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Original Research

Hydraulic model tests for propagation of flow and sediment in floods due to breaking of a natural landslide dam during a mountainous torrent

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ABSTRACT

During mountain torrents, large-magnitude floods may result from heavy rainfall and cause the breakage of landslide dams naturally formed by heavy rainfall, earthquakes, and so on. The characteristics of longitudinal spreading of clear water discharge and changes in flow depth must be clarified because the changes in peak depth have not yet been examined in steep-slope torrents and because there are few data on spreading of flash floods and related sedimentation in mountainous torrents. In the present study, experimental data were collected through hydraulic model tests over a rigid bed, and the spreading of water, fine sediment, bed load, and large boulders due to flooding are discussed assuming that flash flooding/debris flows occur in the upstream reach. The effects of changes in flow width, such as expansions and contractions in the flow width, as well as changes in meandering channels, sediment transportation, and spreading flow depth resulting from bores are examined using flume data for a steep-slope torrent. The data obtained in the present study reveal that fine sediment components are transported to the downstream reach if large-magnitude floods occur and that the spreading rate and peak lags of the fine sediment and water level indicate the occurrence of a flood in the upstream reach.

1. Introduction

Flash floods and debris flows can form as a result of heavy rainfall and/or earthquakes (e.g., Ashida & Egashira, 1986) that break naturally forming landslide dams. Temporal and spatial changes in discharge, flow depth, and bed variations occur during flooding. The peak flows usually spread from upstream to downstream. Those peak flows usually are caused by several factors in mountainous torrents. Especially, it is well known that such floods take place by formation and breaking of natural landslide dams (e.g., Costa & Schuster, 1988; Fleming et al., 1988; Schuster & Costa, 1986; Takahashi, 2007), and formation of a debris flow with a relatively large magnitude may result in the case of the breaking of a natural landslide dam due to overtopping. Evidence of those floods usually is examined in the downstream reach because the time of occurrence of floods usually is unknown. Complete data on the flood and dam break are not available (e.g., Costa, 1988; Hungr et al., 2013), because there are few data on the temporal change of hydraulic quantities and the flood is usually observed at a section quite far downstream of the break if data even are obtained. A lot of research on outburst from natural landslide dams and related floods due to the dam break has been done through experimental (e.g., Cao et al., 2011a, 2011b; Carrivick, 2010; Horiuchi et al., 2010; Takahashi, 2007) and numerical approach (Chanson, 2005; Horiuchi et al., 2010; Satofuka et al., 2010; Walder, 1997) seems to focus on reproduction of the outburst of real and modeled, through scale-down, natural landslide dams and estimation of peak discharge due to the outburst.

The focus of the study reported here is on floods with large magnitudes in the temporal change in the rate of discharge (over the rise and fall of the flood wave) somewhere in the upstream reach after an overtopping break of a natural landslide dam. The magnitude and spreading speed of the flows below the dam break need to be examined for cases when countermeasures are applied, because floods and sediment spreading by floods due to breaking of natural landslide dams in mountainous reach are not

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understood well. Also, changes in the peak stage have not been fully examined for steep-slope torrents resulting from landslide dam breaks. In addition, fine sediment, bed load and large boulders can be transported due to particle-to-particle shear stress and by the main flow, and so the transportation distance for each sediment particle differs with the sediment transport mode.

Flood flow is analyzed using the dynamic-wave and kinematic-wave theories. The propagation of the initial part of a flood wave can be theoretically evaluated for cases in which the propagation can be calculated using the kinematic-wave method, which is also referred to as the Kleitz-Seddon law. Few studies have examined flood spreading due to outburst from a natural landslide dam in detail, rather typical studies for flood spreading and classification of the wave characteristics after landslide dam break have been analyzed based on governing equations and those linearly simplified equations for floods and bores of clear water flows in a prismatic open channel (e.g., Hayashi, 1953; Keulegan & Patterson, 1943; Kleitz, 1877; Takahashi, 1970). Flood flow due to a natural landslide dam break usually has fine to coarse sediment particles, and the characteristics of propagation can be different from the spreading of clear water flows. In addition, floods and debris flows are spreading to a downstream reach after the dam break, and there are numerical estimations for the flood and debris flows (e.g., Horiuchi et al., 2010; Satofuka et al., 2010). However, it seems that there are few studies discussing the influence of flow width changes, such as expansion and contraction, on flow spreading due to a natural landslide dam break in a natural torrent channel, though numerical modeling has been proposed in arbitrary cross-sections in clear water flow (e.g., Jacovkis & Tabak, 1996). The hydraulic model tests reported here aim to determine characteristics of flow spreading along a meandering channel due to break of a natural landslide dam. The change and spreading of flow depth is the focus of the flume tests reported here, because those processes could be quite difficult to directly measure in field monitoring if such a flood takes place.

In the study reported here, experimental data obtained through hydraulic model tests were collected over a rigid bed, and the spreading of water, fine sediment, bed load, and large boulders due to a flash flood is discussed under the assumption that flash floods/debris flows occur somewhere in the upstream reach due to a break of a natural landslide dam whose storage area is filled with water. The effects of flow width changes, which include the expansion and contraction of the flow width, and a meandering water channel on the sediment transportation and the spreading of flow depth are discussed using temporal/spatial changes of water and sediment spreading in a steep torrent.

2. Hydraulic model tests

2.1. Model and similarity

In the model, the longitudinally averaged bed slope is 1/70, and the flow width ranges from 50 to 100 m, section by section. The schematics of a river reach with a main stream and the plan shapes of river channels are specified based on representative mountain torrents in Japan, such as the Abe River and the Jyo-gan-ji River, because there are several cross sections with expansion and contraction of the flow width along a meandering torrent in steep slope channels. These rivers have bed slopes ranging from 1/100 to 1/50 and flow widths ranging from 50 to 100 m. The watershed area of the middle reach of the representative torrent is several hundred square kilometers.

Fig. 1 shows the experimental flume, which is approximately 5.0 m wide and 48 m long, and the model is assumed to be a 1/75 scale model. The model scale needs to be decided in order to reproduce flow patterns and bed variations as shown in prototype, and it is well known that the model scale is usually specified taking into account workability and efficiency in flume tests though the setting of a larger scale is preferable. The model scale is specified focused on the reproduction of the flow depth (e.g., several centimeters in a model) and the shear velocity Reynolds number (e.g., on the order of 10^2 to10^3 in a model) in the flume tests reported here. Actually, the shear velocity Reynolds numbers takes a value around 74 (on the order of 10^2) in peak stage of floods in the flume tests reported here (See Table 4 shown in Section 2.2.1), and the effects of the shear velocity Reynolds stress on the reproduction of flow are negligible. Fig. 2 shows a plan view of the experimental flume. As can be seen in the figure, there are a lot of curved parts and sections of changing flow width, such as contractions and expansions.

Table 1 lists the flow widths left to right bank for cross sections shown in Fig. 2. Table 2 shows the meandering rate of the curved parts of the experimental flume, which is defined as the rate of an arc for a chord. The roughness of the bed was formed in smooth mortar using trowels on the side and bottom beds.

Fig. 3 shows the longitudinal profiles of the free surface (water level) measured along the main stream when the water is supplied steadily without a sediment supply. The roughness can be

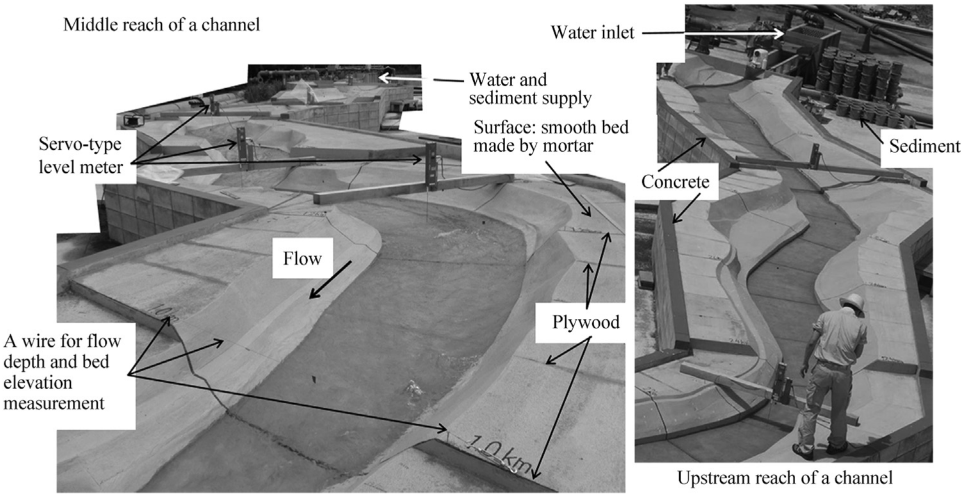

Fig. 1. Experimental flume.

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