Pulsation in Debris Flows and its Mechanism

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Discussions on pulsation in debris flows that rush down from Kamikamihorizawa torrent of Mount Yakedake, Japan, Jiang-jia torrent in Yunnan Province, China, and Aa torrent in Karakorum, Pakistan suggest that 1) periodic pulsation at Kamikamihorizawa is caused by flow instability, and non periodic one by response to rainfall intensity; 2) periodic pulsation at Jiang-jia is produced by both or one of two mechanisms: discrete mobilization of visco-plastic slurry deposits and instability in the flows; 3) pulsation in the flows at Aa torrent is brought about by drainage instability of melt water from glaciers. Its periodicity is brought about by both daily variation in solar radiation and storage capacity of melt water to a threshold for a drainage instability; 4) Non periodic pulsation is also brought about in a situation that multiple landslides are induced in succession to generate debris flows. The 20 August 2014 Hiroshima debris-flow disaster seems to have been enlarged by such a pulsation.

Key words: debris flow, multiple surges, pulsation, periodicity, discrete mobilization, flow instability

1. INTRODUCTION

The 20 August 2014 heavy rainstorm induced debris flows at 75 torrents and claimed 74 persons at the residential area in the eastern part of Hiroshima City, Japan. In some torrents, loss of lives and houses were enlarged by successive attack of debris flows, namely by pulsation of debris flows.

For instance, one of the firefighters was successful in rescuing a 3-year old boy who was attacked by a primary debris flow from a torrent at a district of Kabe-Higashi, Asa-Kitaku. However both the firefighter and the boy were immediately incorporated by a secondary debris flow and lost their lives [Asahi-Shinbun Co., 2014a]. One of the residential districts at Yagi-Sanchome, Asa-Minamiku was attacked one after another by multiple debris flows from a torrent, and loss of lives and buildings were markedly enlarged [Asahi-Shinbun Co., 2014b; Yamamoto and Kobayashi, 2014]. Totally three major landslide scarps were found in the upstream tributaries in the single drainage basin, which suggests this district were attached by at least three major debris flows that correspond to those three landslide scarps [e.g., Takebayashi and Fujita, 2015]. Besides these cases, we find many examples of secondary disasters, namely secondary loss of lives and properties by pulsation of debris flows [e.g., Masaki and Iida, 1979].

Debris flows seldom occur as a single episode, they often occur as a series of discrete episodes of multiple surges. Debris-flow monitoring studies often report pulsation in debris flows [e.g., Li et al., 1983; Suwa and Sumaryono, 1996; Suwa et al., 1997]. Monitored data of debris flows at Kamikamihorizawa-torrent of Mount Yakedake, Japan, those at Jiang-jia torrent in Yunnan Province, China, and those at Aa torrent in Karakorum, Pakistan are compared in order to discuss the mechanism of pulsation in debris flows.

The word "pulsation" is used as a term to incorporate the meaning for a debris flow event that consists of a series of multiple episodes of debris-flow surge, while a term "surge" allows a single episode.

2. DEBRIS FLOWS FROM KAMIKAMIHORIZAWA TORRENT

2.1 Study slopes

Debris flows are often induced by heavy rain storm at several torrents on Mount Yakedake, Japan
which is an active volcano made of andesite lava dome. Its last phreatic explosive eruption occurred in 1962. Kamikamihorizawa torrent on the eastern slope was selected as a monitoring site of debris flows in 1970 [See Fig. 1]. Since then the study group of Disaster Prevention Research Institute of Kyoto University has continued monitoring of debris flows cooperating with Matsumoto Sabo Office of the Japanese Ministry of Land, Infrastructure, Transport and Tourism. During the last 45 years, data were obtained from 93 debris-flow events that contained more than 210 episodes of debris-flow surges [Suwa et al., 2011].

2.2 Pulsation of surges with boulder dam

Debris flows from Kamikamihorizawa torrent generally consist of several surges whose front is massive and composed of marked focusing of numerous boulders, which is called as boulder dam. Figs. 2 and 3 show two different cases of debris flow at Kamikamihorizawa. Nine surges of debris flow are found during 15 minutes in the case shown by Fig. 2. And 5 surges among them rushed down every 1 minute. Namely high periodicity is found in the pulsation. On the other hand Fig. 3 shows that three debris flows occurred in response to strong rainfall-intensity. No periodicity is found in this case, and the result seems reasonable when rainfall variation don’t assume any periodicity.

3. FLOWS FROM JIANG-JIA TORRENT

3.1 Study slopes

Debris flows often occur being induced by rainstorm at many tributaries of Xiao-Jiang river in Yunnan Province, China which is a tributary of Chang-Jiang river. The vast area covering Xiao-Jiang basin is under rapid dissection onto the Permian sedimentary rock. The rapid dissection has been promoted by two factors: heavy weathering processes against sedimentary rock and tectonically active movement of the earth crust. Jiang-jia torrent is dissected along an active fault which obliquely crosses Xiao-Jiang active fault [e.g., Li et al., 1983].

A study group of Disaster Prevention Research Institute of Kyoto University has continued monitoring of debris flows at Jiang-jia torrent, a tributary of Xiao-Jiang river, cooperating with a group of Chengdu Institute of Mountain Hazards and Environment of Chinese Academy of Science.
from 1991 through 1998 [See Fig. 4]. The Chengdu Institute took over a debris-flow monitoring observatory, Dongchuang Debris Flow Observatory, in 1980 which was originally established in 1973 by Lanzhou Institute of Glaciology and Geocryology of Chinese Academy of Science [Li et al., 1983; Cui et al., 2005].

3.2 Pulsation of muddy type debris-flow surge

Muddy type debris flows often induced by rainstorm at Jiang-jia torrent. Bulk density of the flow is very high as much as 2.1 ton/m³ to make the flows highly cohesive and viscous. Different from those at Kamikamihorizawa, debris flows at Jiang-jia contain neither large boulders nor boulder dam. A single event of debris flow contains numerous episodes of debris-flow surges as many as several tens to a few hundreds as found in Fig. 5. This diagram shows temporal changes in peak depth, frontal velocity, time spacing, and volume of successive discrete surges.

The figure shows depth, velocity and volume of the surge assume a temporally decreasing trend, and time spacing does a temporally increasing trend. However the fluctuation amplitude of the time spacing increases with time. The mean of the time spacing is one minute in the initial stage and 2 minutes in the last stage, which indicate a certain level of periodicity exists in the pulsation.

4. DEBRIS FLOWS FROM AA TORRENT

4.1 Study slopes

Debris flows attacked Kande, a small village on the fan of Aa torrent, in Karakorum in the late July 1997, leaving a serious disaster. The author visited Kande to investigate the hazard in the late July of 2000, and unexpectedly encountered another debris flow from Aa torrent. Condition for debris flow occurrence is unique. Debris flows occurred on the clear sky days without any rainfall. Suwa [2003] estimated the debris flows are induced by melt-water flash floods from glaciers in mid summer. Aa torrent is an upstream tributary of Indus River as shown in Fig. 6. Glaciers are prevalent over the high altitude slopes of Aa torrent upstream reaches and basin. The substratum of the region consists of gneisses: one type of metamorphic rocks. Mean of annual precipitation at Skardu, a main city in the regions, is as small as 200 mm.
4.2 Pulsation of glacial surge

Rushing down of debris flow from Aa torrent was evaluated as follows and is shown in Fig. 7 from the interviews to the residents in July 2000 [Suwa, 2003]. In 1997, the 1st surge of the debris flow on July 25 attacked Kande around 4:45 p.m. Totally 5 surges rushed down on the first day. The last surge around 10 p.m. on the day was the biggest. Subsequent debris flows occurred every day until July 30. The frequency of surges was 2 to 4 times a day. During the 6-day period, totally 20 surges at least rushed down. Clear sky was kept all through the period without any rainfall and with high air temperature at daytime. The debris flows killed three people, injured more than ten people, and completely destroyed houses of 27 families, one mosque, two schools, and 20 ha of farmland. The population of Kande village was about 800 composing about 140 families.

In 2000, debris-flow surge ran out repeatedly again as shown in Fig. 7 during 4 clear days. The last one shown in the figure is the surge the author encountered. Peak discharge of this surge was estimated between 500 m³/s and 1000 m³/s on the fan head. The inclination of the slope at the apex of the fan was 8.5 degree, and the peak flow depth was about 4 m with a frontal velocity between 5 m/s-10 m/s and the width of 50 m [Suwa, 2003]. More than 10 debris-flow surges rushed down during the 4-day period. These hazards in 2000 caused no fatalities, but the houses of 130 families were lost as well as 60 ha of farmland destroyed.

These debris-flow surges repeated with time spacing between a few hours and more than ten hours. Namely a certain level of periodicity is found including a higher frequency of debris flows in the afternoon.

5. DISCUSSIONS ON PULSATION MECHANISM

Some of the pulsation of debris flow assumes periodicity and others no or a lower periodicity. Pulsation may be created by the following 5 mechanisms.

5.1 Instability of quasi-uniform flow

Instability of quasi-uniform flow may create periodic pulsation in the flow. Namely it is difficult for debris flows to maintain uniform flow for a long distance down to lower reaches even if the flow is uniform at source reaches. The concept is explained by the illustration in Fig. 8. Steepness of the channel bottom, low uniformity of the flow, and spatial heterogeneity in the flow composition must let the flow unstable to cause periodic pulsation in the flow.

A similar phenomenon of roll-wave train is known as one of a result of flow instability in shallow stream flow on steep slopes. The processes
Fig. 8 Conceptual scheme of creating process of pulsation by flow instability

Fig. 9 Conceptual scheme of discrete mobilization of visco-plastic slurry deposits

may be analogous to a kind of traffic jam called as “bunch-up-together flow” on highways, which jam is naturally generated when traffic density reaches a certain threshold.

For instance, at a steep slope of 20 degree in the source reaches of Kamikamihorizawa torrent, generation process of multiple surge is incidentally observed in which quasi-uniform slurry flow generates solitary surge one after another with time spacing between 5 and 10 seconds [Okuda et al., 1978]. While at a gentle slope of 5 degree near the fan apex of Jiang-jia torrent, new solitary surges are also born from quasi-uniform slurry flow, in addition to a pulsation of multiple surges which comes from the upper reaches [Suwa et al., 1997]. These solitary surges seem to be generated by flow instability.

5.2 Discrete mobilization of visco-plastic slurry deposits

Continuous earth flows from steep slopes that is induced by rainfall create deposits layer made of slurry on the bottom of source reaches [Suwa, 2003]. Such slurry deposits may sometimes assume visco-plastic behavior. Namely it shows yield strength against shear stress. The slurry deposits may behave like a kind of Bingham fluid. Namely the super-layer of the deposits starts flowing when shear stress overcomes resisting yield strength of the sub-layer. This process may become effective when threshold thickness is attained by the super-layer as shown in Fig. 9. This type of deposits-layer breach may periodically repeat when earth flows keep supplying slurry materials to the bottom of source reaches as suggested by Davies et al. [1991]. Pulsation observed in Jiang-jia torrent seems to originate mainly from this discrete mobilization. However the pulsation at Jiang-jia may be superimposed with additional surge generation from flow instability during the motion.

5.3 Instability in the melt-water drainage from glacier

Anderson et al. [1999] found a drastic transition in the pattern of melt-water drainage from glacier. Namely, they found a transition from daily-periodical and stable discharge to unstable and impulsive discharge in the early summer of Alaska as found in Fig. 10. They attributed a drastic transition to a subglacial drainage shift from a distributed drainage system to a more efficient conduit one. A similar transition may contribute to debris-flow events at Aa torrent. On the other hand, Walder and Driedger [1995] reported that outburst floods from a glacier on Mount Rainier caused debris flows. They suggested that outburst floods were triggered by rapid water input to the glacier bed, causing transient water-pressure that destabilized the linked-cavity system for drainage [Kamb, 1987]. Similar outburst-flood processes may operate in Aa torrent.

On the other hand, non-periodic pulsation may be caused by other processes. The followings may be dominant processes for this type of pulsation.

5.4 Variation in the rainfall intensity

Debris flows may be easily generated by a flash flood on a steep slope which slope consists of movable cohesionless bed materials or
low-cohesion bed materials. In case rapid surface runoff is induced by large intensity of rainfall, the pulsation of debris flows occur corresponding to large rainfall intensity as indicated by the observed data shown in Fig. 3. In these cases, pulsation may be generally non-periodic except a case in which rainfall intensity assumes periodicity.

5.5 Multiple debris flow sources of landslide

Multiple debris flow sources of landslide can create multiple surges of debris flow. In this case, time spacing may be controlled by the time of landslide and length of the channel reaches between the landslide scarp and the exit of the torrent, so that the pulsation may not assume periodicity.

Recently, time of landslides often detected by seismometer networks and analyzed to discuss their processes [e.g., Siwa and Yamakoshi, 2000; Siwa et al., 2008; Yamada et al., 2012]. And relationship between the time of landslide and the time of debris-flow hazards is discussed [e.g., Siwa and Yamakoshi, 2000].

5.6 Condition for a debris-flow event which consists of a single episode of flow surge

A participant gave the author a comment at the session of DFHM6 that he can find a debris-flow event which consists of only a single episode of debris-flow surge in the video record collection from Kamikamihorizawa torrent, and asked what condition can issue such a single episode of debris-flow surge. This author replied that he has an idea any event of debris flows at Kamikamihorizawa consists of multiple surges, namely assume pulsation due to flow instability on steep slopes of upstream reaches, based on the monitoring data [Okuda et al., 1981; Siwa, 2008]. However surges often attenuate on the gentle slope of downstream, especially in the cases surges are small. Namely we monitor multiple surges by the video cameras upstream and do only a single surge at the downstream exit of Kamikamihori torrent. A single episode of surge may be monitored at exits of torrents in a similar flow process.

Generation process of multiple surges at Kamikamihorizawa torrent is observable near the source of debris flows as described in the section 5.1. However further discussion on the hydraulic condition is difficult so far due to no monitored hydraulic data of the flow there. Discussion might become possible in the future referring to relevant study results [e.g., Zanuttigh and Lamberti, 2007; Arai et al., 2013].

6. CONCLUSIONS

This study results in the followings:
1) Periodic pulsation in the debris flows at Kamikamihorizawa torrent is caused by flow instability, and non periodic ones by response to rainfall intensity variation.
2) Periodic pulsation in the flows at Jiang-jiia torrent might be generated mainly by discrete mobilization of source materials consisting of visco-plastic slurry deposits. This pulsation might be superimposed by another type of pulsation which is generated by flow instability. The fluctuation of time spacing found in Fig. 5 may indicate effects of this superimpose.
3) Periodic pulsation in the flows at Aa torrent might be brought about by a drainage instability of melt water from glaciers that occurs at hot mid-summer weather conditions. Periodicity may originate from daily change in solar radiation and flash flood release due to instability in melt-water drainage from glaciers that repeat in shorter time spacing.
4) Pulsation of debris flows found at the 20 August 2014 Hiroshima disaster seems to be generated both by multiple slides which must have collapsed one after another. And the pulsation may be superimposed with an additional surges generated by flow instability.

Although the evaluation for Hiroshima debris flow event may not as definite as those for other events at 3 monitoring sites because of difference in data quality, the study results suggest that not only people in rescue teams but also residents should know these marked characteristics of “Pulsation in debris flow”. It may be effective for them to save their lives who live and move in the area that is prone to debris-flow hazards.

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