Advances in Engineering Research, volume 199

Proceedings of the 4th International Conference on Sustainable Innovation 2020–Technology, Engineering and Agriculture (ICoSITEA 2020)

A Theoretical Model for Debris Flow Initiation by Considering Effect of Hydrodynamic Force

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ABSTRACT

Debris flow is a sediment disaster that mostly occurs in mountainous area. In Merapi Volcano, Indonesia, debris flow frequently caused damage of infrastructures, destroyed bridges, houses, and fatalities. According to historical debris flow events, debris flow in Merapi area is predominantly triggered by erosion process. Several researchers were developed formulas to predict initiation of debris flow. However, effect of hydrodynamics force have not been explicitly included in developing theory of debris flow mechanism. This paper proposed a theoretical method to predict initiation of debris flow through modification of previous formulas. Effect of hydrodynamics force were represented by friction factor and being considered in the theory. This research was supported by experimental test. It was carried out on flume with movable bed layer and steep slope condition. Critical flow depth at varied bed slope gradient was identified to investigate behavior of initiation mechanism of debris flow. Critical depth that was determined by this theory is considered overestimated the real debris flow compared to previous studies, yet it can give safer condition for debris flow warning case.

Keywords—debris flow initiation, steep slope, friction factor, entrainment sediment

1. INTRODUCTION

Debris flow is a sediment disaster that mostly occurs in mountainous area. In Merapi Volcano, Indonesia, debris flow frequently caused damage of infrastructures, destroyed bridges, houses, and fatalities [1]. Debris flow can be initiated by several mechanisms, such as landslide [2] [3], dam collapses [4], and bed erosion in steep slopes [5] [6] [7]. In Merapi Volcano, debris flow is predominantly triggered by erosion process [8]. The abundant volume of volcanic material deposited on the river channel was easily entrained by surface flow [9]. This erosion increases when it takes pleace in steep slope channel. As known that steep slope is typical characteristics of stream in volcanic area. Discharge of the runoff in a steep slope stream is generally greater than in mild slope stream [10]. Thus, bed erosion on steep slope stream is more severe than mild slope stream. The more severe erosion, the higher risk of debris flow occurrence.

Takahashi [4] used the concept of equilibrium condition of a saturated soil mass to predict debris flow triggered by bed erosion. Debris flow initiates when the resisting shear stress, τ_r subjected to a saturated soil mass is lower than driving shear stress, τ. Takahashi proposed critical condition in terms of relative flow depth, *h/d*, to predict debris flow initiation. This theory is widely applied in some researchers to develop debris flow warning system and to replicate mechanism of debris flow initiation through numerical simulation [11] [12]. Prediction of debris flow initiation is essential for debris flow mitigation. Applying the prediction theory is one of the non-physical countermeasures of debris flow hazard. However, this theory is still arguable since hydrodynamics force that contributes enhancing erosion process are negligible. Gregoretti [5] and Guo et al. [3] developed theoretical model for debris flow initiation due to bed erosion by taking into account the effect of surface runoff. Yet, they did not explain mechanism of debris flow initiation in varied slope explicitly. It is known that slope gradient is one of the critical factors in triggering debris flow. Thus, the mechanism of the initiation of debris flow in different slope is important to study. Not only for applying the suitable non-physical countermeasure, but also physical countermeasure. Implementation of countermeasures should consider initiation process for debris flow so it can reduce the impact of the debris flow hazard effectively [13]. Through experimental study, this paper aims to investigate mechanism of debris flow initiation in steep slope channel. Critical condition in which debris flow initiates from the experiment is compared to the theoretical model developed by Takahashi [4].

2. A THEORY OF DEBRIS FLOW INITIATION

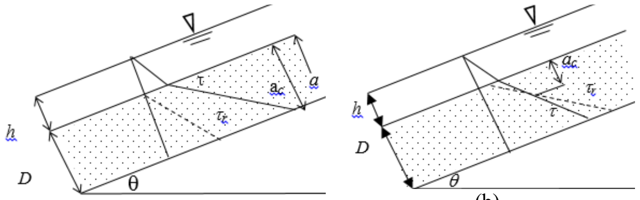
The initiation of debris flow was described by Takahashi [4] in term of slope stability. Slope stability was predicted using limit equilibrium analysis. Slope failure occurs when the driving shear stress along sliding block, τ is greater than the resisting shear stress, τ_r . Driving shear stress is caused by weight force, while the resisting shear stress is caused by frictional resistance at the base of sliding block. If a is assumed as the depth coordinate referring to the channel bed and h is surface flow depth, the driving shear stress is estimated as the following equations.

$$\tau = \left(\rho\left(h+a\right)+\left(\rho_s-\rho\right)a\,C_*\right)g\sin\theta \tag{1}$$

while the resisting shear stress is as follows

$$\tau_r = \left(\rho_s-\rho\right)C_*\,a\,\cos\,\theta\tan\varphi \tag{2}$$

By assuming shear stress distribution is linear along the depth, two possibility cases may occur as shown in Fig. 1(a) and Fig. 1(b), respectively. a_c is the depth of unstable bed layer that is measured from the soil surface to the intersection of driving shear stress and resisting shear. Debris flow is identified when the inclined slope of τ is greater than that of τ_r ($a_c \leq 0$ and $0 < a_c \leq D$). If the inclined slope of τ is smaller than that of resisting stress ($0 < a_c \leq D$), debris flow may occur in the upper bed layer. If a_c is less than mean diameter, d, the sediment layer itself is stable and only individual grains on the surface will be entrained by the fluid dynamic force in the surface flow. However, it is defined as debris flow if it is larger than d [4].



(a) (b)

Fig. 1. Diagram describing greater driving shears stress than resisting stress

Based on the aforementioned possibilities, when the soil layer is in saturated condition and surface runoff exists, sediment bed tends to be unstable if it satisfies the following equation.

$$\tan\theta = \frac{\left(\rho_s-\rho\right)C_*}{\left(\rho_s-\rho\right)C_*+\rho\left(1+{h}/{a_c}\right)}\tan\varphi \tag{3}$$

In the form of critical relative submergence, Equation (3) is expressed as follows

$$\frac{h}{a_c} = \Delta C_*\left(\frac{\tan\varphi}{\tan\theta}-1\right)-1 \tag{4}$$

where $$\Delta = \frac{\rho_s-\rho}{\rho}$$

If the hydrodynamic effect of surface runoff is taken into account, distribution of bed shear stress τ_f caused by surface runoff are presented in Fig. 2. τ_1, τ_2, and τ_3 represent shear stress due to weight force, due to friction between water and grains, and due to soil deformation. This additional shear stress is yielded by lift and drag force subjected to the grain sediment. Since the lift and drag force are difficult to measure directly, τ_f is widely applied as a proxy. τ_f is based on flow resistance coefficient derived from empirical approach.

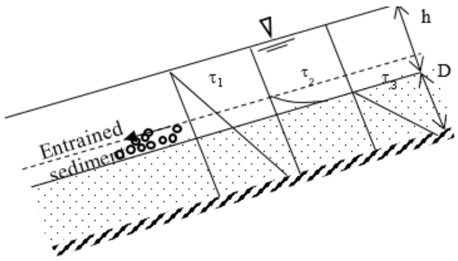


Figure 2. Schematic of driving stress distribution

The initiation of soil mass movement is analyzed by the force balance equation. There are four forces that contribute in triggering bed movement, i.e. lift force F_L, drag force F_D, buoyancy force F_B, and gravity force W. Considering forces balance equation at the equilibrium, ratio of tangential forces and normal force are equal to angle of repose of soil layer at initiation of motion [14].

$$\tan\varphi = \frac{F_D+W_x}{W_y-F_L} \tag{5}$$

$$\tan\varphi = \frac{\left(0.5C_D\rho u^2A\right)+\left(\left(\left(\rho_s-\rho\right)C_*+\rho\left(1+h/a_c\right)\right)g\sin\theta\right)}{\left(\left(\rho_s-\rho\right)C_*a_cg\cos\theta\right)-\left(0.5C_L\rho u^2A\right)}$$

where A is a cross-sectional area, and C_D is drag coefficient that depends on the shape and particle exposure to the flow, C_L is drag coefficient. If boundary shear stress created by hydrodynamics force on the surface bed, τ_f , is considered related to drag and lift force. The equation becomes

$$\frac{h}{a_c} = \Delta C_*\left(\frac{\tan\varphi}{\tan\theta}\text{-}1\right)-1-\frac{\tau_f}{\rho g\,a_c\cos\theta} \tag{6}$$

Shear stress caused by surface runoff can be expressed as follows

$$\tau_f = \frac{1}{8}\rho\,f\,u^2 \tag{7}$$

Modified formula to identify initiation of debris was also studied by Gregoretti [5]. Two coefficients namely C and K were added into Shields critical stress to accommodate the influence of small relative submergence, gravity, and seepage force on incipient motion. C is a coefficient that represents effect of seepage force, and K is the ratio of critical shear stress at any streamwise bed slope angle to the corresponding value at slope angle 0°. Considering a large Reynolds number, critical Shield stress, τ_* was about 0.06, so the equation was expressed as follows.

$$h = 0.06\,C\,K\left(\frac{\rho_s-\rho}{\rho}\right)\frac{d}{\sin\theta}-0.5\left(1-C_*\right)d \tag{8}$$

3. EXPERIMENT SET UP

The experimental tests were carried out in a 1.5 m length, 0.07 m width, and 0.2 m height flume (Fig. 3). Uniform grain size with 4.0 mm of diameter, 42° friction angle φ, and 2650 kg/m^3 bulk density was used for bed material. The flume was filled with 0.05 m thickness of grain material. Impermeable weir was placed in the downstream end of the flume to maintain initial bed thickness, while the upstream condition was permeable wall to let the groundwater flow fill in the bed layer. At the beginning of each running, bed sediment was saturated, then the flow discharge was immediately raised to the given flow discharge to investigate the movement of grain particle or bed layer. Erosion mechanism, water level, and flow velocity were observed from the image captured by camera using particle tracking velocimetry method. The tests were performed in the range of 10°-22°. Before continuing investigation of the subsequent flow discharge, bed surface was set like the initial condition. Flow depth in this study was characterized as the depth *h* that corresponds to the distance from initial elevation of bed surface to the elevation of free surface during the passage of flow (Fig. 4). Result of the experiment was compared to the original Takahashi formula and Gregoretti formula.

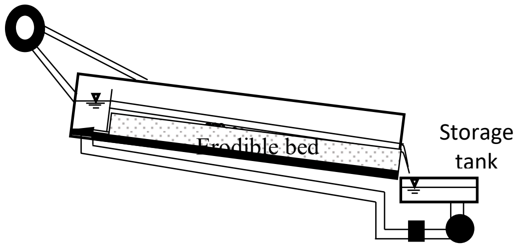
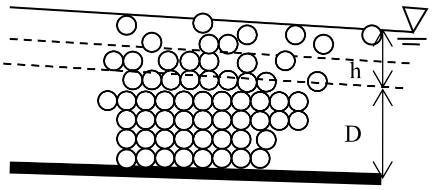


Figure 3. Experiment set up



Flow condition

Fig. 4. Identification of flow depth

4. RESULTS AND DISCUSSIONS

4.1. Initiation of Sediment Movement

Different mechanism of debris flow initiation can be seen in Fig. 5, while in detail, those mechanisms at each test run were illustrated in Fig. 6. Several types of sediment particle movement were observed at different slope angles and surface flow discharge. When the slope channel is less than 15°, single particle movement only takes place near the bed surface. Particles are entrained by lift and drag force of the surface runoff. This typical initiation does not change even if the flow discharge increases. It indicates that mechanism of bed load transport are significant for the slope channel less than 15°. As the steepness slope increase, the debris flow initiation is no longer dominated by bed erosion. In the case of slope 20° and 22°, debris flow was initiated by slope failure. It can be seen that bed surface layer slowly slides down and gradually develops debris flow. It occurs even before the bed layer was fully saturated. A transition phase takes place between the bed erosion and slope failure. It generally occurs when the eroded particle disperses throughout the water depth and collides each other. Takahashi [4] considered this phenomenon as immature debris flow. When the slope angle is in the range of 15 ° and 17.5°, surface runoff causes progressive erosion. For the high flow discharge, this phenomenon is sometimes associated with the bed layer movement.

Critical condition occurs when the driving shear stress is greater than the resisting shear stress. Incipient motion of sediment particle was determined based on the condition in which bed load transport generally took place in a whole channel surface. Shear stress distribution of bed sediment at critical condition was calculated using Equation (1) and (2). Unstable bed thickness, a_c is expressed by distance from the bed surface to the intersection of driving and resisting shear stress. If the slope angle is less than 15°, the a_c is less than d. As revealed by Takahashi [4], lahar occurs when the a_c exceeds $2d$. It means that lahar occurs if the slope angle is steeper than 15°. The calculated a_c for slope 17.5°, 2°, and 22° were $4d$, $8d$, and $10d$, respectively.

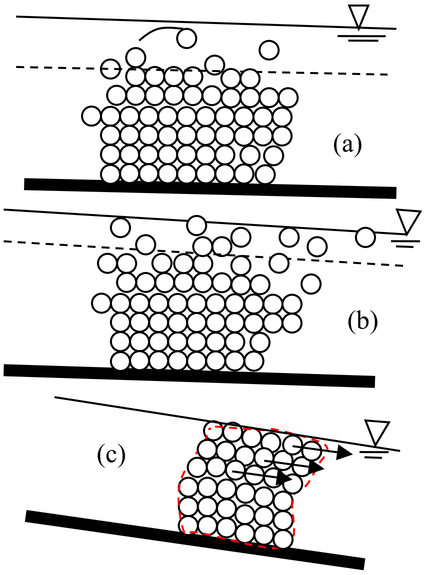


Fig. 5. Types of sediment movement (a) bed erosion at slope less than 10°, (b) immature debris flow at slope less than 15° and 17.5°, (c) slope failure at slope larger than 17.5°

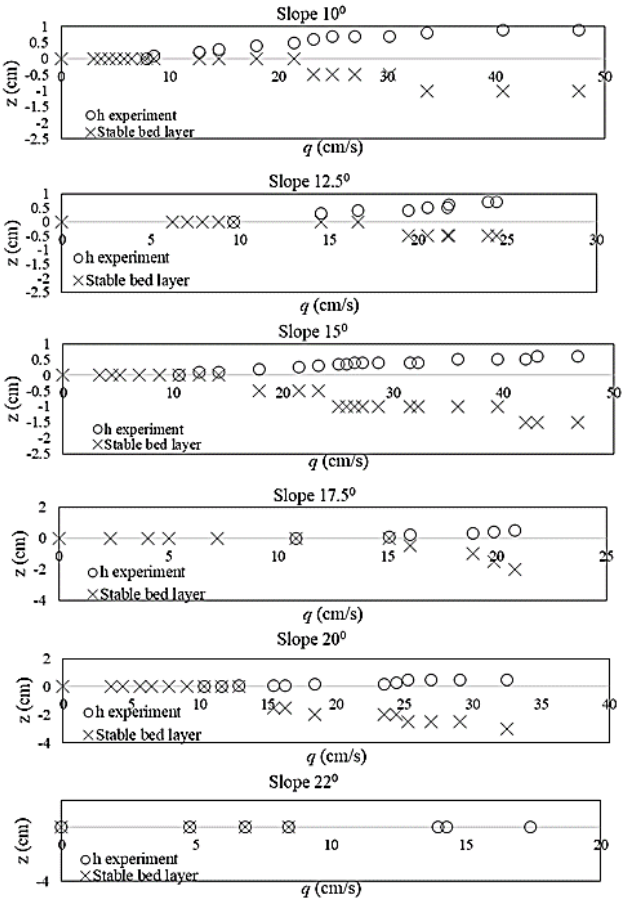


Fig. 6. Changes of water profile (h) and bed sediment thickness for different flow discharge

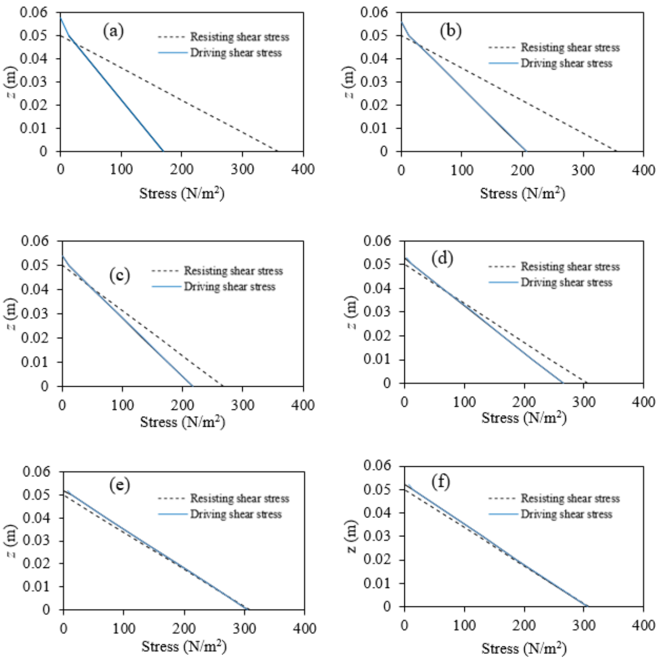


Fig 7. Shear stress distribution of bed sediment at critical condition (a) slope 10°; (b) slope 12.5°; (c) slope 15°; (d) slope 17.5°; (e) slope 20°; and (f) slope 22°

4.2. Critical Flow Depth Triggering Debris Flow on Steep Slope

Critical flow depth observed from the experiment results is presented in Fig. 8. Implementation of modified formula as shown in Equation 6 shifted the critical relative flow depth to the left side of Takahashi formula. **Figure 8** shows theoretical model of the lahar initiation that compares the proposed model and previous models. The threshold of the initiation of mass movement analyzed by Takahashi formula can be underestimated since critical flow depth yielded from experiment were lower than that of Takahashi formula, while the Gregoretti formula seems to be lower than experimental data. The experiment of initiation of sediment showed that modification of Takahashi corresponding to the bed shear stress caused by hydrodynamic force of surface runoff can be applied to identify initiation process of lahar. Effect of bed shear stress due to hydrodynamic force apparently weakens with the increase of slope. Critical flow depth predicted by this formula was between values obtained by Gregoretti [5] and Takahashi [4] equation. It is considered overestimated the real lahar, yet it can give safer condition for lahar warning case.

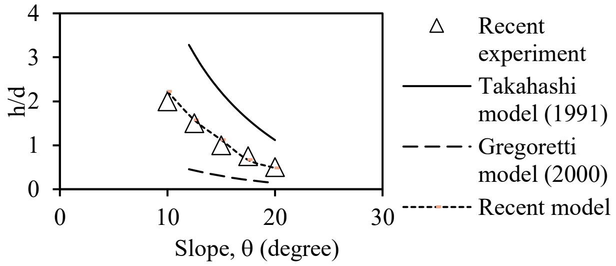


Fig. 8 Incipient threshold of sediment movement for variation of slope angle

5. CONCLUSIONS

The experiment results showed different mechanism at variation of slope angle. Bed load transport are significant for the slope channel less than 15°. As the steepness slope increase, the debris flow initiation is no longer dominated by bed erosion. In the case of slope 20° and 22°, debris flow was initiated by slope failure. A transition phase takes place between the bed erosion and slope failure which considered as immature debris flow. The experiment of initiation of sediment showed that modification of Takahashi corresponding to the bed shear stress caused by hydrodynamic force of surface runoff can be applied to identify initiation process of lahar. Effect of bed shear stress due to hydrodynamic force apparently weakens with the increase of slope. Critical flow depth predicted by this formula was lied between other two previous model proposed by Takahashi and Gragoretti. It is considered overestimated the real lahar, yet it can give safer condition for lahar warning case.

ACKNOWLEDGMENT

The authors would like to acknowledge to Prof. Masaharu Fuijta as Head of Ujigawa Open Laboratory, DPRI, Kyoto University for valuable discussions and giving permission to utilize the instruments for this research. The authors also thanks to Ministry of Education of Indonesia for its financial support to this research.

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