is the k-th sediment erosion/deposition velocity and C_* is sediment concentration by volume in the movable bed layer.

Meanwhile, sediment concentration of the slope for the equilibrium concentration of debris flow is calculated using Takahasi [6] equation:

$$C_d = \frac{\rho \tan \theta}{(\sigma - \rho)(\tan \varphi - \tan \theta)} \quad (3)$$

where σ is mass density of bed material, ρ is mass density of liquid, φ is internal friction angle, θ is slope angle of river and C_d is concentration of debris flow.

Then, the peak debris-flow discharge is calculated using the following equations:

$$Q_{sp} = 0,01 \times \Sigma Q \quad (4)$$

$$\Sigma Q = \frac{V_{dq} C_*}{C_d} \quad (5)$$

where Q_{sp} is peak of the sediment supply per second (m^3/second), ΣQ is total amount of moveable material (m^3), V_{dq} is volume of the sediment (m^3) and C_* is sediment concentration by volume in the movable bed layer.

Input data parameters in this simulation should be equated in all scenario. These parameters have been obtained based on field conditions, physical property analyses of debris materials, geomorphology conditions and hydrogeological conditions. Therefore, parameters used in this debris flow modeling can resumed as listed in table 1 [6].

Table 1. Parameters used in the debris flow modeling (after [6]).

Parameters	Unit
Simulation duration	second
Calculation time interval	second
Diameter of materials	m
Mass density of bed materials	kg/m^3
Mass density of fluid phase (water, mud and silt)	kg/m^3
Concentration of movable bed	unitless
Gravity acceleration	m/s^2
Coefficient of erosion rate	unitless
Coefficient of accumulation rate	unitless
Internal friction angle	°
Minimum depth at the front of debris flow	m
Minimum flow depth	m
Manning's roughness coefficient	unitless
π (pi)	3.14

3. Results and discussions

Three cases of debris flow in Java Island have been chosen to be numerically simulated using Kanako Version 2.00 Debris Flow Numerical Simulator, which are the December 12, 2002 Pacet landslide, the January 4, 2006 Sijeruk landslide and the February 23, 2010 Tenjolaya landslide.

3.1 The December 12, 2002 Pacet landslide

The Pacet landslide was mainly struck along Dawuhan River, Mojokerto, with the source area of debris materials come from Mount Welirang having a watershed area of around 4.5 km^2 . Rainfalls in the upstream area of the watershed when the incident took place reaches 60 mm, on contrary to at the downstream which only 16 mm recorded. The victims died reached 32 people and dozens more injured [7]. It was assumed that the debris flow occurred due to the natural dam in the upstream collapsed, along with the rain water moving to the downstream.

Mount Welirang is generally composed of lithology of limestone, sandstone, marl and claystone, which mostly in strongly weathered conditions to form a fairly thick residual soils. These lithologies have been identified as debris materials, which flowing from the southward to the north direction,

undergoing a relative change to the northwest. This change of direction due to the altitude on the north side slopes of the Dawuhan River. Because of this change, the debris flow passed to the Pacet hotspot site area.

Debris flow modeling includes morphology of hills with 1 grid representing an area of $8 \times 8 \text{ m}^2$. The viscosity value of 0.4 became the best fit scenario to this debris flow. In this case, the debris materials carried by the water flow have a relatively small number, so that this debris flow quite resembled to debris flood or water rich flood-like landslide. Figure 2 shows the distribution of debris flow materials seen from the northwest. Results of the modeling indicated that the debris materials flowing along the flow track reached a speed of 19.8 km/h. Volume of the materials were estimated to reach $42,445 \text{ m}^3$ with a speed of 7.92 km/h at the depositional area. The debris materials got in the depositional area is estimated for 297 seconds or around 5 minutes.

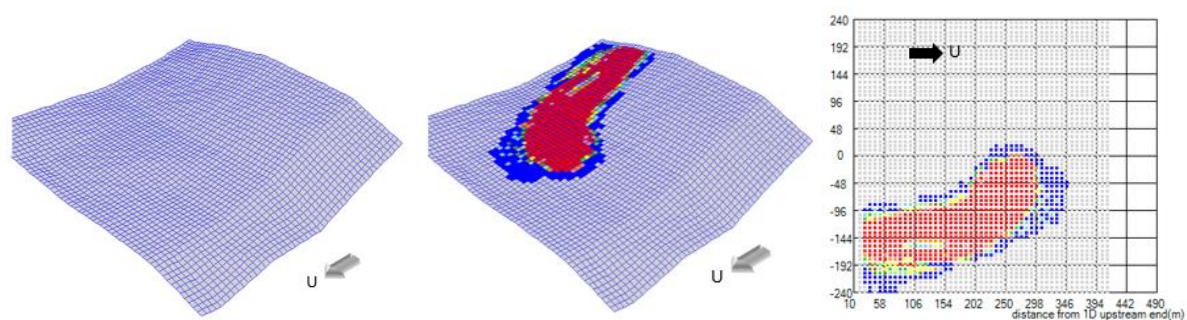


Figure 2. Pacet landslide simulation 2D area (left), run-out distribution of debris materials in 2D area (middle) and corresponding 2D map (right).

3.2 The January 4, 2006 Sijeruk landslide

The Sijeruk landslide was occurred at Mount Pawinihan, Banjarmasin having elevation of around 990 m above sea level. Over this landslide, as many as 77 people were killed and 8 people missing. Mount Pawinihan lithologically consists of lava, pyroclastic breccia and colluvial which found locally. This Sijeruk landslide followed by the debris flow had uniqueness in the flow track, which showed a sharp deflection. This deflection might cause by a ridge hindering the flow track of debris materials which at first flowed southward, turning to the southeast. This happened on steep to very steep slopes of the mountains with a slope angle of around 20° - 60° . The deposition area was in the southeast following the flow track direction and general slope condition.

The best fit modeling of debris flow from the Sijeruk landslide use scenario of 0.45 viscosity value. Figure 3 shows the topographic of the Pawinihan slope with 1 grid representing the $25 \times 25 \text{ m}^2$. The sharp deflection mechanism of flow track direction and the distribution of debris materials in the depositional area can be also seen in figure 3. The volume of debris flow materials might reach $127,735 \text{ m}^3$. When debris material entered the flow track, they moved at a speed of 21.17 km/h. The debris flow materials slowly moved in the deposition area at a speed of 5.4 km/h. The time it taken the debris flow materials to reach the depositional area was 891 seconds or 14 minutes 51 seconds.

3.3 The February 23, 2010 Tenjolaya landslide

The Tenjolaya landslide was occurred at Dewata Tea plantation area of southern Bandung. This landslide had caused 44 people dead, 27 houses and 6 buildings damaged. Furthermore, more than 5 Ha tea plantation were being swept away. It was happened on the mountainous morphology with altitude of between 1200-1500 m above sea level and slope angle of around 3° - 61° , which mainly consisted of pyroclastic breccia and tuff. Thick soils as results of breccia weathering dominated the landslide location having slope angle of around 15° - 30° . The debris materials resulted from the landslide flowed towards the south direction, turned westward and then turned to south direction again. These changes of direction make the existing settlements in southwest area almost entirely swept by debris flow. The total distance

of debris flow reached more than 800 m from the source area. It was recorded from Dewata Rainfall Station that rainfall intensity within February 2010 reached 800 mm.

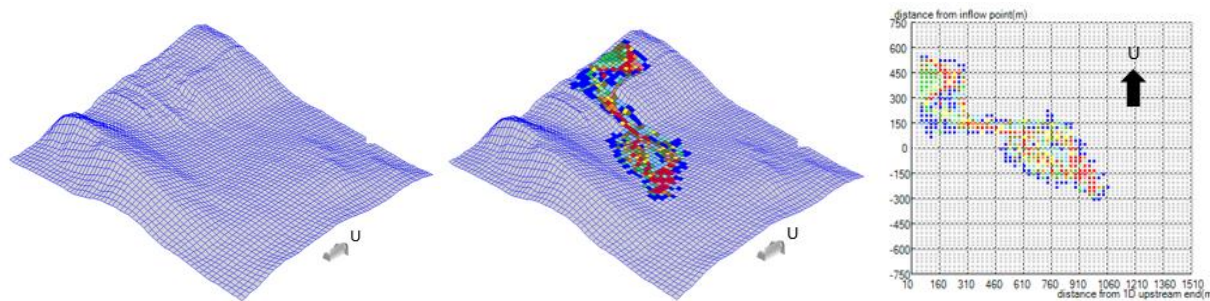


Figure 3. Pawinihan landslide simulation 2D area (left), run-out distribution of debris materials in 2D area (middle) and corresponding 2D map (right).

Figure 4 shows the debris flow feature from southwest direction and topographical condition from 2D simulation of Tenjolaya landslide with 1 grid representing area $6 \times 10 \text{ m}^2$. The scenario viscosity value of 0.38 shows the most closely to the debris flow conditions. Debris materials might flow along flow track with the flow rate reaching to 21.46 km/h and decrease into average flow rate of 2.36 km/h in the depositional area. The volume of debris materials that flow from the source area was estimated at about $31,280 \text{ m}^3$. It seemed that in the deflection area, strong lateral erosion increased supply of the debris materials. Figure 5 shows the run-out distribution of debris flow materials along the flow track into the depositional area at which the settlements located. After passing through the settlement, debris flow is still move relatively toward south. The time needed for debris materials to reach the depositional area is estimated for 757 seconds or 12 minutes 37 seconds.

4. Conclusion

The December 12, 2002 Pacet landslide, the January 4, 2006 Sijeruk landslide and the February 23, 2010 Tenjolaya landslide have been numerically simulated with regard to determine run-out distribution characteristics of debris materials at the depositional areas. The best fit scenario of run-out distributions of Pacet landslide has been properly modeled using a viscosity of 0.4 with a flow rate reaching to 19.8 km/h along flow track and 7.92 km/h in the depositional area. The total volume of debris materials that flowing into the depositional area was estimated about $42,445 \text{ m}^3$ and time needed for debris materials to reach the depositional area is estimated for around 5 minutes. The modeling of run-out distributions of debris materials from Sijeruk landslide has been modeled precisely using with a viscosity of 0.45 and a flow rate reaching to 21.17 km/h. Flow rate of the debris materials decreased into average flow rate of 5.4 km/h in the depositional area in which needed around 14 minutes 51 seconds the debris materials to reach this are. The total volume of debris materials was estimated about $127,735 \text{ m}^3$. Meanwhile, run-out distribution of Tenjolaya landslide was modeled with the best fit viscosity scenario of 0.38. It gave a flow rate reaching to 21.46 km/h along flow track and 2.36 km/h in depositional area. The time needed for debris materials to reach the depositional area was estimated for around 12 minutes 37 seconds with total volume of about $31,280 \text{ m}^3$. In general, the results of these modeling will be very useful for prediction of run-out distributions in some areas which might experience to the similar landslide events.

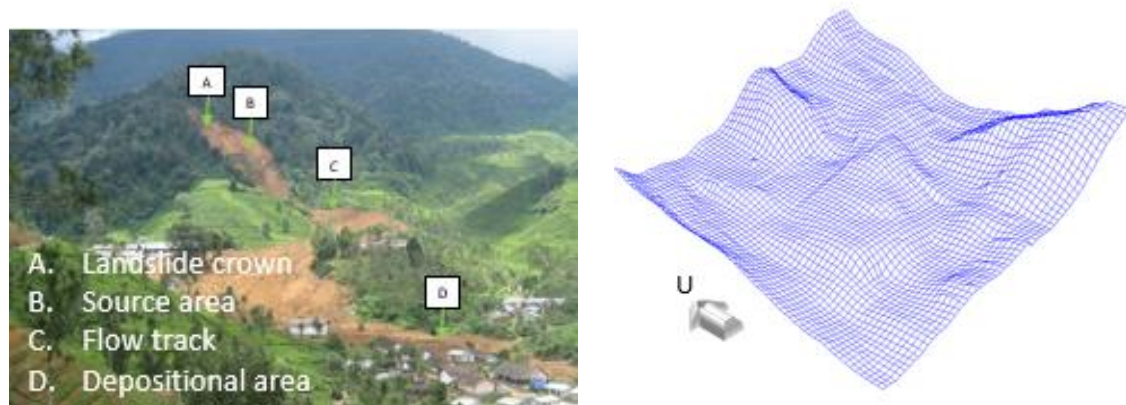


Figure 4. Tenjolaya debris flow feature from southwest direction (left) and topographical condition from 2D simulation (right).

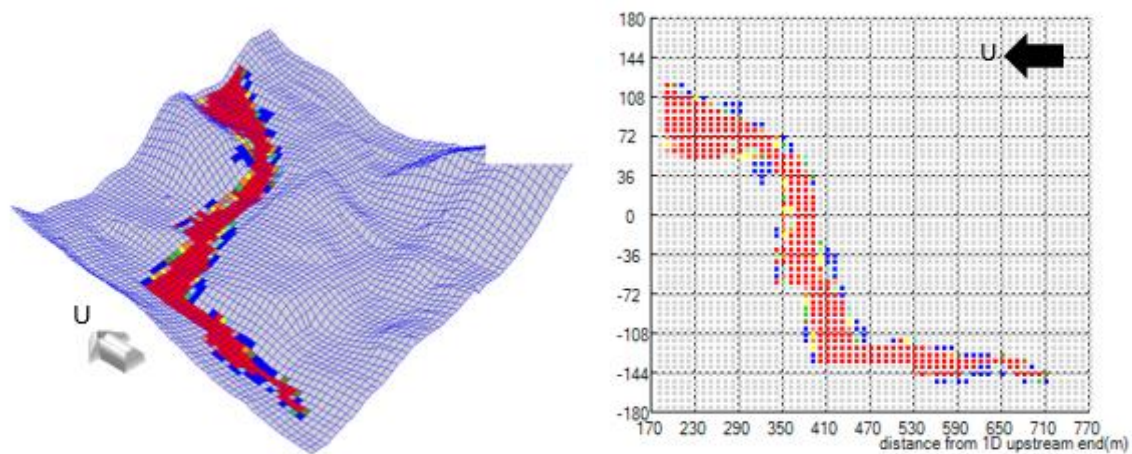


Figure 5. Run-out distribution of debris materials from Tenjolaya landslide in 2D area (left) and corresponding 2D map (right).

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