River morphology modeling at the downstream of Progo River post eruption 2010 of Mount Merapi

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Abstract

Mt. Merapi is one of the most active volcanoes in Indonesia. Some of the rivers that the origin is located at Mt. Merapi have a large amount of sediment resources after eruption in October-November 2010. The total volume of sediment is estimated at 130 million m³. The deposited sediment flows to the downstream area as a debris or bed load transport in high density. Few studies considered downstream change along volcanic rivers due to a high density of bed load transport. Using numerical simulation, the impact of high concentration of bed-load transport is applied in Progo River, Yogyakarta, Indonesia. The results show that the high bed-load transport rate increases the mid-channel bar grow rate and the bed degradation near the bank toe. The increase of bed degradation is an important parameter of bank erosion process. Furthermore, the bed morphology on the downstream after 2010 eruption of Mt. Merapi should be considered intensively.

Keywords: volcanic rivers; bed-load transport supply; numerical; bank toe

1. Introductions

1.1. Background

Mt. Merapi in Central Java, Indonesia had a major eruption in late October and early November 2010. The eruptions produced ash plumes, lahars, and pyroclastic flows. Therefore, a large number of sediment is deposited at the upstream of several volcanic rivers. It is approximately 130 million m³. During rainy season, the deposited...
sediment flows to the downstream area and produces debris flow. The presence of debris flow increases the possibility riverbank erosion in some river reach, causing significant damage to various infrastructure and river structures. Hence, the secondary disaster in term of rainfall induced debris flow may occur in long term period.

Using numerical model, this research is to investigate lahar occurrence as a supply of bed-load transport and its impact on riverbed deformation near the bank toe. The bed degradation at the vicinity of the bank slope which increases in the relative river bank height has a significant influence on the stability of the bank.

1.2. Study Area

The watershed area of Progo River is around 17,432 square kilometers. Several tributaries of Progo River are located in the Mt. Merapi. The irrigation water of Sleman and Kulon Progo Distric is taken from the river. Many structures, for example, bridges, railway bridges, cross the river. Therefore, the sustainability of the river should be monitored by Yogyakarta government. Due to the major eruption in October 2010, the sediment supply is more than the equilibrium condition. The river reaching of Progo River and located in Bantaris chosen in order to examine the interaction of channel geometry, sediment supply and bed deformation. Fig. 1 shows the Progo River system.

2. Numerical Model

Numerical simulations are performed using the horizontal two-dimensional flow model which the equations are written in general coordinate system. The model uses the finite difference method to solve different equations. Relationship between Cartesian coordinate system and General coordinate system is as follows.

\[
J = \frac{1}{\left(\frac{\partial x}{\partial \xi} \frac{\partial y}{\partial \eta} - \frac{\partial x}{\partial \eta} \frac{\partial y}{\partial \xi}\right)}
\] (1a)
Where, $\xi$ and $\eta$ are the coordinates along the longitudinal and the transverse directions in generalized coordinate system, respectively, $x$ and $y$ are the coordinates in Cartesian coordinate system. Computation of surface flow is carried out using the governing equation of the horizontal two-dimensional flow averaged with depth. The conservation of mass, i.e., inflow and outflow of mass by seepage flow, is taken into consideration as shown in the following equation [1].

$$
\Lambda \frac{\partial}{\partial t} \left( \frac{z}{h} \right) + \frac{\partial}{\partial x} \left( \frac{\xi}{h} \right) + \frac{\partial}{\partial y} \left( \frac{\eta}{h} \right) + \frac{\partial}{\partial \xi} \left( \frac{\xi}{h} \right) + \frac{\partial}{\partial \eta} \left( \frac{\eta}{h} \right) = 0
$$

(2)

Where, $t$ is the time, $z$ is the water surface level. Surface flow depth is represented as $h$, seepage flow depth is $h_g$. $U$ and $V$ represent the contra variant depth averaged flow velocity on bed along $\xi$ and $\eta$ coordinates respectively. These velocities are defined as

$$
U = \frac{\partial \xi}{\partial x} u + \frac{\partial \xi}{\partial y} v
$$

(3a)

$$
V = \frac{\partial \eta}{\partial x} u + \frac{\partial \eta}{\partial y} v
$$

(3b)

where, $u$ and $v$ represent the depth averaged flow velocity on bed along $x$ and $y$ coordinates, respectively. $U_g$ and $V_g$ represent the contra variant depth averaged seepage flow velocity along $\xi$ and $\eta$ coordinates, respectively. These velocities are defined as

$$
U_g = \frac{\partial \xi}{\partial x} u_g + \frac{\partial \xi}{\partial y} v_g
$$

(4a)

$$
V_g = \frac{\partial \eta}{\partial x} u_g + \frac{\partial \eta}{\partial y} v_g
$$

(4b)

where, the depth averaged seepage flow velocities along $x$ and $y$ coordinates in Cartesian coordinate system are shown as $u_g$, $v_g$ respectively. $\Lambda$ is a parameter related to the porosity in the soil, wherein $\Lambda = 1$ as $z < z_b$, and $\Lambda = \lambda$ as $z > z_b$, where $z_b$ is the bed level and $\lambda$ is the porosity in the soil. Seepage flow is assumed as horizontal two-dimensional saturation flow. Momentum equations of surface water are as follows.
Where, \( g \) is the gravity, \( \rho \) is the water density. \( \tau_{\xi \xi} \) and \( \tau_{\eta \eta} \) represent the contra variant shear stress along \( \xi \) and \( \eta \) coordinates, respectively. These shear stresses are defined as

\[
\tau_{\xi \xi} = \frac{\partial \xi}{\partial x} \tau_{xx} + \frac{\partial \xi}{\partial y} \tau_{yx}
\]

\[
\tau_{\eta \eta} = \frac{\partial \eta}{\partial x} \tau_{xx} + \frac{\partial \eta}{\partial y} \tau_{yx}
\]

where, \( \tau_x \) and \( \tau_y \) are the shear stress along \( x \) and \( y \) coordinates, respectively as follows.

\[
\tau_x = \tau_b \frac{u_b}{\sqrt{u_b^2 + v_b^2}}
\]

\[
\tau_y = \tau_b \frac{v_b}{\sqrt{u_b^2 + v_b^2}}
\]

\[
\frac{\tau_b}{\rho} = u_b^2
\]
\[ u_*^2 = \frac{n_m^2 \frac{g}{R^{1/3}}(u^2 + v^2)}{/} \]

Where, \( u_* \) is the friction velocity, \( n_m \) is the Manning’s roughness coefficient, \( R \) is the hydraulic radius, \( k_s \) is the roughness height. \( u_b \) and \( v_b \) represent velocity near the bed surface along \( x \) and \( y \) coordinates, respectively. Velocities near the bed are evaluated using curvature radius of streamlines as follows.

\[ u_b = u_b \cos \alpha_x - v_b \sin \alpha_x \quad (10a) \]

\[ v_b = u_b \sin \alpha_x + v_b \cos \alpha_x \quad (10b) \]

\[ u_{hs} = 8.5u_* \quad (11) \]

\[ v_{hs} = -N_* \frac{h}{r} \quad u_{hs} \quad (12) \]

Where, \( \alpha_x = \arctan (v/u) \), \( N_* \) is 7.0 \[2\], \( r \) is the curvature radius of streamlines obtained by the depth integrated velocity field as follows \[3\].

\[ \frac{1}{r} = \frac{1}{(u^2 + v^2)^{1/2}} \left\{ u \left( \frac{\partial v}{\partial x} - v \frac{\partial u}{\partial x} \right) + v \left( \frac{\partial v}{\partial y} - v \frac{\partial u}{\partial y} \right) \right\} \quad (13) \]

\( \sigma_{xx}, \sigma_{yy}, \tau_{xy} \) and \( \tau_{yx} \) are turbulence stresses as follows.

\[ \sigma_{xx} = 2v \frac{\partial u}{\partial x} \quad (14a) \]

\[ \sigma_{yy} = 2v \frac{\partial v}{\partial y} \quad (14b) \]

\[ \tau_{xy} = \tau_{yx} = \sqrt{\left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)} \quad (15) \]

\[ \nu = \frac{\kappa u_h}{6} \quad (16) \]

Where, \( \nu \) is the coefficient of kinematics eddy viscosity, \( \kappa \) is the Karman constant, \( k \) is the depth-averaged turbulence kinetic energy \[1\].

\[ u_g = -k_{hs} \left( \frac{\partial \xi}{\partial x} \frac{\partial z_b}{\partial \xi} + \frac{\partial \eta}{\partial x} \frac{\partial z_b}{\partial \eta} \right) \quad (17a) \]
\begin{equation}
\nu_s = -k_{gy} \left( \frac{\partial z_h}{\partial y}, \frac{\partial \eta}{\partial \xi} \right) + \frac{\partial \eta}{\partial \eta} \left( \frac{\partial z_h}{\partial \eta} \right) \tag{17b}
\end{equation}

Where, \( k_{gx} \) and \( k_{gy} \) is the coefficient of permeability along the longitudinal and the transverse directions, respectively. When the water depth of surface flow becomes less than the mean diameter of the bed material, the surface flow is computed only in consideration of pressure term and bed shear stress term in the momentum equation of surface flow [4]. Grain size distribution is evaluated using the sediment transport multilayer model as follows [5]:

\begin{equation}
\frac{\partial}{\partial t} \left( \frac{c_i E_k f_{jk}}{J} \right) + (1 - \lambda) \frac{\partial}{\partial t} \left( z_i \right) + \frac{\partial}{\partial \xi} \left( c_i E_k f_{jk} \frac{\partial z_i}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( c_i E_k f_{jk} \frac{\partial z_i}{\partial \eta} \right) = 0 \tag{18}
\end{equation}

In the formulae above, \( f_{jk} \) is the concentration of bed-load of size class \( k \) in the bed-load layer, \( f_{dlk} \) is the sediment concentration of size class \( k \) in the \( m \)th bed layer, \( c_i \) is the depth-averaged concentration of bed-load. \( E_{be} \) is the equilibrium bed-load layer thickness; it is estimated by the following equation [6]:

\begin{equation}
\frac{E_{be}}{d_m} = \frac{1}{c_j \cos \theta (\tan \phi - \tan \theta)} \tau_m \tag{19}
\end{equation}

Where \( d_m \) is the mean diameter of bed-load, \( \phi \) is the angle of repose, and \( \tau_m \) is the non-dimensional shear stress of mean diameter. \( E_{sd} \) is the sediment layer thickness on cohesive sediment bed. \( E_b \) is the bed-load layer thickness, \( q_{b\xi k} \) and \( q_{b\eta k} \) are the bed-load of size class \( k \) in \( \xi \) and \( \eta \) directions, respectively. \( q_{b\xi k} \) and \( q_{b\eta k} \) are the bed-load of size class \( k \) in \( x \) and \( y \) directions, respectively as follows [7] [8].

\begin{align}
q_{b\xi k} &= q_{b\xi} \cos \beta_k \tag{20a} \\
q_{b\eta k} &= q_{b\eta} \sin \beta_k \tag{20b} \\
q_{b\xi k} &= 17 \frac{\partial u^2_{e_k}}{(\rho_s - \rho) g} \left( 1 - \sqrt{K_c \frac{u_{ek}}{u_e}} \right) \left( 1 - K_c \frac{u^2_{ek}}{u_e} \right) f_{jk} \tag{20c}
\end{align}

Therein, \( \rho_s \) is the sediment density, \( u_{e_k} \) is the effective shear velocity; the non-dimensional critical friction velocity of size class \( k \) is evaluated as follows [7].

\begin{equation}
\frac{u^2_{e_k}}{u^2_{cm}} = \left[ \frac{\log_{10} \frac{19}{\log_{10} \left( 19 \frac{d_k}{d_m} \right)}}{d_k \frac{d_m}{d_k}} \right] \tag{21a}
\end{equation}

Iwagaki’s formula which is formulated for uniform bed material is used for evaluating \( u_{e\xi m} \). \( K_c \) is the correction factor due to the influence of bed inclination on sediment motion [9].

\begin{equation}
K_c = 1 + \frac{1}{\mu_s} \left[ \frac{\rho_s}{\rho_s - \rho} + 1 \right] \cos \alpha \tan \theta_\xi + \sin \alpha \tan \theta_\eta \tag{22}
\end{equation}
where $\alpha$ is the angle of deviation of near-bed flow from the x direction, $\mu_s$ is the coefficient of static friction. $\theta_x$ and $\theta_y$ are bed inclinations in x and y directions, respectively. Evolution of bed elevation is estimated by means of the following formulae.

$$\frac{\partial}{\partial t} \left( \frac{\alpha E_0}{J} \right) + (1-\lambda) \frac{\partial}{\partial x} \left( \frac{\alpha E_0}{J} \right) + \frac{\partial}{\partial z} \left( \frac{\alpha E_0}{J} \right) + \frac{\partial}{\partial y} \left( \frac{\alpha E_0}{J} \right) + \frac{\partial}{\partial z} \left( \frac{\alpha E_0}{J} \right) + \frac{\partial}{\partial y} \left( \frac{\alpha E_0}{J} \right) = 0$$

(23)

In them, $n$ represents the number of the size class of sediment.

3. Simulation Model

3.1. Simulation Data

Figure 1 shows the grain size of riverbed material. The discharge for all simulation is 115 m$^3$/s. The boundary of downstream model end is the water stage with the initial condition is at the normal depth.

Fig. 2. Grain size distribution of riverbed material

3.2. Simulation Scenario

The river bed deformations were compared by applying three conditions of bed-load transport supply at the upstream model. First condition is the bed-load supply which is same as the potential equilibrium sediment transport rate, $q_b$. The volume is 100% $q_b$ namely Case1. The second and third conditions are the bed-load transport that is more than $q_b$. The bed-load transport supplies are 125% $q_b$ and 150% $q_b$ and named as Case 2 and Case 3, respectively. The first case describes the river when there is no sediment supply from the upstream area. The second and third cases represent the river when the flow has sediment supply from deposited sediment at the upstream area. To evaluate the bed deformation along the vicinity of bank slope, the changes of elevation near the bank toe are investigated. The grid is developed to represent the initial channel topography.
4. Results and Discussions

Figure 4, 5 and 6 show the long profile of the right bank toe in Case 1, Case 2 and Case 3, respectively. The solid line indicates the initial elevation and the dash line indicates the elevation after 1 hour simulation. At the 200 m distance from upstream end model (see the circle dash line), comparing to Case 1, the bed degradation in Case 2 and Case 3 is deeper. It may be due to the impact of a mid-channel bar growing at around this station. It means that the possibility of river bank will not only collapse but also increase. Around station 600 m, the aggradations process due to sediment supply can be seen clearly.
Figure 7, 8 and 9 show the long profile of the left bank toe in Case 1, Case 2 and Case 3, respectively. On the left bank toe, the deformation is a similar phenomenon comparing to the right bank toe. Some locations are aggravated due to a large of sediment supply. Moreover, the occurrence of bed degradation is deeper than when the sediment supply is in equilibrium condition.
5. Conclusions

According to the simulation results, after the eruption of Mt. Merapi in 2010, Progo River has not only sedimentation problem but also bed degradation. The bed degradation is the main parameter in bank erosion process. Furthermore, the changes of river morphology (bank erosion) should be considered by the government to manage the river structure, for example bridge abutment, revetment, and so on.

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References