Original Article

Debris Flow Flooding and Debris Deposition Considering the Effect of Houses: Disaster Verification and Numerical Simulation

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Debris flow causes flooding and sediment deposition when it reaches alluvial fans. Many houses have been constructed on alluvial fans, and this can affect debris flow flooding and deposition. In this study, we first conducted a field survey on recent debris flow disasters in Japan; one such disaster, the Izu Oshima sediment disaster, occurred in October 2013. Houses located upstream, in lower areas, and those facing small bridges and crossroads suffered greater damage than those located in other areas. Secondly, we performed numerical simulations using debris flow simulators (KANAKO 2D and Hyper KANAKO) to determine the effect of houses on debris flow flooding and deposition. For the simulations, grid points of the locations of houses were set taking into consideration the height of the houses from the ground elevation. We simulated typical debris flow condition and real disaster cases. The simulation results showed that when houses are present, the spread of debris flow is wide in cross-direction upstream of the houses. Houses also affect the deposition area. The presence of houses increased flooding and deposition damage in some areas, whereas it reduced damage in others. When setting the houses, the areas between the houses were set lower than the houses located at the grid points. Such areas were designated as roads, and the results showed that the flow occurred along the roads, as in real disasters.

Key words: debris flow, effect of houses, field survey, disaster verification, numerical simulation

1. INTRODUCTION

Debris flow causes flooding and sediment deposition when it reaches an alluvial fan. Urban development in Japan has resulted in the construction of many houses on alluvial fans, and this has affected the flow and deposition of debris flow [Mizuyama and Ishikawa, 1989; Ishikawa et al., 1992]. Some studies have considered the influence of residential areas on flooding without sediments [Iwasa et al., 1980; Takahashi et al., 1985]. Although various studies have focused on debris flows [Takahashi and Tsujimoto, 1984], few previous studies [Takahashi et al., 1988; Ghilardi et al., 2000; Lin et al., 2011; Loup et al., 2012] have considered the effect of houses on disasters associated with debris flow, especially through model experiments or numerical simulations.

In this study, we first gathered data on debris flow disasters such as the area and height of the flooding and deposition, and information on the affected houses, such as the location and degree of damage by debris flow due to disaster reports and papers. We also conducted a field survey to collect information on recent debris flow disasters in Japan, such as the Izu Oshima sediment disaster that occurred in October 2013 [Ishikawa et al., 2014].

Secondly, we performed numerical simulations using the debris flow simulators KANAKO 2D [Nakatani et al., 2008] and the advanced GIS-based system Hyper KANAKO [Nakatani et al., 2012] to determine the effect of houses on debris flow flooding and deposition. For the simulations, the grid points of the location of the houses were set...
taking into consideration the height of the house from the ground elevation, which has been reported in previous studies to be an effective method [Nakatani et al., 2013; 2014b]. We simulated typical debris flow condition and real disaster cases.

2. DEBRIS FLOW DISASTER IN IZU OSHIMA

We conducted a field survey and refereed disaster reports to collect information on recent debris flow disasters in Japan, such as the Izu Oshima sediment disaster that occurred in October 2013. We gathered data on debris flow disasters such as the area and height of the flooding and deposition, and information on the houses such as the location and degree of damage by debris flow.

2.1 Outline of the Izu Oshima debris flow disaster

Izu Oshima is in Tokyo prefecture, about 22 km south of Tokyo city, off the east coast of the Izu Peninsula (Fig. 1).

Heavy rain caused by Typhoon No. 26 fell on the Izu Oshima town on October 15–16, 2013, and a 24 h precipitation of 824.0 mm was recorded. Many sediment disasters, including landslides and debris flows, tragically resulted in 39 missing or dead and 73 destroyed buildings in Okanazawa, as shown in Fig. 2. Furthermore, Izu Oshima, a volcanic island, had its most recent major eruption in 1986, and debris flows have occurred many times in the past. Therefore, the topography of this island is a result of volcanic activity and the movement of sediment.

By comparing the landforms before and after the disaster, the characteristics of the erosion/deposition area could be classified by slope distribution. In the upstream eastern area, the slope was larger than 8–10°, and the amount of erosion was remarkable. In the downstream western area, the slope was less than 8–10°, and the amount of deposition was remarkable. Figure 3 shows the longitudinal profile of Okanazawa; the slope degree values shown are the average of each section.
2.2 Damage in Okanazawa

Kandachi village in the upstream area was damaged by the debris flows. Here, several debris flows struck the village from the main stream, Okanazawa, and from left branch which was a subsidiary stream. A portion of the flow crossed over the basin boundary because of the large scale of the debris flow and the shallow valley typical of volcanic islands. In Kandachi, most of the houses were directly damaged by debris flow and many of the houses were completely destroyed and swept away. Figure 4 shows a photo of the Kandachi area and Motomachi area after the disaster.

Motomachi village in the downstream area was also damaged. Flooding and deposition were remarkable, especially at small bridges where wood debris caused blockages. Downstream of the blocked bridges, the flow moved along the roads and some part of the flow and sediment spread in a transverse direction. However, debris wood mostly stopped along the flow channel and did not spread.

Figure 5 shows the downstream area of Okanazawa. The upper photo was taken on Oct. 16, 2013, just after the disaster occurred, when the sediment and debris wood were not removed, and bridges blockaded with debris wood can be seen in the photo. The lower figure shows the maximum flow trace and the area of sediment movement; the data was provided by Public Work Research Institute (PWRI), JAPAN. Here, maximum flow trace shows the maximum depth in the whole event. Places that deposition happened, the value shows the maximum flow depth plus deposition thickness. Place that only flooding happened, the value shows the maximum flow depth during the event. Figure 5 also shows the degree of damage to houses, debris wood blockages at bridges, and deposition information from aerial photos and field surveys. Contour lines shown in the lower figures are the data before the disaster in 2 m interval.

Looking at the maximum flow traces in Kandachi area, many points are higher than 1.5 m and most of the damaged houses were completely destroyed. Upstream houses suffered greater damage from direct hits by large volumes of swift debris flow. Some houses less damaged in Kandachi were located at higher elevations than the surrounding area.

For the Motomachi area, the flow trace values vary from high to low. Most of the points higher than 1.5 m are close to the bridges blockaded with debris wood. Most of the damaged houses are located along the channel. Some of the houses are not directly along the channel, but are located close to the blockaded bridge and crossroads. Most of the damaged houses were partly destroyed in Motomachi, and some completely destroyed houses are located close to the blocked bridge.

Downstream of the blocked bridges, the flow moved along the road and some part of the flow and sediment spread in a transverse direction. However, debris wood mostly stopped along the flow channel and did not spread. In the narrow range around the crossroad, the value of the trace shows the wide distribution; point close to the bridge shows higher than 1.5 m, on the other, some points show such as 1.0-1.5 m, 0.75-1.0 m, and 0.5-0.75 m.

Debris flow generally moved downwards along a straight line. However, in the Izu Oshima disaster, especially in downstream areas, the flow direction changed around houses and along roads, which were the areas with the lowest elevation in the
residential areas. 
Houses in lower locations suffered more damage from the gathering of the flood waters and debris. Houses facing small bridges were damaged because debris wood was blocked by such bridges, resulting in high flow depths, overflow of the channel, and flooding and sediment deposition around the bridges.

Therefore, in the Okanazawa area, houses located upstream, in lower areas, and those facing small bridges and crossroads suffered greater damage than those located in other areas.

3. DEBRIS FLOW NUMERICAL SIMULATIONS CONSIDERING HOUSES

We performed numerical simulations using the debris flow simulators KANAKO 2D and the advanced GIS-based system Hyper KANAKO to determine the effect of houses on debris flow flooding and deposition.

In both simulation system, the debris flow numerical simulation is based on the model presented by Takahashi [Takahashi et al., 2001; Takahashi, 2007]. Governing equations include equations for momentum, continuation, riverbed deformation, erosion/deposition, and riverbed shearing stress.

The $x$-axis flow (main flow direction) is given by the following momentum equation:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial H}{\partial x} - \frac{\tau_x}{\rho h}$$  

(1)

The $y$-axis flow (cross flow direction) also uses a momentum equation, as follows:

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial H}{\partial y} - \frac{\tau_y}{\rho h}$$  

(2)

The continuity equation for the total volume of the debris flow is as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = i_b$$  

(3)

The continuity equation for determining the debris flow of particles is

$$\frac{\partial Ch}{\partial t} + \frac{\partial Chu}{\partial x} + \frac{\partial Chv}{\partial y} = i_b C_s$$  

(4)

The equation for determining the change in the bed surface elevation is as follows:
In Eqs. (1)–(5), \( u \) is the x-axis flow velocity, \( v \) is the y-axis direction flow velocity, \( t \) is time, \( g \) is the acceleration due to gravity, \( H \) is the flow elevation \( H = h + z \), \( h \) is the flow depth, \( z \) is the bed elevation, \( \tau_x \) and \( \tau_y \) are the riverbed shearing stresses in the x- and y-axis directions, \( \rho \) is the interstitial fluid density, \( i_0 \) is the erosion/deposition velocity, \( C \) is the volumetric sediment concentration in the debris flow, and \( C^* \) is the sediment concentration by volume in the movable bed layer.

For the simulations, the grid points of the house locations were set taking into consideration the height of the houses from the ground elevation. We also performed simulations without incorporating houses. We performed simulations of typical debris flow condition and real disaster cases.

### Table 1 Simulation cases

| Case   | Houses conditions          |
|--------|----------------------------|
| Case 1 | Without houses             |
| Case 2 | With small houses (10m×10m) |
| Case 3 | With large houses (20m×20m) |

### Table 2 Simulation parameters

| Parameters/Variables | Value | Unit |
|----------------------|-------|------|
| Simulation time      | 900   | s    |
| Time step            | 0.01  | s    |
| Diameter of material | 0.15  | m    |
| Mass density of bed material | 2650 | kg/m² |
| Mass density of fluid (water and mud, silt) phase | 1000 | kg/m² |
| Concentration of movable bed | 0.6 |       |
| Internal friction angle | 35   | deg  |
| Acceleration of gravity | 9.8  | m/s² |
| Coefficient of erosion rate | 0.0007 |       |
| Coefficient of deposition rate | 0.05 |       |
| Manning's roughness coefficient | 0.03 | s/m³/² |
| 1D area interval     | 5     | m    |
| 1D area simulation points | 50   |       |
| 1D area channel width | 5     | m    |
| 2D area interval (flow direction× cross direction) | 5×5 | m×m |
| 2D area simulation points | 50×64 |       |

### 3.1 Typical conditions for landform and debris flow scale

#### 3.1.1 Simulation conditions

First, we considered typical landform and debris flow scale conditions. For landform conditions, we set the landform as shown in Fig. 6—a mountainous torrent in the upstream area—considered as a 1D simulation area, and alluvial fans as residential areas and the 2D simulation area.

In both areas, the transverse direction was set as flat. We supplied only water from the upstream end as shown in Fig. 7, and movable sediment on the 1D area was eroded and debris flow occurred and developed. The peak discharge and duration time was set considering that small-scale debris flow occurs with high frequency in Japan.

For the houses, we set the height as 6 m, which corresponds to two-floor houses. The simulations were run for cases without houses, with small houses, and with large houses, as shown in Table 1. The size of houses described as small (100 m²) and large (400 m²) are comparing with 122 m², average of homeownership houses in 2013, Japan. The simulation parameters used in this study and shown in Table 2 are widely applied in debris flow simulations in Japan, such as diameter of material and mass density of fluid. The 2D mesh size was set as 5 m mesh because the 2D area is small as 0.08 km², and we need to set smaller mesh size comparing to house size.

#### 3.1.2 Simulation results

Deposition thickness after the simulations is...
shown in Fig. 8. Results shows that when houses are present, the debris flow spreads widely in a cross direction upstream of the houses.

Houses located in the debris fan influence the deposition area. At the upstream of the houses in Case 2 and Case 3 with houses, larger deposits occur than with Case 1 without houses. The presence of houses led to flooding and deposition damage in some places and reduced the damage in others. When houses were present, the flow moved down between the houses, especially in Case 3, with houses; as in the real disaster cases flow moved down towards the roads.

3.2 Real disaster cases

In this section, we present the simulations of the debris flow disaster in Izu Oshima using the Hyper KANAKO system.

3.2.1 Simulation conditions

Hyper KANAKO can use two different landform data formats, LP data, which is the standard format for sabo works in Japan, and 10-m mesh digital elevation data provided by the Geospatial Information Authority of Japan (GSI), which has a wide area of application. In this study, we used the data from GSI before the disaster occurred.

Usually, when performing debris flow simulations, the user sets a 1D area for the steep-torrent upstream area and a 2D area for the downstream mild-slope area. However, for the Izu Oshima debris flow, because undulating surfaces exist in the steep area, this method does not describe the disaster situation well. The authors have previously applied a new method, setting a 2D area for the upstream steep area, which showed the flooding and deposition situation for the Izu Oshima debris flow case relatively well [Nakatani et al., 2014a]. Therefore, we applied this new method in this study.

The landform condition was set as shown in Fig. 9, using a 2D area from the steep upstream area. The green line shows the 1D area and the blue rectangle shows the 2D area; the Okazawa sabo dam, Kandachi area and Motomachi area are also shown. In the downstream Motomachi area, marked by the yellow polygon, we considered house heights, which were adjusted to the simulation mesh size. For the houses, we set the height as 6 m, which corresponds to two-floor houses. The longitudinal profile and slope degree of the 1D area and the steepest gradient line toward the Okazawa sabo dam are shown in Fig. 10.

We set the hydrograph from the upstream end as shown in Figs. 11 and 12, with 30% sediment concentration. The large hydrograph, hydro1, represents the Izu Oshima debris flow in 2013, and
the peak discharge was set considering the field surveys. The total volume and sediment volume of the small hydrograph, hydro2, was set to be 1/10 of hydro1 since hydro1 represents an extremely large-scale debris flow that occurs less frequently. We did not set movable beds on the 1D and 2D areas. We simulated cases with and without houses, and for the large and small hydrograph cases, as described in Table 3.

The particle diameter was set at 0.2 m, taking into account the coarse sediment deposits on the upstream of the Okanazawa sabo dam. Furthermore, Izu Oshima is a volcanic island and the debris flow consisted of fine sediment, and therefore, 1,200 kg/m$^3$ was set as the mass density of the fluid (water and mud + silt) phase. Other simulation parameters were set as in Table 4. The mesh size of 2D area was set as 10 m by 10 m. It seems large for considering houses existence. However, original landform data from GSI was 10 m by 10 m, and the houses and roads installation were displayed using this mesh size. Therefore, we applied 10 m mesh in this simulation.

The real damage appears to have occurred from several torrents and multiple flows; in this study, we set the scenario for only one debris flow from the main stream.

3.2.2 Simulation results

Figure 13 shows the results of the maximum trace (flow depth plus deposition) that occurred in the simulation. Our definition of the maximum trace is based on the following phenomenon. When deposition occurs, the landform and riverbed elevation change from their initial conditions; therefore, using only the flow depth from the initial riverbed cannot accurately express the flooding and damage. For areas in which deposition did not occur, such as the downstream mild-slope area, the maximum trace was the same as the maximum flow depth. The sediment movement area from PWRI, JAPAN, is shown in the white framed area.

All cases’ results show that the debris flow moved down toward the channel. At the Okanazawa sabo dam, a high trace is shown in all cases.

The large hydrograph cases, Case 4 and Case 5, describe the disaster area well. Traces including flow depth and deposition are 5 m upstream at the sabo dam and show flooding in the Motomachi area, describing the disaster situation well. Unlike the real situation, the Kandachi area did not show a large trace; this is because we supplied debris flow from the main stream. In the Kandachi area, as

| Table 3 Simulation cases |
|-------------------------|
| Case | Houses condition | Supplied hydrograph |
|------|------------------|---------------------|
| Case 4 | Without houses | hydro1 (large) |
| Case 5 | With houses | hydro1 |
| Case 6 | Without houses | hydro2 (small) |
| Case 7 | With houses | hydro2 |

| Table 4 Simulation parameters |
|-----------------------------|
| Parameters/Variables | Value | Unit |
| Simulation time | 1200 | s |
| Time step | 0.01 | s |
| Diameter of material | 0.2 | m |
| Mass density of bed material | 2650 | kg/m$^3$ |
| Mass density of fluid | 1200 | kg/m$^3$ |
| (water and mud, silt) phase | | |
| Concentration of movable bed | 0.6 | |
| Internal friction angle | 35 | deg |
| Acceleration of gravity | 9.8 | m/s$^2$ |
| Coefficient of erosion rate | 0.0007 | |
| Coefficient of deposition rate | 0.05 | |
| Manning's roughness coefficient | 0.03 | s/m$^{1/3}$ |
| 1D area interval | 5 | m |
| 1D area simulation points | 51 | |
| 1D area river width | 10 | m |
| 2D area interval (flow direction × cross direction) | $10 \times 10$ | m × m |
| 2D area simulation points | $202 \times 104$ | |
Fig. 13 The maximum trace (flow depth plus deposition) during simulation; figures on the right show a zoomed-in Motomachi area (black pentagon shows the area considering houses)

noted in Chapter 2, damage from the left branch of the stream debris flow was large. However, the Kandachi area was also damaged by the main stream’s debris flow, which the results explain well.
Furthermore, in the large hydrograph cases, the debris flow moved down in multiple directions with diversion and confluence at the upstream area. They show wider trace areas compared to the small hydrograph cases at the downstream area, especially in the Motomachi area. In addition, in the small hydrograph cases, the debris flow moved down toward the channel as compared to the situation in the large hydrograph cases.

Houses caused different trace ranges in the both hydrograph cases. In the large hydrograph case, Case 5, with houses, the flow direction changed, flowing to the left bank (south) side of the channel, while in Case 4 with no houses, the flow direction changed to the right bank (north) side.

Both results explain the real disaster situation well. However, Case 5, with houses shows a higher trace at the crossroad point, close to the downstream blockaded bridge, spreading toward the roads. In Case 4, Motomachi downstream area shows almost same value such as 0.1-0.5 m and 0.50-1.0 m widely. On the other hand, in Case 5, the value distribution is wide in the narrow range around the crossroad; some part shows high 3.0-5.0 m, whereas other part shows 1.0-3.0 m, 0.50-1.0 m, and 0.1-0.5 m. As mentioned in Chapter2, the value of trace shows wide distribution close to the crossroad, therefore, Case 5 considering house case present the disaster well.

In the small hydrograph Case 7, the trace in the area with the houses is smaller than the case with no houses, Case 6. Flow stopped at the upstream area of Motomachi in Case but not in Case 6. A larger trace of 3 m occurred at the downstream area in Case 7, while it was 0.1–1 m at the downstream area in Case 6. This appears to have occurred because the presence of houses caused higher flow depth and deposition upstream of the houses.

Therefore, for both large and small hydrograph cases, the presence of houses affects the debris flow flooding and deposition areas.

4. CONCLUSIONS

In this study, we gathered data on debris flow disasters such as the area and height of the flooding and deposition, and information on the houses damaged by debris flow. Then, we conducted a field survey to collect information on the Izu Oshima debris flow disaster. We performed numerical simulations using the debris flow simulators KANAKO 2D and Hyper KANAKO to determine the effect of houses on debris flow flooding and deposition. We simulated typical debris flow condition and real disaster cases. The results show that the presence of houses increased flooding and deposition damage in some places, while reducing the damage in others. When houses were present, the flow moved down between the houses; as in the real disaster cases the flow moved down toward the roads. In Izu Oshima simulation, the value distribution is wide around the crossroad when considering houses, which was indicated in the real disaster. Therefore, considering hazard area and non-structural countermeasure such as evacuation, simulation method of taking in the houses influence will be effective to explain the disaster scenario well.

In the Izu Oshima disaster, houses facing small bridges and crossroads suffered greater damage than those located in other areas. In the simulation, we did not consider the bridges-blockade phenomena caused by debris wood. We also didn’t consider the houses structure and destruction. Furthermore, applying smaller mesh size will enable to indicate detail housing, pathway and houses direction to the debris flow. In future studies, we will improve the method and system to take this process into account to explain and predict disasters, and for the prevention and reduction of debris flow disasters.

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