One-dimensional numerical simulation for sabo dam planning using Kanako (Ver. 1.40): A case study at Cipanas, Guntur Volcanoes, West Java, Indonesia

Sumaryono¹, Kana NAKATANI², Yoshifumi SATOFUKA³ and Takahisa MIZUYAMA²

¹ Ministry of Energy and Mineral Resources Geology Agency, Center for Volcanology and Geological Hazard Mitigation (Diponegoro road No.57 Bandung 40122, Indonesia)
² Dept. of Erosion Control Engineering, Kyoto University (Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto, Kyoto 6068502, Japan)
³ Dept. of Civil Engineering, Ritsumeikan University (Noji-higashi 1-1-1, Kusatsu, Shiga 5258577, Japan)

A debris flow is a phenomenon in which large quantities of water, mud, and gravel flow down a stream at a high velocity. Because debris flows have such high density and velocity, they can be highly destructive and can have severe and tragic results such as destruction of homes, bridges, and infrastructures, as well as loss of life. Numerical simulations are important to ensure that countermeasures such as sabo dams will be efficient before construction. This paper presents one-dimensional numerical simulations of a debris flow using Kanako, a user-friendly GUI-equipped debris flow simulator that allows good visualization and easy explanation. Kanako (Ver. 1.40) was applied to a case study at Cipanas, Guntur Volcanoes, West Java, Indonesia. Simulations tested various conditions including cases without any sabo dams, with various types of sabo dams either alone or in a series, and with full sabo dams.

Keywords: Debris flow, effective countermeasure, one-dimensional numerical simulation, sabo dam

1. INTRODUCTION

Sediment-related disasters such as debris flows, mudflows, and flash floods (called “banjir bandang” in Indonesia) are common type of natural disasters in Indonesia. These kinds of disasters frequently occur in Indonesia, especially during the rainy season. Heavy rains may form landslide dams; when these break, they may cause large surges or debris flows. The alluvial fan area is most likely to be affected. A large-scale sediment-related disaster occurred almost every year from 2002–2007: in 2002, a debris flow in Pacet, East Java killed many people and damaged many cottages in the hot spring area; in 2003, a sediment-related disaster occurred in the Bahorok River, North Sumatra, killing more than 155 people; similar events occurred in Bawakaraeng, South Sulawesi in 2004, in Jember, East Java, Sinjai, Central Sulawesi in 2006, and in Tahuna, North Sulawesi and Morowali, Central Sulawesi in 2007. Thus, debris flows can have very severe and tragic results such as destruction of homes, bridges, and infrastructures, as well as loss of life.

At present, countermeasures and early warning systems for debris flows in Indonesia are not well developed. The Hyogo Framework requires that sustainable development policies and planning incorporate debris flow disaster risk reduction (DRR) and effective early warning systems. Disaster risk reduction is a national and local priority with a strong institutional basis for implementation; knowledge, innovation, and education will be required to build a culture of safety and resilience at all levels.

1.1 Background

In January 2007, a small debris flow occurred in a river in the Guntur Volcanoes. Debris flowed down the torrent as far as 500 m from the source. Many hot springs, settlements, and resort areas are located approximately 700 m southeast from this accumulation of debris. The area is economically important because it attracts considerable domestic tourism, especially on weekends. Unfortunately there are currently no torrent countermeasures in
The accumulated upstream debris flow is estimated at 7600 m$^3$. Therefore a secondary debris flow could form, affecting the downstream area. To address this situation, the Garut local government is planning to construct dams to protect the area or to remove material from the river. Moreover, the area is already designated as a conservation area of the Guntur Volcanoes.

We used Kanako Ver. 1.40 to simulate debris flow with and without sabo dam construction in Cipanas, Garut Regency, West Java Province. Our study included many conditions: 1) cases without sabo dams and with empty sabo dams; 2) cases with various types of sabo dams, either alone or in series; and 3) cases with full or sediment filled sabo dam.
1.1.1 Location

The study area was Cipanas, Tarogong District, Garut Regency, West Java Province, approximately 60 km from the capital of West Java (Bandung) and located between 7°9’58.8” – 7°10’41.1” S and 107°51’28.6” – 107°52’29.6” E. This area consists of the middle portion of the Guntar Volcanoes, which are active and have a long history of eruption. The river is 1.64 km from upstream to the confluent, and the watershed has an area of approximately 0.378 km². This river only has water in the rainy season. As shown in Fig. 1, many settlements, resorts, hotels, and cottages are located downstream in a recreational hot spring area. The case study for sabo dam planning focused on the upstream area before the confluence; this section has 950 m length.

1.1.2 Climatic conditions

The typical climate in West Java is tropical and influenced by a monsoon system. It can be divided into two seasons: dry and rainy with a high intensity of rainfall. Based on the Oldeman Climate Classification, Garut Regency is a type C₂ climate, with an annual rainfall of approximately 1,800 mm/year. The dry season is normally from May to October, and the rainy season is normally from November to April. Temperatures range from 17.4–31.6°C and monthly averaged 22.6–24.8°C in 2006 and 2007. Fig. 2 and Fig. 3 show the climatic conditions in the Garut Regency area.

1.1.3 Geological conditions

The Garut area includes three geological categories:

1) basaltic lava from the Guntur Volcanoes (Qhg);
2) undifferentiated efflata deposits of young volcanic: volcanic ash and lapillus, sandy tuff, and blocks of andesite-basalt, laharc breccias, and efflata; and
3) young volcanic: efflata and andesite-basaltic lava.

2. NUMERICAL SIMULATION METHOD WITH KANAKO
Kanako Ver. 1.40 was used to apply numerical simulations of debris flows, controlled with closed, slit, and grid sabo dams, to model variations in mountainous riverbeds. The model incorporates two grain size classes for sediment material and uses one-dimensional governing equations to simulate stony debris flows and the resulting erosion [Satofuka and Mizuyama, 2005]. These equations are solved using a finite difference method [Takahashi and Kuang, 1986; Takahashi and Nakagawa, 1986]. Kanako makes simulation very easy, because it is equipped with a GUI.

During a simulation, the user can watch an animated debris flow and the process of erosion/deposition as well as a hydrograph and sediment graph, as an example shown in Fig. 4.

2.1 Governing equations

The basic debris flow equations are shown below. The momentum equation is

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} = -gh \frac{\partial H}{\partial x} - \tau_b$$  \hspace{1cm} (1)

The continuity equation for the total volume of debris flow is

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} = s_T$$  \hspace{1cm} (2)

and the continuity equation for particles is

$$\frac{\partial Ch}{\partial t} + \frac{\partial CM}{\partial x} = C_s s_T$$  \hspace{1cm} (3)

Here, the sediment material includes two grain sizes: larger grains, which can block grid-type sabo dams; and smaller grains, which do not block dams. The average grain size of all sediment material was used when considering riverbed deformation, except for the upper areas where a grid-type sabo dam was modeled. Changes in the bed surface elevation can be determined using the following equation:

$$\frac{\partial z_b}{\partial t} = -s_T$$  \hspace{1cm} (4)

For Eqs. (1)–(4), $h$ is the flow depth, $v$ is the flow velocity, $M = vh$, $g$ is the acceleration due to gravity, $\rho_m$ is the density of the liquid phase, $\rho_m = (\sigma - \rho)C + \rho$, $\rho$ is the interstitial fluid density, $\sigma$ is the density of particles, $H = h + z_b$, $z_b$ is the bed elevation, $s_T$ is the erosion/deposition velocity [$s_T \geq 0$: erosion], $C_s$ is the sediment concentration in the movable bed layer, $\tau_b$ is the riverbed shearing stress, and $t$ is time.

2.2 Simulation procedures and input data

![Fig. 4 An example of a screenshot of Kanako 1.40 during a simulation.](image)
Three types of scenarios were simulated and compared as follows (See Fig. 5).

1) cases with and without sabo dams,
2) a series of various types of sabo dams, and
3) conditions of empty and full sabo dams.

For each case, debris flow was simulated based on actual river topography to clarify erosion, sedimentation, and changing hydrographs at each observation point. Single dams of various types were modeled at various locations to estimate the sabo dam design effectiveness. Different series of dams were then considered. Full sabo dams were also simulated to compare their effects with those of empty sabo dams and cases with no sabo dams.

2.3 Data input

2.3.1 Simulator model variables

Kanako includes 17 variables that must be set for numerical calculation; the values were the same for all scenarios, and are listed in Table 1.

2.3.2 River profile data

The river's longitudinal profile was obtained from topographic maps; Fig. 6 details the river bed condition, the observation points and sabo dam location. The river width was set at 10 m from the upstream end to the downstream end. A 1-m movable bed layer was modeled in the 275-m section at the upper end of river. An unmovable bed was prescribed initially for the downstream sections.

2.3.3 Supplied hydrograph

Nakayasu's synthetic hydrograph method [Nakayasu, 1949] was used to supply a hydrograph for the upstream section. The sediment concentration included coarse material (set at 0.4) and fine material (set at 0.1). Fig. 7 shows the supplied hydrograph used for the simulations.

3. RESULTS AND ANALYSIS

3.1 Without a sabo dam

Fig. 8 shows the river discharge at each hydrograph observation point simulated without countermeasures. The debris flow discharge lessened downstream from Obs.1, possibly because the slope lessened gradually from the upstream to downstream sections. This also indicates sedimentation processes. The results clearly indicate that when the slope was similar, the reduction in discharge was also similar (see Obs. 1 and 2).

3.2 With a sabo dam

3.2.1 Location of the sabo dam

The location and type of sabo dam (closed or slit) were given for each case. The number of sabo
dams was fixed at 1; the sabo dam height was fixed at 20 m, and the slit width for slit dams was fixed at 0.5 m.

Four simulations were conducted with differing sabo dam locations and types. The observation points were the same as those described in the previous section. The results of each case are presented below and in Fig. 9.

**Case 1: Sabo dam placed 237.5 m from the upstream simulation boundary**

A closed sabo dam placed at this point reduced the coarse sediment discharge to 46% upstream of the dam (Obs. 1) and 62% downstream of the dam (Obs. 2). It also reduced the fine sediment discharge to 52% upstream of the dam and 64% downstream of the dam. A slit sabo dam placed at this point reduced the coarse sediment discharge to 7% upstream of the dam and 9.3% downstream of the dam, and reduced the fine sediment discharge to 10% upstream of the dam and 12% downstream of the dam.

### Table 1: Simulation parameters.

<table>
<thead>
<tr>
<th>Parameters/Variables</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation time</td>
<td>5400</td>
<td>s</td>
</tr>
<tr>
<td>Time step</td>
<td>0.01</td>
<td>s</td>
</tr>
<tr>
<td>Diameter of coarse material</td>
<td>1</td>
<td>m</td>
</tr>
<tr>
<td>Diameter of fine material</td>
<td>0.1</td>
<td>m</td>
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<tr>
<td>Mass density of bed material $\sigma$</td>
<td>2650</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Mass density of fluid (water and mud, silt) phase $\rho$</td>
<td>1100</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Concentration of movable bed $C_*$</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Internal friction angle $\tan \phi$</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Volumetric ratio of coarse material in the movable bed</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Volumetric ratio of fine material in the movable bed</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Acceleration of gravity</td>
<td>9.8</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>Coefficient of erosion rate</td>
<td>0.0007</td>
<td></td>
</tr>
<tr>
<td>Coefficient of accumulation rate</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Minimum flow depth</td>
<td>0.01</td>
<td>m</td>
</tr>
<tr>
<td>Manning's roughness coefficient</td>
<td>0.03</td>
<td>s/m$^{1/3}$</td>
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<tr>
<td>Number of calculation points</td>
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<tr>
<td>Interval of calculation points</td>
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<td>m</td>
</tr>
</tbody>
</table>

**Fig. 6 Longitudinal profile of the Cipanas River. (The upper 275-m section of the riverbed has a moveable layer 1 m thick.)**

**Fig. 7 Supplied hydrograph.**
Case 2: Sabo dam placed 387.5 m from the upstream simulation boundary
A closed sabo dam placed at this point reduced the coarse sediment discharge to 49% upstream of the dam (Obs. 2) and 54% downstream of the dam (Obs. 3), and reduced the fine sediment discharge to 49% upstream of the dam and 59% downstream of the dam. A slit sabo dam reduced the coarse sediment discharge to 1.5% upstream of the dam and 0.3% downstream of the dam, and reduced the fine sediment discharge to 0.9% upstream of the dam and 1% downstream of the dam.

Case 3: Sabo dam placed 537.5 m from the upstream simulation boundary
A closed sabo dam placed at this point reduced the coarse sediment discharge to 49% upstream of the dam (Obs. 3) and 57% downstream of the dam (Obs. 4), and reduced the fine sediment discharge to 53% upstream of the dam and 58% downstream of the dam. The simulations revealed that a slit sabo dam would not be effective at this location because it would not reduce the fine or coarse sediment discharge.

Case 4: Sabo dam placed 687.5 m from the upstream simulation boundary
A closed sabo dam placed at this point reduced the coarse sediment discharge to 36% upstream of the dam (Obs. 4) and 95% downstream of the dam (Obs. point 62.5 m downstream from the sabo dam location, 750 m from the upstream simulation boundary, and reduced the fine sediment discharge to 31% upstream of the dam and 95% downstream of the dam. A slit sabo dam reduced the coarse sediment discharge to 2.6% upstream of the dam and 0.6% downstream of the dam, and reduced the fine sediment discharge to 3.4% upstream of the dam but had little effect downstream.

These simulations revealed that sabo dams located 237.5, 387.5, and 537.5 m from the upstream simulation boundary were more effective. Based on the simulation results, this point is ideal for installing a sabo dam because the topography is good and the location is effective for protection compared with other locations. When topological conditions were also considered, two locations emerged as the best choices for sabo dam installations: 237.5 and 537.5 m from the upstream simulation boundary. Furthermore, it shows that closed dam is more effective than slit dam.

3.2.2 Series of sabo dams
These simulations included four variables: the number of sabo dams, and the height, type, and location of the sabo dams. Because the simulations were conducted to assess the effects using a series of sabo dams, the locations and number of sabo dams were fixed while the other variables were varied to examine how they affected the sediment discharge. In these simulations, the observation points were same as those used above, except that Obs. 4 was changed from 600 m to 625 m from the upstream
simulation boundary, where the slope is 16.64°. Table 2 lists the conditions for all four cases. The results of each case are shown in Fig. 10. The simulations revealed that the discharge conditions at
Obs. 2, located between dams No. 1 and 2 (62.5 m downstream from dam No. 1 and 237.5 m upstream from dam No. 2) were influenced by the sabo dams. The closed sabo dam No. 1 dominated the discharge conditions at this point. The results did not differ greatly between Cases 1 and 3, possibly because the sediment was already retained by the first sabo dam, which type was closed, so that the second dam was less effective.

The results also did not differ greatly between Cases 2 and 4 because the slit sabo dams had little effect on the sediment discharge. The best conditions occurred at Case 3 because the second dam trapped all the sediment. Case 4 was the least effective, possibly because the discharge was relatively small so that the slit sabo dams were ineffective.

The effect of the second sabo dam was examined at Obs. 4 (87.5 m downstream from dam No. 2). The results indicated that a closed second sabo dam was more effective. The effect of the second sabo dam differed only slightly between Cases 1 and 2, although different type of sabo dam is set. In Case 2

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Table 2 Variables for the series of sabo dams
(Slit dams had a slit width of 1.5 m.)

<table>
<thead>
<tr>
<th>No. 1 dam (located at 237.5 m)</th>
<th>No. 2 dam (located at 537.5 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Height (m)</td>
</tr>
<tr>
<td>Case 1</td>
<td>Closed</td>
</tr>
<tr>
<td>Case 2</td>
<td>Slit</td>
</tr>
<tr>
<td>Case 3</td>
<td>Closed</td>
</tr>
<tr>
<td>Case 4</td>
<td>Slit</td>
</tr>
</tbody>
</table>

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Fig. 10 Sediment discharge for the series of sabo dams.
second closed type sabo dam retained more sediment flowing down through first slit sabo dam. In Case1, second slit sabo dam cannot retained much sediment but first closed sabo dam retained more sediment therefore less sediment flowed down to Obs.4. Case 4 had very low effectiveness compared with the other cases.

The most appropriate type of sabo dam design for the Cipanas River is a series of closed sabo dams or closed and slit sabo dams. The closed dams were more effective in the upstream sections of the river, comparing to the case without sabo dam. This is indicated from the reduction rate of sediment discharge being larger at Obs.2 and Obs.3, area that No.1 upstream sabo dam effects, than Obs.4 area that No.2 downstream sabo dam effects. The second sabo dam is optional, but if it is used, it should be a closed sabo dam. The most effective two-dam case was:

**Dam No. 1**: a closed sabo dam with a height of
20 m, located 237.5 m from the upstream simulation boundary; and

Dam No. 2: a closed sabo dam with a height of 15 m, located 537.5 m from the upstream simulation boundary.

3.2.3 Effectiveness of full sabo dams

In this simulation, the effects of a full closed sabo dam were compared with those of an empty closed sabo dam. The effect of not using a sabo dam was also examined. For these simulations, closed sabo dams with heights of 20 m were modeled at a location 237.5 m from the upstream simulation boundary. The observation points were the same as indicated in section 3.2.2.

Fig. 11 shows that at Obs. 1 (87.5 m upstream from the sabo dam), the sediment discharge was at first lower when the sabo dam was full than when it was empty, but this changed after 2600 seconds. The overall sediment discharge was lower when the sabo dam was empty than when the sabo dam was full or when no sabo dam was installed. When the sabo dam became filled with sediment, the riverbed slope was reduced, which affected the debris flow discharge and consequently the erosion and deposition.

Based on simulation results at Obs. 2–4, a sabo dam filled with coarse and fine material had a higher rate of discharge than an empty sabo dam, and a lower rate of discharge than when no sabo dam was installed. Therefore, even when a sabo dam is completely full, it can still function to control the movement of material, but not all the sediment can be retained.

An analysis of the full and empty sabo dam simulations highlighted some important findings:

a. Both full and empty sabo dam controlled the sediment movement than case without dam.

b. Erosion downstream from the sabo dam tended to be larger when sabo dam is full comparing with empty sabo dam

Maintenance such as excavation is required when sabo dams are full. Full sabo dams are unable to reduce debris flows as effectively as empty sabo dams when they are subjected to equal quantities of flow.

4. CONCLUSIONS

The simulated debris flows yielded the following findings with regard to the Cipanas River.

1) The sediment discharge was reduced gradually downstream, possibly because the slope was decreased, even there is no sabo dam.

2) Simulations using Kanako 1.4 revealed that a series of closed sabo dams was more effective than the use of slit sabo dams.

3) Full sabo dams could still control sediment movement, but not as well as empty sabo dams. Therefore, full sabo dams require maintenance such as excavation. Full sabo dams are unable to reduce debris flows as effectively as empty sabo dams when they are subjected to equal quantities of flow.

4) Kanako 1.4’s user-friendly GUI allowed it to simulate and present the effects of sabo dams visually to users without advanced training in sabo engineering or numerical simulation.

REFERENCES


