Experimental Study on Effect of Houses on Debris-Flow Flooding and Deposition in Debris Flow Fan Areas

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ABSTRACT

This study conducted model experiments to determine the influence of houses on debris flow flooding and deposition. We applied uniform and also coarse-grained sediment in the following scenario cases: without houses; with houses; with houses and fences; and with houses that can be destroyed. The model experiments showed that when houses are present, the debris flow spreads widely in the cross direction immediately upstream of the houses. Houses located in the debris fan also influence the deposition area. Especially when fences exist around the houses, flow moves down between the fences, as in the real disaster cases, where flow moves down towards the roads. Finally, when houses are destroyed, flow moves down through the destroyed houses, and changes the flooding and deposition process compared with the non-destroyed houses case. With debris flow containing coarse-grained sediment, most of it deposits in the upstream area of the houses when houses exist.

KEYWORDS

debris flow; debris flow fan area; house influence; model experiment

INTRODUCTION

Debris flow causes flooding and sediment deposition when it reaches the debris flow fan area. In Japan, houses are usually built in debris flow fan areas through urban development, and these buildings affect flow and deposition during a debris flow event. As the number of people living in debris flow fan areas has increased because of rapid urban development, debris flow disasters, such as the one that occurred in August 2014 in Hiroshima Prefecture, Japan, have caused widespread damage to human lives and infrastructure. However, few studies have examined the effect of houses on debris flow disasters. This study conducted model experiments to determine the influence of houses on debris flow flooding and deposition.

METHODS

First, we considered typical landform and debris flow-scale conditions. For landform conditions, we set a mountainous torrent in the upstream area as a rectangular straight open channel with a length, width, and slope of 5 m, 0.1 m, and 15°, and debris flow fans as

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residential areas in the downstream area (Fig.1). The model scale was 1/50, and the transverse direction was set as flat. We covered the experimental channel with 0.1-m-thick sediment and supplied a steady flow of water from upstream to generate a debris flow.
The peak discharge and continuance time were set by considering that small-scale debris flow occurs at a high frequency of 2.0 L/s for 30 s and 5.0 L/s for 20 s. We examined cases of uniform sediment (diameter 3 mm) and uniform sediment with 5% coarse-grained sediment (diameter 20 mm). The sediment density was 2.58 g/cm³ and supplied sediment volume was 45 L (including void). As shown in Table 1, we considered the scenarios of without houses, with houses, with houses and fences, and with destructible houses. To model actual two-story 6-m-high houses and 2-m-high fences, 0.12-m-high house and 0.04-m-high fence models were used. In this study, we set destructible houses to see how the flow depth and deposition caused by debris flow change from cases with non-destructible houses. Therefore, we modeled the destructible house which can be destroyed with debris flow caused by supplied discharge 5.0L/s, and didn't consider the strength of house.

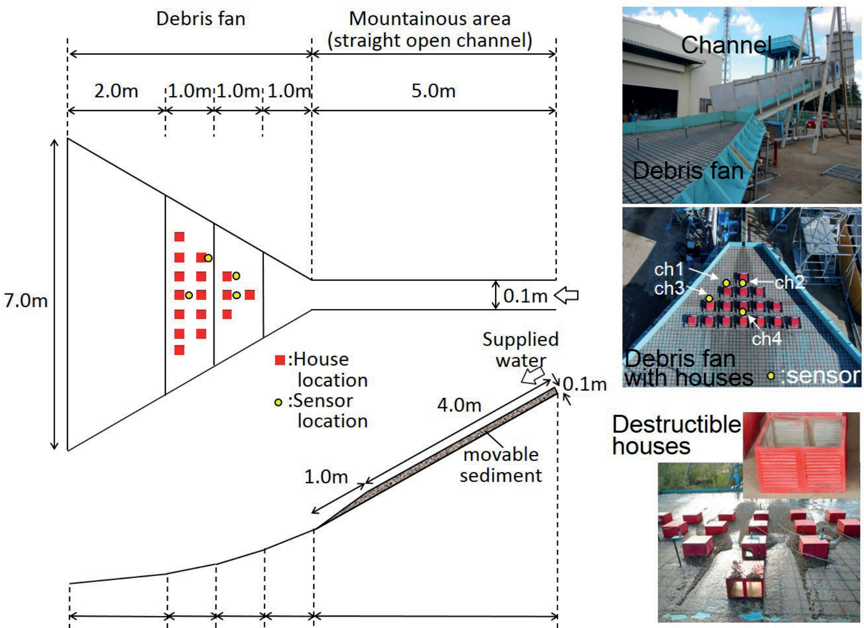

Figure 1: Cross-sectional (top left) and longitudinal (bottom left) profiles of the debris flow experiment model (top right), houses and sensors location (middle right) and destructible houses (bottom right)

Table 1: Experiment cases

Case	Sediment	Supplied discharge(L/s)	Supplied time (s)	Houses	Fences
1	Uniform sediment	2	30	without	without
2				with	without
3				with	with
4		6	20	without	without
5				with	without
6				with (destructible houses)	without
7				with	with
8	Uniform sediment with 5% coarse-grained sediment	6	20	without	without
9				with	without
10				with (destructible houses)	without

To see the time series difference of debris flow direction in debris fan due to houses and fences existence, we recorded the experiments in video and the time series of flow depth and deposition thickness using ultrasonic wave sensors (see Fig.1). The sediment thickness and range were also measured after the experiments.

RESULTS

The model experiments showed that when houses were present, the debris flow spread widely in the transverse direction immediately upstream of the houses (Fig. 2 left). Houses located in the debris flow fan also influenced the deposition area. In the case of houses with fences, the flow moved down between fences, which is similar to actual disasters where debris flow moves down toward the roads.

Fig. 3 shows the results of deposition thickness distribution. From results with no houses and uniform sediment cases, 2 L/s (Case 1) showed deposition in the upstream side where the incline changed from 12° to 9°. With 6 L/s (Case 4), results showed deposition in the downstream side where the incline changed from 9° to 6°. It is assumed that the deposition was affected by the change in the vertical section-like incline. When compared with the uniform sediment case and the case with 5% coarse-grained sediment, the result that included coarse-grained sediment showed deposition widely in the downstream area. When houses exist, results show deposition especially in the upstream of the house in the steepest location (Case 2). When fences exist around the houses, deposition becomes more remarkable around the houses and fences (Case 3). Results in 6 L/s cases show the same trend. When houses and fences exist, flow spreads in the transverse direction and deposition occurs in the upstream area compared with the cases without houses. When fences exist, flows are obstructed and deposition seems to occur because the flow move between the fences. When houses are destroyed by the debris flow (Case 6 and 10), flow pass through the inside of the destroyed houses, and results show deposition in the downstream area compared with the results of the cases with non-destructible houses.

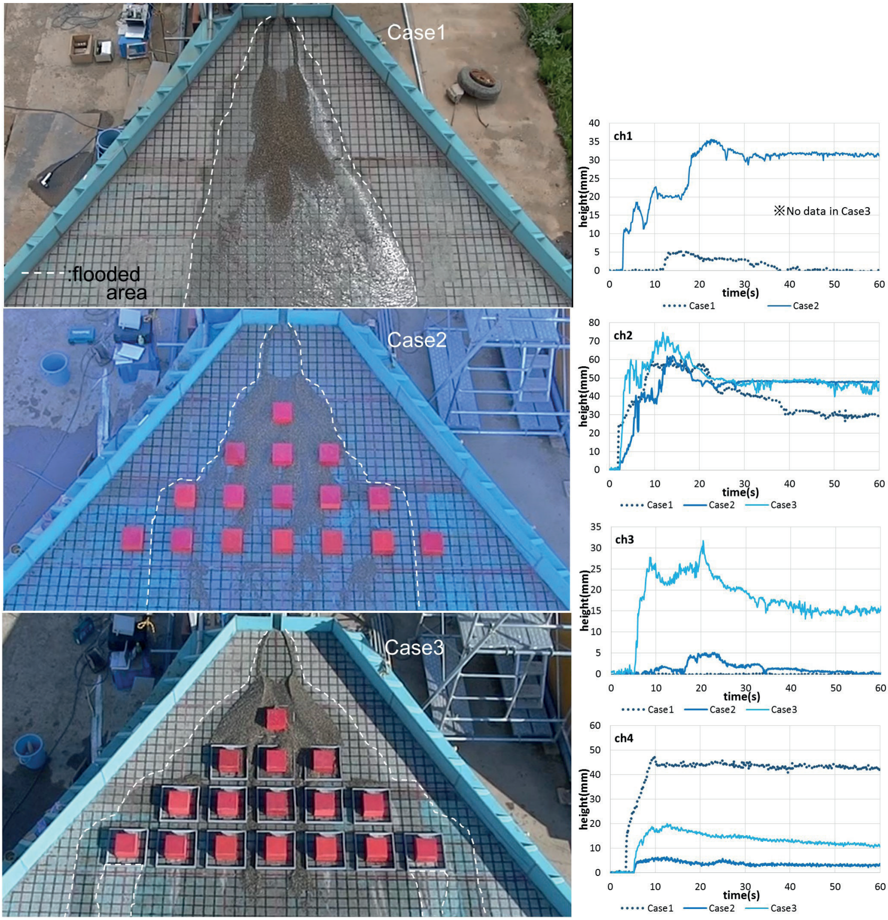

Figure 2: Deposition after the experiment (left) and sensors results (right) for debris flow discharge of 2.0 L/s (Case1-3)

Fig. 4 shows the results of coarse sediment distribution and surface deposition. The plot shown in a circle in the figure represents the position of the coarse sediment in the surface; coarse sediment inside the deposition layer is not plotted as a circle.
In the cases without houses (Case 8), little coarse sediment exists in the center line of the alluvial fan in the surface, in the 12–6° step-gradient. This seems to happen because when the flow reaches the fan from the channel, flow spreads widely, and then coarse sediment is left on the side where flow depths become small. Meanwhile, in the low-gradient (6–3°) area, coarse sediment deposits in the center of the surface.

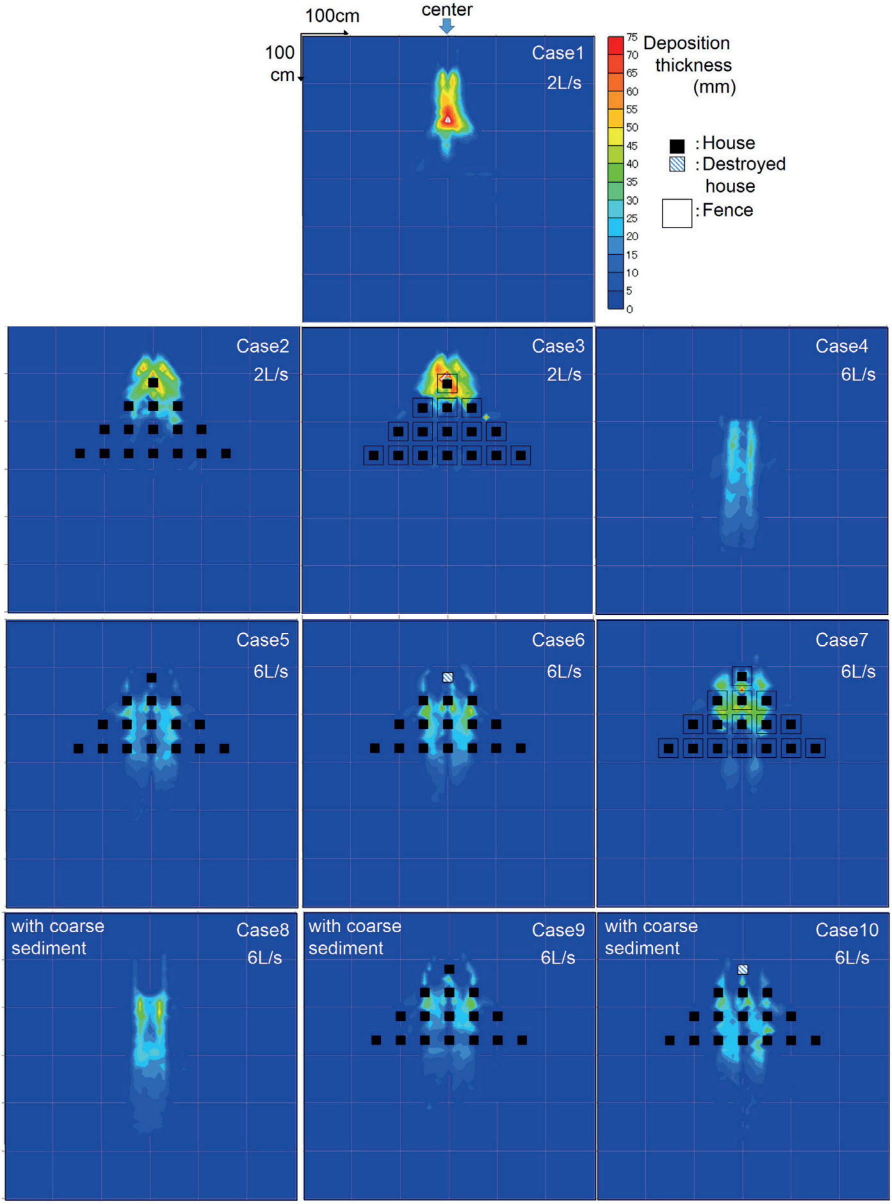

Figure 3: Sediment deposition thickness distribution for all the cases

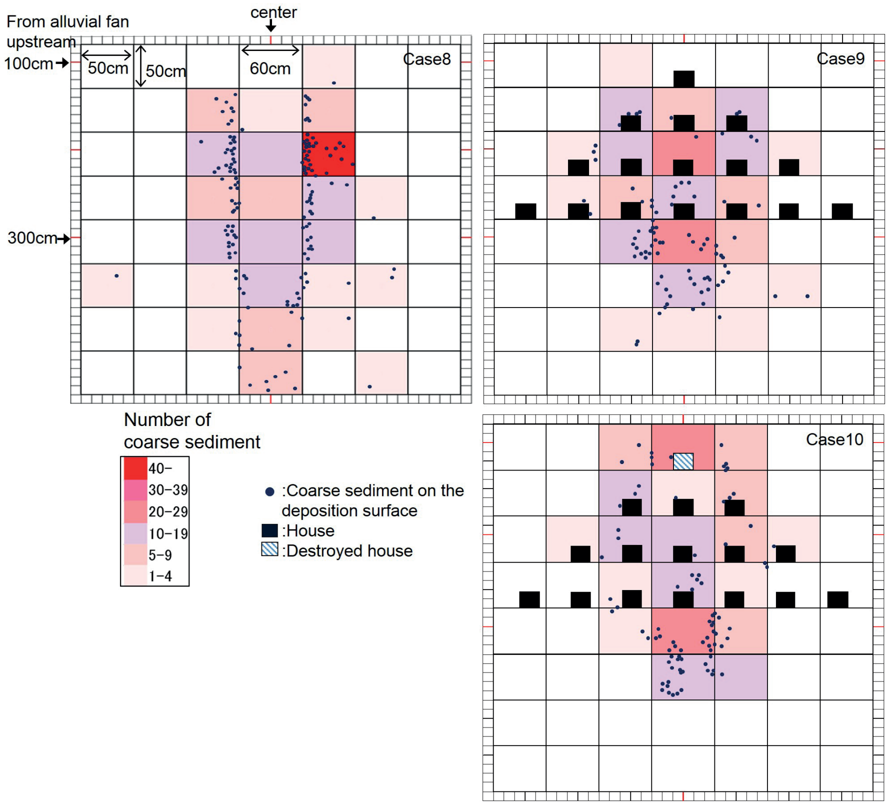

Figure 4: Coarse-sediment distribution and surface deposition (Cases 8-10)

In the case of houses without destruction (Case 9), a larger deposition of the gravel occurs on the upstream side because of the influence of the houses. In the upstream section in the figure, no deposition can be seen, but in the 2nd and 3rd sections from the upstream, deposition of the gravel can be noted. Passing through the area with the houses, gravel moves downstream to the low-gradient 6–3°area. In Case 10 (houses with destruction), the distribution of the gravel is slightly different compared with Case 9. In Case 10, deposition of gravel can be seen in the upstream section because a large amount of gravel deposited upstream of the houses and on the inside of the destroyed houses.
Fig.5 shows the data measured by the ultrasonic sensor. Note that in 6 L/s cases, flow splashed on the ch2 sensor due to the existence of houses, and data could not be acquired. During the experiment, the sensor measured the flow depth and the deposition thickness, and after the experiment it showed the deposition thickness.

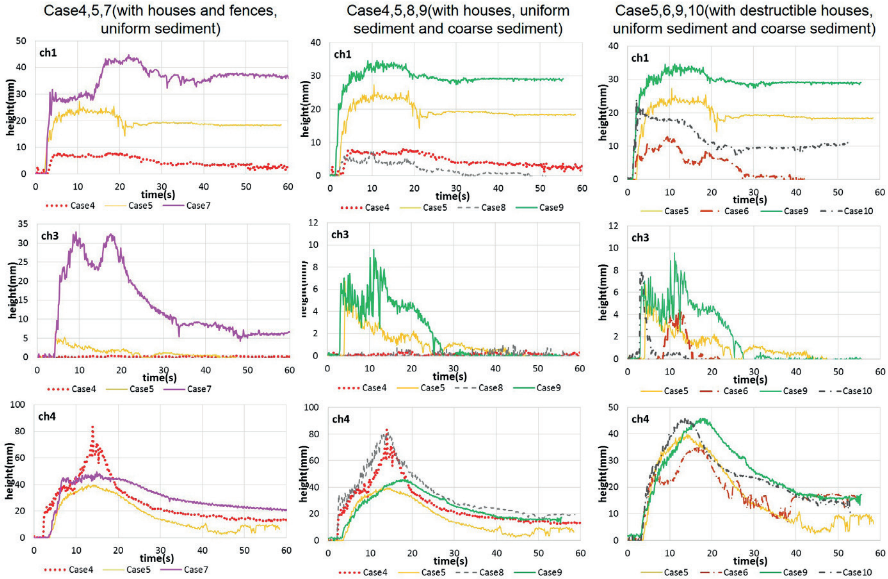

Figure 5: Sensor results of height in Cases 4, 5, 7(left), in Cases 4, 5, 8, 9 (center) and in Cases 5, 6, 9, 10(right)

From Fig. 2 right, Case 2 showed high value compared to Case1 in ch1. Case 3 data was not recorded due to sensor trouble in ch1. Since the ch1 sensor is placed on the right bank side, the sensor reaction shows that flow expanded from the house located most upstream, and it reached the position of ch1. After 60 s passed, Case 2 still showed a large height, which reveals that deposition occurred in the front of the house. In the ch2 sensor, no major changes can be seen at the start of the value increase. Case 3 showed a slightly larger value at the start. After the increase, Case 1 height seems to decrease. However, values of Cases 2 and 3 remained same and did not decrease. This seems to happen because sediment was not eroded. In ch3, Case 1 sensor did not react. In Cases 2 and 3, the sensor reacted and showed that flow and deposition had occurred. The extension of flooding and deposition occurred because of the existence of houses, which was more significant in Case 3. In ch4, Case 1 showed the largest value, second largest was Case 3, and smallest was the Case 2. The reason why Case 3 showed a lager value than Case 2 is that when fences exist, flow seems to be inhibited between the fences and deposition occurs in that position.

Fig. 5 left show the cases of 6 L/s comparing the existence of houses and fences. Case 7 showed the largest value, second largest was Case 5, and the smallest was Case 4 in ch1. These results are due to the effect that flows spread in the transverse direction when houses and fences exist. In ch3, Case 4 did not react, Case 5 value increased to 5 mm, and Case 7 increased to 30 mm, then decreased and showed 5 mm deposition at 60 s. In Case 7, two peaks of the value can be seen. From the experiment observation, the first peak happened when flow reached the alluvial fan, flowed down the center of the fan, and moved toward ch1, then ch3 from the outer side. The second peak happened when the flow reached the alluvial fan, moved down the center of the fan, passed through the area between the fences, and moved towards ch3. In ch4, Case 4 showed the largest value, followed by Case 7, and the smallest was Case 5's.

Fig. 5 center show the cases of 6 L/s comparing the influence of the existence of houses and the coarse-sediment. Case 5 and Case 9 results showed a larger value than cases without houses in ch1. Case 9 result including coarse-sediment showed the largest value. In Cases 4 and 8, flow reached the alluvial fan, spread in the transverse direction, then reached the ch1 sensor and showed reaction. Case 4 showed a larger value than Case 8. In ch3, the sensor did not react in cases without houses because flow did not reach this area. Cases 5 and 9 showed reaction in ch3, and the largest value was shown in Case 9, as in ch1. In ch4, the sensor showed a high value at the peak in Cases 4 and 8. In the latter half of the experiment, the value decreased in all cases and no significant change could be seen.

Fig. 5 right show the cases of 6 L/s comparing the influence of the existence of destructible houses and the coarse-sediment. In ch1, cases of destructible houses showed a smaller value compared with the cases of non-destroyed houses. Case 6 showed the smallest value, and the next smallest was Case 10. This difference seems to happen because of the house destroyed time. The house located at the top was destroyed earlier in Case 6 than in Case 10, therefore flow passing through to the downstream became larger and flow moving in the transverse direction to ch1 decreased. In ch3, the sensor reacted in Cases 5 and 9. In cases with destroyed houses, the value is small and also the duration is short in ch3. In ch4, almost all cases show the same start of the data increasing to the peak value. Cases 9 and 10 showed almost the same peak value, and Case 10 showed a slightly earlier peak time. This was because the flow passed through the destroyed house and flowed downstream in Case 10. On the other hand, Case 9 took more time because flow moved around the houses. In uniform sediment Cases 5 and 6, initially flow reached ch4 and showed the same reaction. After 8 s, Cases 6 and 5 showed different reactions. This was because house destruction in Case 6 occurred at the top, and flow moved down and deposition occurred around and inside the destroyed house. The flow from the upstream to ch4 was temporarily reduced.

CONCLUSIONS

We investigated the effect of the presence of houses and fences, and the destruction of houses in flooding and deposition of debris flow by a model experiment. Results showed that when houses exist, the flooding and deposition area changes, and remarkable deposition occurs upstream of the houses. When houses and fences exist, flow spreads in the transverse direction and deposition occurs in the upstream area compared with cases without houses. When fences exist around the houses, flow moves down between the fences toward the road. When houses can be destroyed, water and sediment pass through the destroyed houses; therefore sediment can move downstream compared with cases with non-destroyed houses. When including coarse-sediment, a large amount of gravel deposits upstream and inside of the destroyed houses.

According to the time-series changes, when fences exist around the houses, flow direction can be changed and more than one peak may occur from the flow passing through the roads. When house destruction happens, the timing of the destruction causes a difference of flow direction and peak time compared with the non-destroyed houses.
On engineering hazard assessment, the area affected by debris flow have been estimated without considering houses influence until now. However, from this study, we confirmed that houses, fences, and the destruction of houses affect the debris flow behavior in an alluvial fan. Therefore, to estimate the hazard area with accuracy and to plan the effective mitigation measurement, it is necessary to consider the houses influence. For future studies, we need to gather more information about the impact of houses, fences, and destruction of houses in a real disaster. Based on these experimental results, we are planning to propose numerical simulation models and programs that can describe the effect of houses on the debris flow behavior in the alluvial fan area.

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REFERENCES

- Nakatani, K., Okuyama, Y., Hasegawa, Y., Satofuka, Y., Mizuyama, T. (2013): Influence of housing and urban development on debris flow flooding and deposition, Journal of Mountain Science, Volume 10, Issue 2, pp. 273-280.
- Nakatani, K., Kosugi, M., Hasegawa, Y., Satofuka, Y., Mizuyama, T. (2015): Experimental study on debris flow behavior in debris fan area: considering influence of houses. Journal of the Japan Society of Erosion Control Engineering 67(6): 22-32. (in Japanese)