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Influence of Housing and Urban Development on Debris Flow Flooding and Deposition

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Abstract: Debris flows form deposits when they reach an alluvial fan until they eventually stop. However, houses located in the alluvial fan might affect the debris flow flooding and deposition processes. Few previous studies have considered the effects of houses on debris flow flooding and deposition. This study conducted model experiments and numerical simulations using the Kanako2D debris flow simulator to determine the influence of houses on debris flow flooding and deposition. The model experiments showed that when houses are present, the debris flow spreads widely in the cross direction immediately upstream of the houses, especially when the flow discharge is large or the grain size is small. Houses located in the alluvial fan also influence the deposition area. The presence of houses led to flooding and deposition damage in some places and reduced the damage in others. The simulation also demonstrated the influence of houses. Both the model experiment and the simulation showed that houses change the flooding and deposition areas.

Keywords: Debris flow; Alluvial fan; House; Model experiment; Numerical simulation

Introduction

Debris flows from a mountain river gradually form deposits upon reaching an alluvial fan, which in turn causes the slope of the fan to decrease until the debris flows eventually stop (Mizuyama and Shimohigashi 1985). Now, residential areas are commonly located in such alluvial fans, and these may influence debris flow flooding and deposition (see Figure 1, Mizuyama and Ishikawa 1989; Ishikawa et al. 1992). Some studies have previously considered the influence of residential areas on flooding without sediments (Iwasa et al. 1980; Takahashi et al. 1985). Separately, although various studies have focused on debris flows (Takahashi and Tsujimoto 1984), few have reported model experiments or numerical simulations to consider the effects of residential areas on debris flow flooding and deposition (Takahashi et al. 1988; Ghilardi et al. 2000; Lin et al. 2011; Loup et al. 2012).

In order to determine the flooding and deposition range in alluvial fans, it is necessary to set landform data and generate a mesh for simulation. However, technical limitations mean that presently, the mesh size may be as large as tens of square meters. Consequently, a single grid may contain several houses, making it impossible to accurately model the existence of houses.

Recently, the Geographical Survey Institute and Sabo Offices in Japan have acquired large amounts of accurate laser profiler (LP) data containing detailed digital topographic information. In Japan, wide-scale measurements for sabo work

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Figure 1 Debris flow flooding and deposition in Hofu, Yamaguchi Prefecture, Japan in July 2009 (from the Asia Air Survey Co., Japan)

were conducted from 2008 to 2010 using LPs with a standard data format. These LP data provide detailed topographic information about areas that are prone to sediment-related disasters. The three-dimensional (3D) topographical data in the LP database cover mountainous areas (~55,000 km^2, 15% of Japan's area) and provide accurate information for the Japan Profile for Geographic Information Standards (JPGIS) standard mesh size (1 × 1 m^2). Therefore, it is expected that this data will find widespread use in research on crisis management and sabo work (Horiuchi 2010; Nakatani et al. 2012).

In addition, debris flow numerical models have been extensively developed in previous studies, and with concurrent improvements in graphical user interfaces (GUIs), users can now simulate debris flow flooding and erosion/deposition easily and accurately. For example, Kanako2D is a freely available GUI-based debris flow simulator that is widely used in Japan (Nakatani et al. 2008).

To prevent and reduce the damage caused by debris flows, evacuation from dangerous zones is an essential non-structural measure. However, it is difficult to identify specific high-risk zones because evacuation advisories and directives are generally issued for large areas. Separately, owing to normalcy bias or a lack of belief in the administration, residents often do not adhere to the evacuation directives.

At the same time, it should be noted that it is impossible to effectively cover all dangerous debris flows from mountain streams with a suitable structural measure owing to budget limitations.

Then, as a realistic non-structural measure, to realize effective evacuation from a threatened area, high-risk and safe zones should be accurately identified. For example, houses located upstream of an alluvial fan may face greater risk from a nearby debris flow torrent than would houses located downstream.

This paper evaluated the influence of houses on an alluvial fan. First, the authors conducted model experiments to examine how the existence of houses changed the hydrograph supplied from the upstream and the grain size of the debris flow. Then, this study simulated the debris flow using Kanako2D and compared the experiment and simulation results.

1 Model Experiment

1.1 Methods

In the model experiment, a physical model of an alluvial fan, shown in Figures 2 and 3, was used. A contour map of the physical model (contour interval: 10 cm) is shown in Figure 4. The numbered houses are used to indicate the results.

The model scale was 1/30, and the vertical slope of the alluvial fan ranged from 1/2.7 to 1/5.5. This study placed a rectangular straight open channel with a length, width, and slope of 7 m, 30

Figure 2 Straight channel and physical model

Figure 3 Physical model (left-hand side: with houses; right-hand side: without houses)

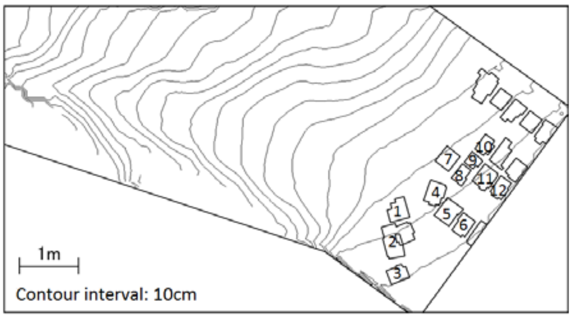

Figure 4 Contour map of physical model (contour interval: 10 cm)

cm, and 1/2.5, respectively, upstream of the physical model. The authors covered the experimental channel with 5-cm-thick sediment and supplied a steady flow of water from the upstream to generate a debris flow. The sediment material used is SiO$_2$.

Table 1 Experiments cases

Cases	Sediment diameter (mm)	Supplied discharge (L/s)	Supplied time (s)	House existence
Case1	1.4	7.5	19	Without
Case2				With
Case3		5.5	27	Without
Case4				With
Case5		3.5	50	Without
Case6				With
Case7	3.0	5.5	35	Without
Case8				With

The authors conducted experiments to examine the effects of the supplied discharge and sediment diameter (uniform size) with and without house models, as shown in Table 1. 20-cm-high house models were used in the experiment to model actual two-story, 6-m-high houses. The model was videotaped while supplying water, and after water passed through the model, measured the sediment thickness and range. The cases are summarized in Table 1.

This study conducted more experiments with and without the house models, and recorded videos. These cases used a sediment diameter of 3.0 mm and discharge of 3.5 L/s or a sediment diameter of 3.0 mm and discharge of 5.5 L/s.

1.2 Results

First, the authors considered the relationship between the supplied discharge and the front velocity of the debris flow. Using the video recordings, the authors measured the time taken to travel from the inflow point of the physical model to upstream of the houses, and calculated the average velocity of the debris flow front, as plotted in Figure 5, according to the discharge supplied.

Figure 5 also shows a plot of the relationship between the discharge and the velocity of clear water based on the Manning formula (Arcement and Schneider, 1989). Discharge refers to water and sediment, and clear water refers only to water. Here, the authors used the average value of the debris flow front width for each case in the video as the wetted perimeter value. This study applied three different values of Manning's roughness coefficient: 0.02, 0.03, and 0.04. The results showed that the front velocity of the debris flow increases with the discharge supplied. This trend is validated from Manning's formula. At an overall level, the results did not differ markedly for each sediment diameter. The videos showed that the velocity increases with the discharge. In addition, at an overall level, for constant discharge, the velocity is higher when the particles are smaller, and consequently, the debris flow spreads more widely in the cross direction just upstream from the houses when it hits them.

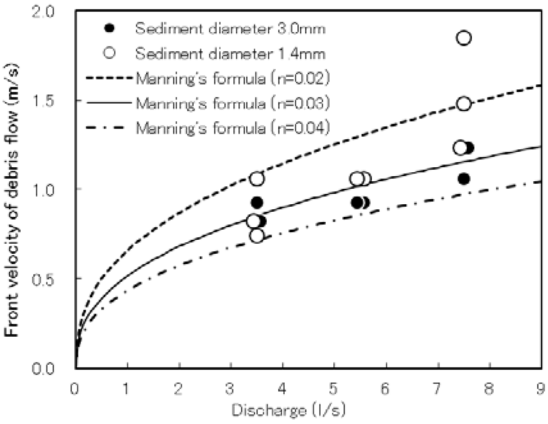

Figure 5 Relationship between supplied discharge and front velocity of debris flow

Figures 6(a)–(h) show the results of the deposition range and thickness measured. This study used a 3D laser scanner to measure the sediment thickness. In these figures, the scale of the landform and deposition are converted to field-scale values (30 times larger than the model scale) so that we can easily compare them with the

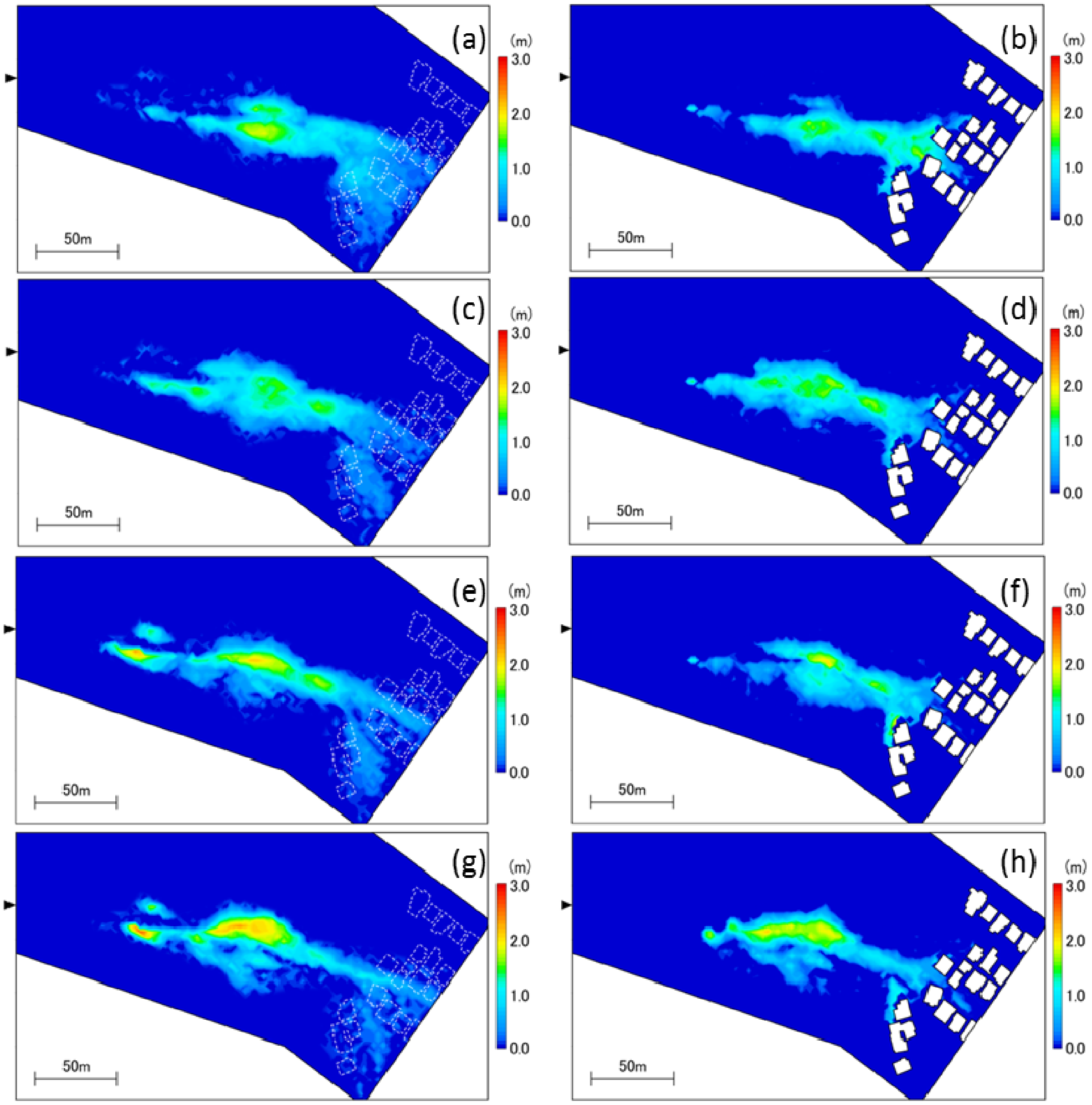

Figure 6 Deposition thickness distribution in experiments (a) Case1; (b) Case2; (c) Case3; (d) Case4; (e) Case5; (f) Case6; (g) Case7; (h) Case8

simulation results mentioned in Chapter 3.

The white area indicates the location of the model houses. For the cases without houses, the dotted lines indicate residential areas. The black triangle on the left-hand side of each figure indicates the inflow point of the physical model. The color legend on the right-hand side of each figure indicates the deposition thickness.

When houses are located in an alluvial fan, the debris flow spreads widely in the cross direction upstream from the houses when hitting the houses. (see Figures 6 (b), (d), (f), (h)). Thicker depositions are observed upstream of houses No. 1, 4, and 7 (Figure 4 shows the locations of houses) compared to the case without houses (see Figures 6 (a), (c), (e), (g)). In particular, compared to the upstream of houses No. 4 and 7, cases without houses show very small (0.5 m in Case 1) or almost no deposition (Cases 3, 5, and 7). On the other hand, compared to the upstream of houses No. 4 and 7, cases with houses show depositions of ~1.0 m. In Case 6 (see Figure 6(f)), 2.0-m-thick deposition is observed locally upstream of house No. 1, whereas in Case 5, no deposition is observed. In Cases 1 and 3, no deposition is observed upstream of houses No. 9 and 10 (see Figures 6 (a), (c)); however, in Cases 2 and 4, in which houses exist (see Figures 6 (b), (d)), 0.5–1.0 m of deposition is observed.

This is because when house exists, they will block the flow; as a result, the flow depth will increase, velocity will decrease, and flow direction will change upstream of the house. Therefore, the deposition range also spreads widely in the cross direction upstream from the houses.

In some areas, debris flow and deposition were less hazardous when there were no houses because the flow depth and deposition thickness were small. The presence of houses altered the flooding and deposition processes by increasing the flow depth and deposition thickness, and the corresponding danger (e.g., upstream of houses No. 1, 7, 8, and 9). Nevertheless, in some places, the presence of houses reduced damage caused by the flow depth and deposition. Downstream of houses No. 1 and 4, both the deposition range and the thickness are small. In particular, in the area where houses No. 2, 5, and 6 are located, deposition decreases.

2 Numerical Simulation

2.1 Methods

Setting the same conditions for the model experiment as those described in Table 1, this study ran debris flow simulations on Kanako2D, which can be used to simulate a steep mountain river as a one-dimensional (1D) area and a gently sloped alluvial fan as a 2D area. Kanako2D is based on Takahashi's model (Takahashi and Kuang 1986; Takahashi and Nakagawa 1991; Takahashi et al. 2001). Kanako2D has been previously applied to some debris flow simulations, and reasonable results were obtained (Liu et al. 2012). In our simulations, the authors set the experimental channel as the 1D simulation area and the physical model as the 2D simulation area. In Kanako2D, the simulation process and GUI maintenance, such as the simulation interval time, interval distance, and mesh size, are developed for actual field scales on a meter scale. Therefore, this study applied Froude's similarity and set the landform data and hydraulic conditions to the field scale (30 times larger than the model scale). The authors then ran the simulations and compared their results with those of the model experiments. The parameters used in our simulation are shown in Table 2. This study applied commonly used values for debris flow numerical simulations, and also used some values obtained from

Table 2 Simulation parameters

Parameter (unit)	Value
Simulation time interval (s)	0.01
Mass density of sediment (kg/m^3)	2,650
Mass density of fluid phase (kg/m^3)	1,000
Concentration of movable bed	0.60
Gravity acceleration (m/s^2)	9.8
Coefficient of erosion rate (Takahashi and Nakagawa 1991)	0.0007
Coefficient of deposition rate (Takahashi and Nakagawa 1991)	0.05
Manning's roughness coefficient (s /m$^{1/3}$)	0.03
Number of 1D area calculation points	22
Interval of 1-D calculation points (m)	10
Number of 2-D calculation points (flow direction × cross direction)	100×50
Interval of 2-D calculation point (m×m)	2.91×2.91

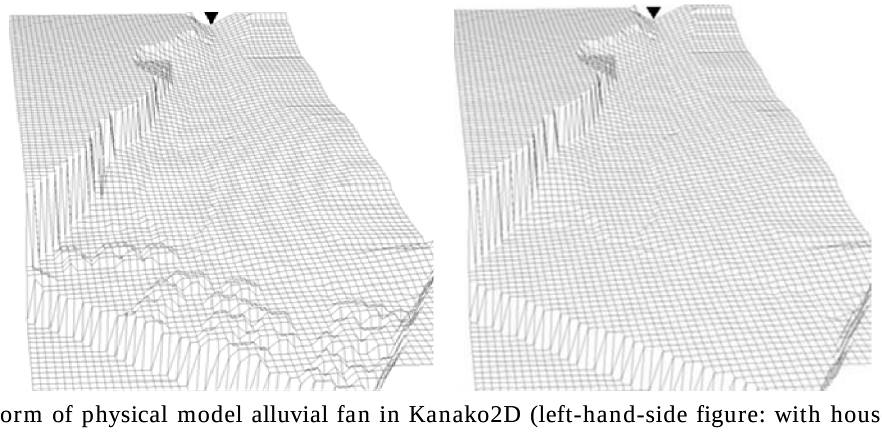

Figure 7 Landform of physical model alluvial fan in Kanako2D (left-hand-side figure: with houses, right-hand-side figure: without houses, black triangle indicates the inflow point of the physical model.)

experiment results. When simulating cases with houses, this study set the landform elevation where the houses would be located to 6 m higher than in the case without houses. Figure 7 shows this difference in the landform.

2.2 Results

Figures 8(a)–(h) show the results of the simulations of deposition range and thickness.

When houses are located in the alluvial fan, the deposits are thicker and are spread more widely upstream from the houses (see Figures 8(b), (d), (f), (h)). This tendency is similar to the results of the model experiment. Upstream of houses No. 1, 2, and 4 (Figure 4 shows the location of houses), thicker depositions are observed compared to the case without houses (see Figures 8(a), (c), (e), (g)). In particular, upstream of houses No. 1 and 2, cases without houses show small (0.5–1.0 m range) deposition.

On the other hand, cases with houses show depositions of ~1.5 m. In particular, upstream of house No. 1, deposition of more than 3.0 m occurs.

In Cases 1 and 3, no deposition was observed upstream of house No. 8, but when houses exist, deposition of 0.5–1.0 m occurs. On the other hand, the presence of houses reduced deposition. In

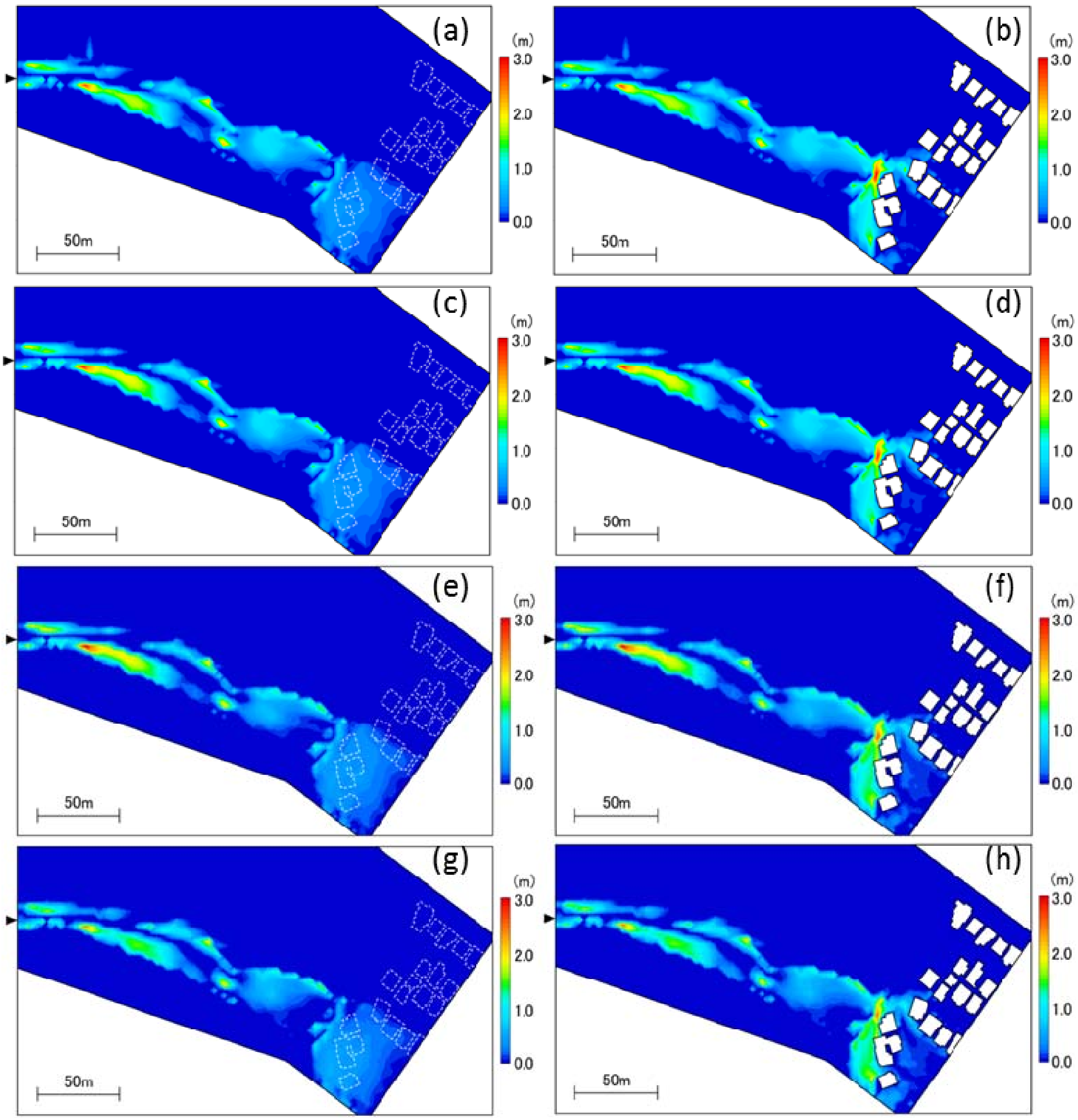

Figure 8 Deposition thickness distribution in simulations (a) Case1; (b) Case2; (c) Case3; (d) Case4; (e) Case5; (f) Case6; (g) Case7; (h) Case8

particular, downstream of houses No. 3 and 6, less deposition is observed where houses are present.

Conversely, with regard to the deposition range in the vertical direction on the alluvial fan, the simulation results show that it is greater in the upstream area than in the experiment. This might be because the mesh generated for the simulation was on a model scale of 10×10 cm^2; therefore, the landforms were averaged. Alternatively, small topographic conditions included in a single mesh might have affected the results.

2.3 Discussion

Both model experiments and simulation results showed that when houses are located in an alluvial fan, the debris flow spreads widely in the cross direction upstream from the houses when hitting the houses. Houses exist on alluvial fan will block the debris flow; as a result, the flow depth will increase, velocity will decrease, and flow direction will change upstream of the house. Then the deposition range also spreads widely in the cross direction upstream from the houses.

Moreover, from both results, in some areas, debris flow and deposition were less hazardous when there were no houses because the flow depth and deposition thickness were small. The houses existence altered the flooding and deposition processes by increasing the flow depth and deposition thickness. Nevertheless, in some area, the houses existence reduced damage.

The authors consider the debris flow mitigation planning on alluvial fans as follows. When possible, setting sabo dam or check dam will be effective because most of the debris flow sediment will be cut off by the dam. However, the lack of fund and a number of debris flow dangerous torrents exist in Japan, covering the entire dangerous site with large structural as dam is unrealistic.

Considering easier and less expensive method that people live in alluvial fans can deal with, following plan can be suggested from this study; setting small constructions as fences upstream of houses. The function of fences is expected as same as training walls on rivers, to change or control the flow direction. Therefore, debris flow will spread upstream of the fence and house damage as flow depth and deposition thickness can be reduced. Thus, if only some of the houses set fences, debris flow flooding and deposition range will change, and surrounding area may be more dangerous. Therefore, it is necessary to consider the best location of setting fences that all the houses in alluvial fan can be safe. Numerical simulations can be applied as a useful tool.

3 Conclusion

This study examined the effect of houses on flooding and deposition through model experiments and numerical simulations. The following conclusions were drawn:

(1) Houses located in an alluvial fan cause the debris flow to spread widely in the cross direction immediately upstream of the houses, thus changing the deposition area.

(2) The debris flow front velocity increases when the flow discharge is high or the grain size is small. When the velocity is higher, the debris flow spreads more widely in the cross direction upstream of houses upon hitting the houses.

(3) Using the debris flow simulation system, this study can describe the impact of houses on flooding and deposition in alluvial fans.

Thus far, planning and countermeasures for debris flow disasters did not consider the existence of houses. The results of this study showed that the existence of houses influences the deposition process, especially upstream houses. In some cases, if houses are present in the upstream area, downstream areas may be safer, because the flow direction and flooding and deposition processes will be changed upstream. Therefore, if the influence of houses is, considered, disasters can be evaluated more practically and more reasonable planning and countermeasures can be suggested.

In the near future, the authors will study the impact of debris flow on house destruction and the impact of the building material used so that could put forward suggestions on how to devise strong, safe houses against debris flow flooding and deposition.

Acknowledgement

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