The drag forces exerted by lahar flows on a cylindrical pier: case study of post Mount Merapi eruptions

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Abstract. Debris flows of lahar flows occurred in post mount eruption is a phenomenon in which large quantities of water, mud, and gravel flow down a stream at a high velocity. It is a second stage of danger after the first danger of lava flows, pyroclastic, and toxic gases. The debris flow of lahar flows has a high density and also high velocity; therefore it has potential detrimental consequences against homes, bridges, and infrastructures, as well as loss of life along its pathway. The collision event between lahar flows and pier of a bridge is observed. The condition is numerically simulated using commercial software of computational fluid dynamic (CFD). The work is also conducted in order to investigate drag force generated during collision. Rheological data of lahar is observed through laboratory test of lahar model as density and viscosity. These data were used as the input data of the CFD simulation. The numerical model is involving two types of fluid: mud and water, therefore multiphase model is adopted in the current CFD simulation. The problem formulation is referring to the constitutive equations of mass and momentum conservation for incompressible and viscous fluid, which in perspective of two dimension (2D). The simulation models describe the situation of the collision event between lahar flows and pier of a bridge. It provides sequential view images of lahar flow impaction and the propagation trend line of the drag force coefficient values. Lahar flow analysis used non-dimensional parameter of Reynolds number. According to the results of numerical simulations, the drag force coefficients are in range 1.23 to 1.48 those are generated by value of flow velocity in range 11.11 m/s to 16.67 m/s.

1. Introduction

Mount Merapi located in the middle of Java Island is a very active volcano which has erupted regularly every two to five years. One of danger emerged by its eruption is a lava flows in the form of debris flow, which is in Indonesian term; it is called ‘lahar’. Term of ‘lahar’ describes a hot or cold mixture of water and rock fragments flowing down the slopes of a volcano and (or) river valleys. When moving, a lahar looks like a mass of wet concrete that carries rock debris ranging in size from clay to boulders more than 10 m in diameter. Lahars vary in size and speed. Small lahar flow less than a few meters wide and several centimeters deep may flow a few meters per second. Large lahars hundreds of meters wide and tens of meters deep can flow several tens of meters per second--much too fast for people to outrun [1].

The debris flows is not a danger which followed an eruptions immediately. The debris flows happened when volcanic materials deposited on top of mountain post eruptions was washed away by heavy rainfall. A debris flow consists of thick sedimentary rocks, gravel, sand, mud, and volcanic ash mixed with water. The debris flow has a high density and velocity; therefore it has potential detrimental consequences against of homes, bridges, and infrastructures, as well as loss of life along its pathway.

After Mount Merapi eruptions, debris flows are frequent and numerous disasters occurred. A protection system to reduce losses due to debris flow was created as sediment retaining that called check dam or sabo dam. The purpose of the sabo structures was to reduce the excess sediment discharge to prevent river degradation further downstream. Recently, sabo works shifted to the control of debris flows. The system of dam can be used to reduce the impact of debris torrents [1]. According to Mount Merapi protection system, sabo dams are built on rivers which are the pathway of debris flows; those are Kali Krasak, Kali Batang, Kali Putih, Kali Gendol and other rivers as seen in Figure 1.

Sabo dam built at some locations in mountainside of Mount Merapi are designed based on hydrological data (rainfall data and watershed maps), location maps, situation maps (topographic maps and geometry of the river), river sedimentation and soil mechanics data. The data are used as basis of the design of the main dam, sub dam, and dam stability control [2].

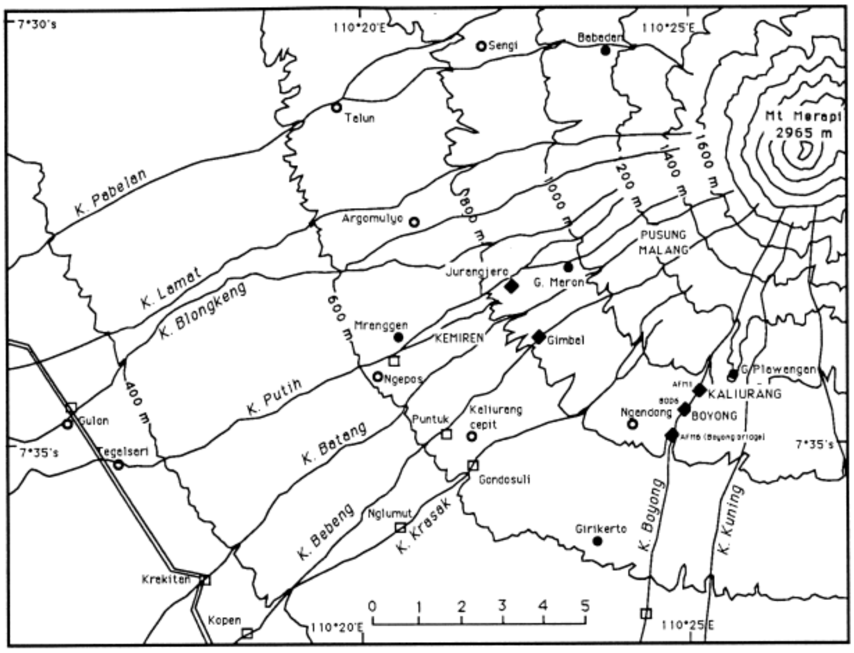

Figure 1. Pathway Map of Mount Merapi lahar flows, Middle Java, Indonesia [3]

Moreover, one of the structures affected by the flow of lahar is the bridge pier, which it is exposed to be directly hit by lahar flow. The situation is compounded by the conditions of the bottom of the piers that already experiencing scour, so that the piers are in a state of hanging. Obviously this situation is very dangerous for the stability of the bridge as shown in Figure 2.

According to [4], there are at least five bridges, the dams, and four houses in Magelang damaged by Merapi lahar flows. It describes the destructive force of lahar flows. Since Mt. Merapi is a strato volcano type, which has a very steep slope, the characteristics of lahar flow is fast-moving with great force. The combination of the flow of volcanic material such as volcanic ash, gravel, gravel, pieces of rock with steep slopes make the lahar flows are also controlled by the acceleration of the gravity force.

Figure 2. Bridge pier damages on Pabelan River, Pabelan, Jawa Tengah [5]

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In the process of flowing lahar, energy generated due to surface run-off is changed according to the square of the velocity. Grain transport capacity of volcanic material will change with the rank of 5 in time in one-dimensional unit. It means that the surface flow rate increases to two times, the number of transported grains material increases 32 times more [4]. These events are normally (in geological time scale) occurred in many areas around the Mount Merapi lahar flows pathways. It has potential detrimental consequences against facilities such as bridge, dam, and river structure.

Figure 3. Collapsed bridge due to the destructive of lahar flow [6]

The aim of this research is to investigate the drag force exerted by lahar flows in the collision against the cylindrical bridge pier by employing numerical simulation of ANSYS Fluent 14.0. The determination of drag force and drag coefficient is referring to rheological properties of lahar. The current numerical modeling is carried out in view of providing the basis for developing methods for prediction of the impact forces of lahar flow on bridge pier.

2. Numerical simulation

In order to numerically model the collision between lahar flow and bridge piers, fluid dynamics approach is implemented using gravity flow concept, which has been widely used in research on fluid flow. In the current study, this method is applied to accommodate the additional effect of flow plasticity on the drag force related to the dynamic pressure which is proportional to lahar density and the squared flow velocity. Therefore, drag force generated by lahar flow on bridge piers can be expressed by traditional fluid dynamic force and rheology properties of non-Newtonian fluid flow as the following equation [7].

$$F_d = \frac{1}{2} \cdot \rho_f \cdot C_d \cdot A \cdot u^2 \quad (1)$$

where F_d is the drag force components perpendicular to bridge piers axis, ρ_f is the lahar density, which is according to [8], in range 1230 kg/m^3 to 1840 kg/m^3. Whereas C_d is the drag coefficient, A is area of bridge piers, which is facing opposite to lahar flow direction, and u is flow front velocity of lahar flow. As seen in Eq. (1), drag force analysis of this interaction is determined by properties of lahar flow as density and velocity together with bridge piers physical attribute of outside diameter (OD) and surface area.

The current numerical simulation is utilizing the ANSYS Fluent 14.0, which provided the broad physical modelling capabilities needed to model the flow. By using the advanced post-processor, examining the results and settings, analysis can be performed in further. The problem formulation is referring to the constitutive equations of mass and momentum conservation for incompressible and viscous fluid, which in perspective of 2D; it is expressed as Eq. (2) and Eq. (3), respectively. Equations of mass conservation is based on principles that rate of inflow is equal to outflow rate [9].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = S_m \quad (2)$$

where ρ is lahar density, u is velocity, and S_m is the mass added to continuous phase from the dispersed second phase (specified mass sources).

While, the momentum conservation is formulated as follow.

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} + \vec{F} \quad (3)$$

where p is the static pressure, $\rho \vec{g}$ and $\vec{F}$ are the gravitational body force and external body force.

Whereas, $\bar{\tau}$ is the stress tensor, which is formulated as follow.

$$\bar{\tau} = \mu \left[(\nabla \vec{u} + \nabla \vec{u}^T) - \frac{2}{3} \nabla \cdot \vec{u} I \right] \quad (4)$$

where μ is lahar viscosity and I is the unit tensor.

Lahar flow analysis used non-dimensional parameter of Reynolds number (Re), which is the ratio between inertia force and viscous force. Inertia force is expressed by using density parameter (ρ_f), velocity (u), and slope of lahar flow velocity (du/dx). While viscous force is expressed by using dynamic viscosity parameter (μ). Reynolds number is expressed as the following.

$$R_e = \frac{(\rho_f \cdot u)(du/dx)}{\mu \cdot (d^2 u / dx^2))} \quad (5)$$

The geometry model was created by using ANSYS DesignModeler (DM). The meshing process was implemented by using the ANSYS Meshing (ANSYS ICEM CFD) with 2D behaviour of plane stress and Lagrangian reference frame. The 18,871 nodes and 18,425 elements were created by using size function of on proximity and curvature with proximity minimum size of 1.2512e-003 m and maximum face size of 2e-002 m. However, the refinement of mesh was definitely depending on the performance of the hardware; higher capability provided better meshing process.

Figure 3 illustrates of the preparation of pre-processing stages. As seen in this figure, lahar flow is modeled as a fluid flow with density of ρf enters into the empty zone as a velocity inlet model. Whereas three sides of model are stated as free flow boundary condition. In addition, applying such boundary condition will allow the lahar flow will be having wave behavior.

According to [3], for several lahars in the years following the 1984 Merapi eruption, a maximum peak flow velocity of 11 m/s was recorded at Jurangjero, Putih River (865 m, 4.5% slope), for the 28 November 1985 event. In the Boyong River, the maximum recorded peak flow velocity was 15 m/s at Kaliurang (850 m, 4.6% slope) on 20 May 1995. Therefore, in the current research, the velocity inlet used varies into 40 km/h to 60 km/h.

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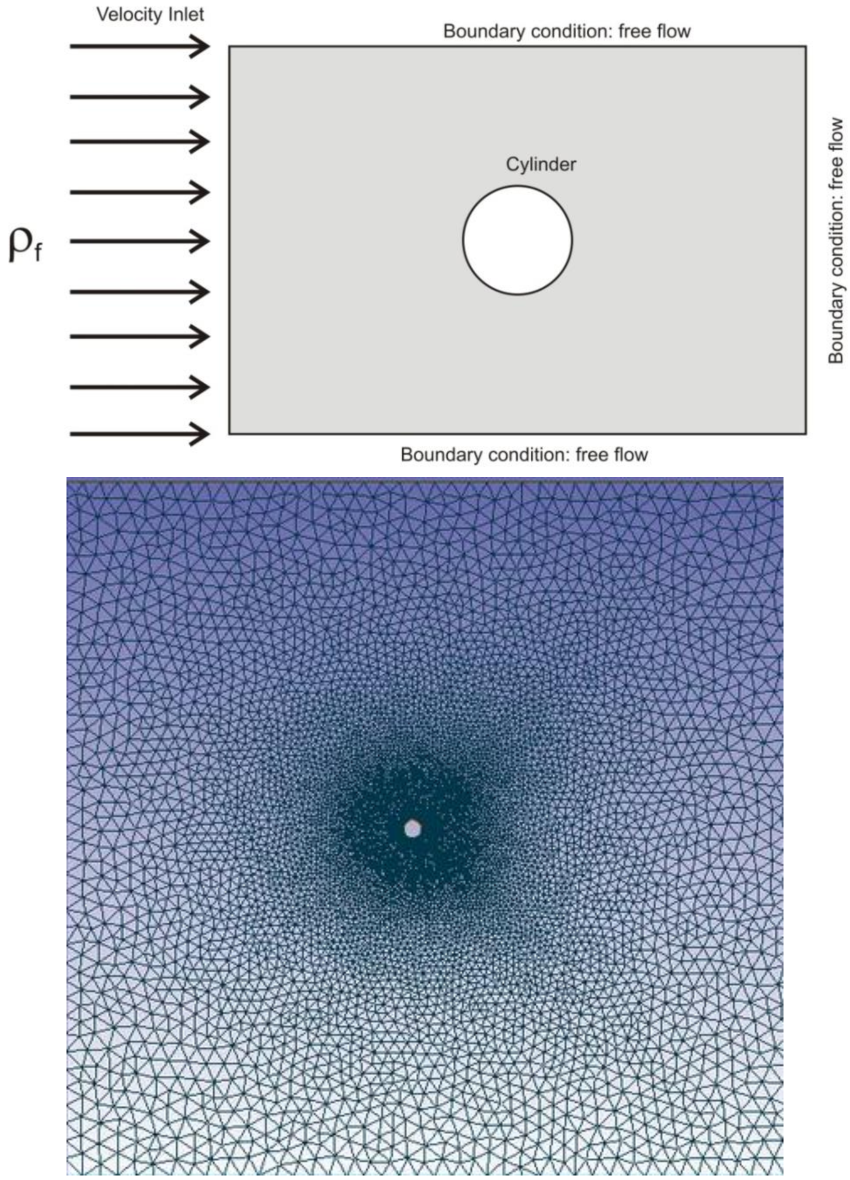

Figure 4. Geometry model and meshed geometry

3. Result and discussion

Non-dimensional parameter of Reynolds numbers (Re) were calculated by using Eq. (5). Values of Re related to lahar flow velocities are as shown in Table 1 below.

Table 1. Reynolds number (Re).

Dia. of Pier (m)	Linear Characteristics [m]	Flow Velocity (u) [m/s]	Density of Lahar [kg/m^3]	Viscosity of Lahar [Pa.s]	Re [x10^7]
2,5	0,942857	11,11	1840	0,000861	0,923
2,5	0,942857	13,89	1840	0,000861	1,54
2,5	0,942857	16,67	1840	0,000861	2,46

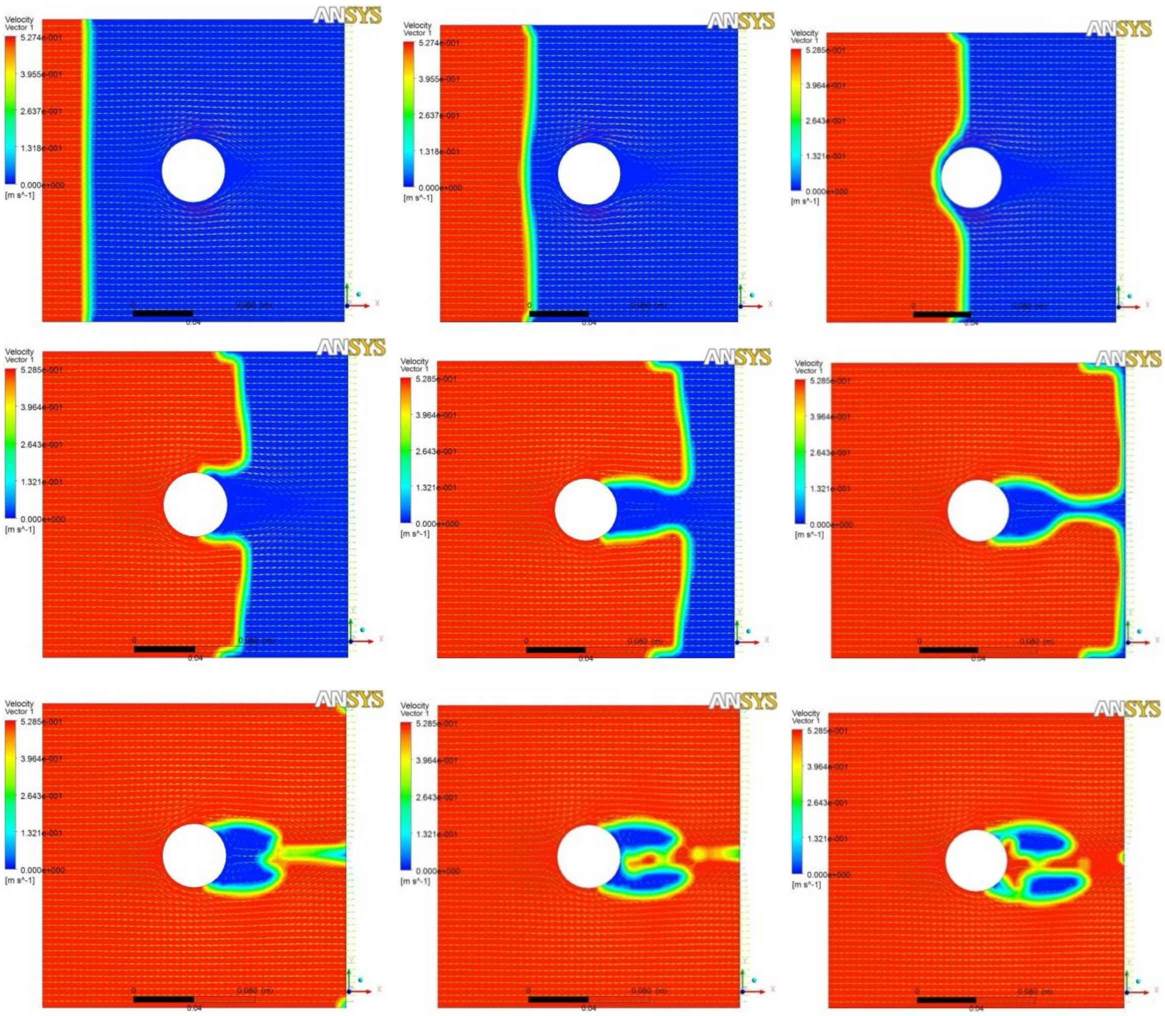

Figure 5. Image capturing in sequence views of the collision between lahar flow and pier

The coefficient of drag force is one of the parameters of drag force equation (Eq. (1)). In using CFD simulations, the used C_d value is the maximum C_d value obtained from each model. The C_d value obtained from simulation is a combination of the parameters of the velocity waves (u) and the size of the diameter of the pillar. The distribution of C_d value of numerical simulation results are shown in Table 2 below.

Table 2. Drag force coefficient (C_d)

Diameter of pier (m)	Flow Velocity (u) [m/s]	Reynolds number (Re) [x10^7]	Drag Force Coefficient (Cd)
2,5	11,11	0.923	1.23
2,5	13,89	1.54	1.3
2,5	16,67	2.46	1.48

Normally, the collision between non-Newtonian fluid flows with cylinder occurs within a relatively short time [10]. One of the outcomes of simulations using CFD on the collision event between lahar flows with bridge pier is a graphical form of distribution values of C_d when the collision takes place in the modeling process. Figure 5 below shows the distribution of C_d values based on the magnitude of the lahar flows velocity used in the numerical simulations.

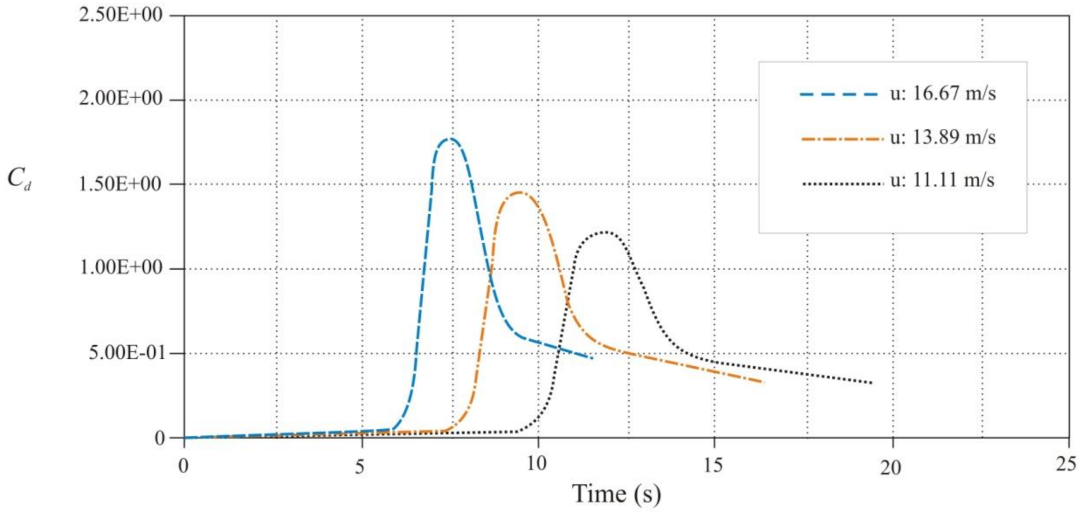

Figure 6. Drag force coefficient (C_d)

4. Concluding remark

The application of commercial software of ANSYS Fluent to simulate the collision event between lahar flows and pier was presented. Simulation setup was implemented as the pressure-based Navier-Stokes (*pbns*) with absolute velocity formulation and mixture-model for multiphase model with two phases of Eulerian phase. It produced the simulation model in the form of sequential views images of lahar flow head impaction and the propagation trend line of the drag force coefficient values. Furthermore, he values of the coefficient of drag force are depending on the diameter of bridge pillar used as well as the velocity of the lahar flows. The larger the diameter used and the greater the velocity of lahar flows will produce the higher drag coefficient. According to the results of numerical simulations, the drag force coefficients are in range 1.23 to 1.48 those are generated by value of flow velocity in range 11.11 m/s to 16.67 m/s.

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