Modelling of the Risks of the Sidoarjo Mud Flow, Indonesia

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Abstract: The Sidoarjo mud flow flooded the part of the Porong area, Indonesia, surrounded by the set of the quickly constructed dams. The objective of the study was quantification of the risks imposed by the mud volcano towards the ECCO Indonesia factory site due to dam breaks and dam overtopping. The distance between the northern dike surrounding the volcano and the PT ECCO is at 4.3 km. This territory is crossed by many small rivers. The two-dimensional numerical model COASTOX_MUD has been developed for modeling of the variable density mud flow. The model is based on the system of four nonlinear partial differential equations using two components description of mud flow as non-Newtonian fluid. The model also has a simplified version which considers mud flow as one-component fluid with an averaged density, i.e. it is based on the system of three shallow water equations used by Laigle and Coussot [1997] and in other previous studies. The two-component version of the model has supplementary benefits compared to single component models as it can simulate mud dilution induced by the rivers as they are traversed by the mud flow. The two-component version of the COASTOX_MUD was used in the study by incorporating the specific weight of the water–sediment mixture and mud viscosity received from on-site sampling and laboratory measurements. The simulation for the dam breaks scenarios and the mud flow conditions of the summer 2007 shows insignificant risk of the factory site flooding by the mud flow due to the dam breaks.

Keywords: Sidoarjo Mud Volcano; Mud Flow, Modelling, Hazards Mapping.

1. INTRODUCTION

The Sidoarjo mud flow, also named "Lusi", is an ongoing eruption of gas and mud from the earth in the sub district of Porong, Sidoarjo in East Java, Indonesia [Cyranoski D., 2007; Wikipedia, 2008]. The mud started to flow on May 28, 2006 and so far the mud has inundated parts of the Porong area. It is considered to be a mud volcano. So far, all efforts to stop the flow have failed. Some 50,000 m³ of hot mud were erupting every day as of August; in September 2006, the amount increased to some 125,000 cubic meters daily. By early September about 25 square km had been flooded by mud. A network of dams and barriers has been erected to contain the mud. The volcano site is located at the distance at 6 km, from the territory of the PT ECCO Indonesia factory site. The continuation of mud release was assessed as potentially long term process, - temporal scale - years [UN OCHA, 2006; Wikipedia, 2008] therefore the relevant risks of the mudflow for ECCO Indonesia factory site located in the vicinity of mud volcano was studied in 2007 by the team of Singaporean, Indonesian and Ukrainian scientists. The paper presents the methodology and the results of the risk assessments based of the modelling of the set of the scenarios of the mud flow propagation towards the PT ECCO Indonesia. The objective of the study was quantification of the risks imposed by the mud volcano towards the ECCO Indonesia factory site due to dam breaks and dam overtopping.

The previous simulations of the mud flow propagation for different scenarios including dam breaks and overtopping were provided on the basis of numerical one dimensional and two dimensional (depth integrated) models [O’Brien et al, 1993; Laigle and Coussot, 1997;
Ming and Fread, 1999; Pudasaini and Hutter, 2007). The structural difference between the 2D Mud Flow Equations (MFE) and Nonlinear Shallow Water Equation (NSWE) is the introduction of a specific “resistance term” into the MFE which parameterizes mud rheology.

For the simulation of the Sidoarjo mud flow the numerical finite volume model COASTOX_MUD has been developed as the extension of the model COASTOX based on the NSWE. COASTOX model has been tested and implemented for a wide range of the water/sediment/radionuclide simulations including dam break problems for the water bodies of the vicinity of the Chernobyl Nuclear Power Plant within the and post-accidental studies described by Kivva and Zheleznyak [2001], Onishi at al.[2007].

COASTOX_MUD is new two component model based on the system of the four nonlinear partial differential equations that simulates mud flow using different fluid mud and water densities. The model also has a simplified version which considers mud flow as one-component liquid with an averaged density, i.e. it is based on the system of three 2D MFE used by Laigle and Coussot [1997] and in the other previous studies. The two component version of the model has supplementary benefits compared to single component models as it can simulate mud dilution induced by the rivers as they are traversed by the mud flow.

The two component version of the COASTOX_MUD was used in the study by incorporating the specific weight of the water–sediment mixture and mud viscosity received from on-site sampling and laboratory measurements.

2. MODEL DESCRIPTION

2.1 Mud Component Formulation

We consider the mud flow as a mixture of two components: a mud with mass fraction $Y_m$ and pure water with mass fraction $Y_f = 1 - Y_m$. The similar approach has been used by Herbert et al. [1988] and Oldenburg and Pruess [1995] for the modeling of variable-density groundwater flow. Assume that the volumes of fresh water and mud are additive:

$$V = V_m + V_f$$  \hspace{1cm} (1)

where $V$, $V_m$, $V_f$ are the volumes of mixture, mud and fresh water, respectively. The mass of mixture is given by

$$M = M_m + M_f$$  \hspace{1cm} (2)

and the mass fractions of mud and water are given by

$$Y_m = M_m / M$$  \hspace{1cm} (3)

$$Y_f = 1 - Y_m$$  \hspace{1cm} (4)

Dividing (1) by (2) and substituting (3) and (4), we obtain for mixture density

$$\frac{1}{\rho} = \frac{V}{M} = \frac{1 - Y_m}{\rho_f} + \frac{Y_m}{\rho_m}$$

or

$$Y_m = \frac{\rho_m}{\rho} \frac{\rho - \rho_f}{\rho_m - \rho_f}$$

where the densities are given by $\rho_f = M_f / V_f$ and $\rho_m = M_m / V_m$.
1.2 Overland Flow

Considering the aqueous phase as a mixture of a mud and pure water, we describe the free-surface mud flow by the vertically averaged, shallow water equations for two-component mixture described in 1.1 above. These equations include continuity equations of mass fraction and two momentum equations presented as follows.

\[
\frac{\partial}{\partial t} (h \rho Y_k) + \frac{\partial}{\partial x_i} (v_i h \rho Y_k) = I \rho_m Y_k (\rho_m)
\]

\[
\frac{\partial}{\partial t} (v_i h \rho) + \frac{\partial}{\partial x_j} (v_j v_i h \rho) + g h \rho \frac{\partial \xi}{\partial x_i} + \tau_i^n = 0
\]

where \( t \) is the time variable (s); \( x_i \) is the spatial Cartesian coordinates (m); \( h = \xi - \eta \) is the flow depth (m); \( v_i \) is the overland flow velocity in the \( x_i \)-direction (m s\(^{-1}\)); \( \xi(x,t) \) is the free surface elevation (m); \( \eta(x,t) \) is the bed surface elevation (m); \( g \) is the acceleration of the gravity (m s\(^{-2}\)); \( \tau_i^n \) is the shear stress at the bed surface (kg m\(^{-1}\) s\(^{-2}\)); \( I \) is the flow rate of mud eruption (m s\(^{-1}\)); \( \rho \) is the fluid density; \( k=1,2 \) is the index of mixture component. The mass fractions \( Y_k \) are computed as a function of \( \rho \), according to

\[
Y_1(\rho) = \frac{\rho_f - \rho}{\rho_m - \rho_f}, \quad Y_2(\rho) = \frac{\rho_f - \rho}{\rho_m - \rho_f}
\]

According to O’Brien and Julien (1993), the shear stress at the bed surface can be defined as:

\[
\tau^n = \tau_y + \tau_v + \tau_t
\]

where \( \tau_y \) is the yield shear stress of the mud-water mixture; \( \tau_v \) is the viscous shear stress; and \( \tau_t \) is the turbulent-dispersive shear stress.

For turbulent flow Reynolds’ stress dominates and viscous stress may be negligible. The boundary shear stress can then be approximated either by the Manning equation as

\[
\tau_{t,i} = \rho g \frac{n^2}{h^{1/3}} v_i |v_i|
\]

or by the Chezy equation as

\[
\tau_{t,i} = \rho g \frac{1}{c^2} v_i |v_i|
\]

where \( n \) is the Manning roughness coefficient (s m\(^{-1/3}\)) and \( c \) is the Chezy friction coefficient (m\(^{1/2}\) s\(^{-1}\)).

The viscous shear stress is calculated by using the following relation

\[
\tau_v = \frac{K \mu(\rho) v_i}{8h}
\]

where \( K \) is non-dimensional friction parameter of the laminar flow that has the value of \( K=24 \) for a smooth bottom surface but it increases with higher roughness and irregularity of the riverbed; \( \mu(\rho) \) is the dynamic viscosity of the mixture.

The yield stress \( \tau_y \) and viscosity \( \mu(\rho) \) increase with the sediment concentration \( C_V \).

Unless a rheological analysis of the mudflow site material is available, the following empirical formulas can be used for their calculations.
\[ \tau_y = \tau_0^V C_V^{3.7} \]  
[Wang, 2002]

and

\[ \mu(\rho) = \mu_f (1 - C_Y)^a \]  
[Lee, 1969]

where \( \tau_0^V = 12000 Pa \), \( \mu_f \) is the viscosity of clear water, and

\[ a = -(2.5 + 1.9 C_Y + 7.7 C_Y^2) \]

The volumetric sediment concentration \( C_Y \) is given by \( C_Y = (\rho - \rho_f) / (\rho_m - \rho_f) \).

3. NUMERICAL SOLUTION

The system of 2-D partial differential equations (5), (6) is solved by the integrated finite-difference (finite volume) method [Kivva and Zheleznyak, 2001]. Transformation of the partial differential equations into algebraic form requires that the physical domain be spatially discretized into a computational domain composed of a number of non-overlapping control volumes. Each control volume surrounds a single grid point which defines the position of intrinsic property variables. The conservation equations are integrated over control volume by assuming a piece-wise profile that express the variation in the primary variable between grid points. The transient equations are solved with a fully implicit time-stepping scheme. The resulting system of algebraic equations is non-linear. The integral finite-difference method conserves quantities such as mass, momentum, and species over each control volume and the entire computational domain.

The non-linear algebraic forms of the conservation equations are converted to a linear form using a residual-based, global Newton’s iteration technique. The technique generally yields quadratic convergence of the residuals with iterations, given initial estimates of the unknowns that are sufficiently close to the solution. A conjugate gradient scheme is used for the solution of the linearized algebraic form of the conservation equations.

4. TESTING OF THE NUMERICAL MODEL

The numerical model has been validated against a number of benchmark test cases widely documented in the publications. COASTOX was used for the simulation of a partial dam-break or rapid opening of a sluice gate with a nonsymmetrical breach for frictionless fluid. This test has been used by Mingham et al. [1998] and Zoppou et al., [1999] for the testing of the numerical models. The computational domain is defined by a channel 200 m long, 200 m wide with horizontal bottom. The non-symmetric breach is 75 m wide and centered at 125 m. The thickness of dam is infinitesimal. Initially, the upstream water depth is 10 m, downstream water depth is 5 m (wet bed) and 0 m (dry bed). The dam wall is then breached, and instantaneously water discharges from the higher to the lower level as a downstream-directed bore while a depression wave propagates upstream. Herein, for comparison with prior works, the computational domain is discretized by a uniform 5x5 m square mesh that exactly fits the domain. The results displaying 3D views of the water surface elevation after dam failure at time \( t=7.2 \) s for wet and dry beds (Figure 1). When there is a finite water depth downstream of the dam, there is always a sharp front moving downstream. For the dry bed case, however, there is no shock. The problem consists of a rarefaction fan, and there is a smooth transition in the water depth from the breach to the dry bed downstream of the dam.

The results of COASTOX numerical simulation are in close agreement with corresponding results presented in the above-mentioned publications.
5. NUMERICAL SIMULATIONS OF THE MUD FLOW PROPAGATION

Basic information about the Digital Elevation Model in the vicinity of the mud volcano and Ecco facility was received from [USGS, 2007] as the data set with a 3 arc seconds horizontal grid dimension (Figure 2.) The resolution for the model was set at grid area of 90*90 meters. The Ecco site is located at 6 km northward from the volcano. The territory is a plain with the topographical elevation from 1 to 7 m above sea level that has a slight slope in North East direction (average slope is at 0.001). The territory is crossed by 8 small rivers flowing mainly from West to East with the discharges from 0.05 to 7 cub.m/sec. The distance between the northern dam surrounding the volcano and the PT ECCO is at 4.3 km. The black rectangular is the border of the simulated domain that will be presented on the following figures (from Figure 3 below) turned by such way that left and right borders of the simulated plot will be vertical. The black broken line inside the borders of the simulated area presents the bund around the volcano.

The computational domain for the COASTOX_MUD model is defined by an area of 7620 m long by 3000 m wide between the ECCO facility and the mud impoundment. The computational domain was simulated using a non-uniform rectangle mesh, the nodes of which were spaced at 8 m – 60 m intervals in the length, and from 8 to 30 m in the width.

To estimate the risk to the ECCO facility from the mudflow the following scenarios have been considered in the numerical experiments.

**Scenario 1:** It is assumed that mud has the same consistency, density and flow properties as pure water and that no rivers or any other structures that could mitigate, impede and/or slow down the mud flowing in the direction of the Ecco facility boundary existed. The consequences of the formation of 100 m wide dam breach are modeled. This scenario represents a ‘worse case’ as pure water will have faster and less impeded flow characteristics than actual mud toward the Ecco facility boundary. The initial mud elevation in the mud basin is 20.0 m.
Scenario 2 is similar to the Scenario 1 however the real mud parameters are used. According to laboratory testing the mud has a density of 1270 kg/m³ and a viscosity at room temperature is 12.84 Pas. The flow rate of mud eruption from volcano was 175000 m³/day. The yield shear stress of the mud was equal to 20 Pa and the friction parameter $K$ was equal to 2285.

Scenario 3 is used the basic assumptions of the Scenario 2, but accounting for actual river channel flows that exist between the mud impoundment and the Ecco facility boundary. The Manning roughness coefficient for each river was assigned as 0.025 s m⁻¹³/³ and 0.11 s m⁻¹³/³ on the remaining part of territory.

Four terrain points (numbers 1-4 at the crosses in Figures 3 and 4) were used to highlight the temporal dynamics of the water level near to the ECCO site boundary. The point 1 is located at 1200 m from PT ECCO in the direction of the potential approach of the incoming mud flow, point 2 is located at 200 m (south-west) from PT ECCO at the southern bank of Blingo River, the Point 3 is at 800 m South East from PT ECCO and the Point 4 is located 1500 m eastward from PT ECCO.

The rivers delay and redirect the propagation of the mood flow after dam break (Figure 3). From the moment of 100 m breach formation the water reaches Point No 1 at 30 min in Scenario 1, at 1 hour 20 min in Scenario 2 and at 5 hours after the dam break for the scenario 3 (Figure 4). The maximum mud elevations at this point for three scenarios are 2.4 m, 2.3 m and 1.7 m respectively.

After passing the Point No 1 flow splits and propagates as two streams eastward and westward from PT ECCO (Figure 4). The territory upfront PT Ecco (south bank of Blingo River) practically is not inundated. In the closest to PT ECCO inundated point No 2 the water level increased 3 hours after breach formation till maximum value equals only 9 cm in the Scenario 1 and till 7.5 cm after 4 h in the Scenario 2.
Figure 4. Flooded territory and water depth at 4 hours after the dam break, for the Scenario 2 (left) and the scenario 3 (right)

In the Scenario 3 under the influence of the river flows the mud flow is diluted and more significantly redirected to the North East than in the scenarios 1 and 2. The points No 2 and No 4 as also all right (South) bank of the Blingo river at PT ECCO will not be inundated in this Scenario driven by the mixing of the river flow and mud flow. The simulated results of the Scenario 3 confirms the results of the more conservative scenarios 1 and 2–the risk of the inundation for PT Ecco in a case of mud flow dam break is insignificant.

6. CONCLUSIONS

The two-dimensional finite volume model COASTOX_MUD has been developed for the simulation of variable density mud flow. The model was customized for the assessment of the consequences of the potential dam breaks at the Sidoarjo mud volcano, Indonesia on the basis of the topographical data, GIS data and mud parameters measured in the Brawijaya University, Malang, Indonesia and National University of Singapore. The two-components five equations model can simulate flow that is created by the mixing of the river channels flows and mud flow in the area between the mud volcano and the ECCO Indonesia factory. In the case of the homogenous mud density the derived system can be reduced to the 2-D three equations model, implemented in the previous studies by O’Brien et al., [1993]; Laigle and Coussot [1997]; Ming and Fread [1999]; Pudasaini and Hutter, [2007].

The conservative “worse case” risk assessment for the factory site inundation was provided in assumption that the mud flow has the same parameters as water flow and that all rivers between the volcano dams and PT ECCO site can be omitted. Within more
realistic scenario the measured mud density and viscosity were used in the model of permanent density. The simulations of the mixed river water – “mud flow were provided by the two components five equations version of the COASTAX _MUD model

The numerical results demonstrate that even in the “worse case” scenario the inundation at the ECCO factory after dam break will be less then 10 cm. For the scenario of the real density and viscosity the peak of the inundation is coming later and it will be lower. The simulation of the river flow impacts on the mud flow has demonstrated significant change of the flow direction (to North East) in this case that fully prevents the inundation of the PT ECCO site

However, in long term perspective if volcano would continue its activities, the next modeling studies should be provided after the mud sedimentation will cause the change of the depth in the mud basin.

The application of the variable density model in this case study shows how river flows can redirect mud flow and diminish significantly its elevation. Such results emphasize the needs for the implementation of variable density models for the realistic assessments of the mud flow propagation cross the rivernets.

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