Erosion processes of the collapsed mass of the gigantic landslide of Mt. Bawakaraeng, Sulawesi, Indonesia in 2004 revealed by multi-temporal satellite images

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On March 26, 2006, a gigantic landslide occurred on the caldera wall of Mt. Bawakaraeng, Indonesia. This paper quantitatively shows the temporal change in gully erosion and sediment yield from the huge amount of the deposit of the landslide by analyzing satellite images. Firstly, the landslide buried the original river channel completely. In the next year, gully erosion dominated the entire landslide deposit, and parts of the gully bed were found to have eroded by up to 60 m. The total amount of sediment discharged from the landslide deposit was estimated to be 36 million m3. In the second year after the landslide, the severe widespread degradation almost ceased and river bed aggradation started to occur in some places. The total amount of discharged sediment drastically decreased and was estimated to be 8.3 million m3. Satellite images of the landslide deposit showed neither intervention by artificial structures nor remarkable revegetation. The drastic decrease in sediment discharge should have occurred independently of such external factors but dependently on some internal factors such as an intrinsic negative feedback process of gully erosion.

Key Words : *caldera wall collapse, morphological change, satellite remote sensing, Mt. Bawakaraeng, Bili-bili dam*

1. INTRODUCTION

A gigantic landslide occurred on the caldera wall of Mt. Bawakaraeng (2,830m, a.s.l.) located in the uppermost reach of the Janeberang River in South Sulawesi, Indonesia, on March 26, 2004 (Fig. 1). A huge mass of debris, measuring 500 m to 800 m in width, created by the landslide traveled about 7 km down the river. Ten people were killed and 22 others went missing in the accident. Twelve houses and one school were crushed or buried in the debris, and the damage was estimated to cost around 2,214 million Rp (Tsuchiya et al., 2004).

The effects of the landslide are still continuing. A large reservoir with a total storage capacity of 0.38 billion m^3 had been completed in 1999 in the downstream part of the Jeneberang River, and there is fear that the huge amount of sediment discharged

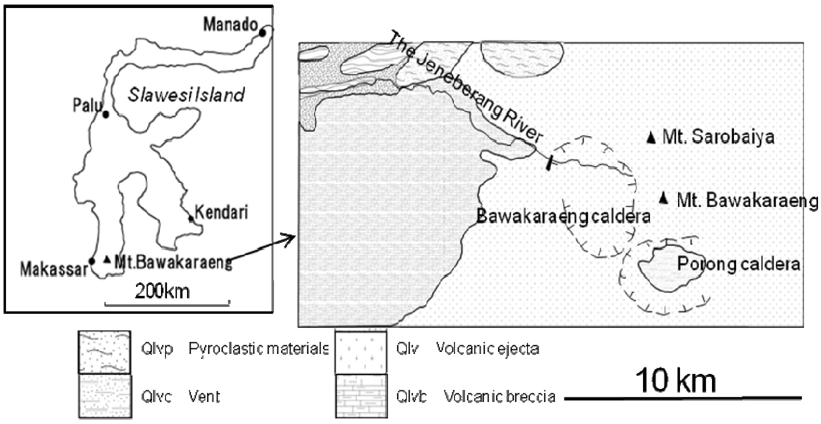

Fig. 1 Location of Mt. Bawakaraeng and the geology in the surrounding area

from the landslide deposits will last for a long time. Long-lasting sediment discharges triggered by an event such as a volcanic eruption, earthquake, or gigantic landslide have been reported and studied in the past. At Mount St. Helens, many studies on post-eruption sediment movement phenomena have been done. According to Collins and Dunne (1986), the severe sediment movement stopped when the gully network in the upper reaches became stable after several years. On the other hand, at Mount Pinatubo in the Philippines, sediment discharge to the downstream temporarily started again in one of the volcanically disturbed river basins when the river system changed naturally in the upper reaches (Daag, 2001).

In this study, the authors examined the erosion processes of the collapsed mass of the gigantic landslide of Mt. Bawakaraeng by using various multi-temporal satellite images. The total volume of erosion was quantitatively estimated and the development of the gully network was clarified. Finally, the erosion characteristics of the collapsed mass were discussed with reference to previous works.

2. GEOLOGIC, TOPOGRAPHIC AND CLIMATIC CONDITIONS AROUND MT. BAWAKARAENG

Mt. Bawakaraeng is located in the southwestern part of Sulawesi Island. The Jeneberang River originates from it and flows into the Strait of Makassar. In the middle reach of the river lies the Bili-bili Dam. The geology of Mt. Bawakaraeng belongs to Lompobattang volcanics, which is an andesitic volcanic material formed by volcanic activities in the Pleistocene epoch, and consisting of lava, pyroclastics and secondary deposits.

In the northeastern part of Mt. Bawakaraeng there is a large caldera with a diameter of approximately 5 km. The caldera is notched on the west side, and the Jeneberang River originates from this caldera.

Sulawesi Island has a tropical climate, with a marked dry season from May to November and a wet season from November to May. According to rainfall data acquired in the village which faces the Jeneberang River at the exit of the caldera of Mt. Bawakaraeng, the total rainfall and maximum daily rainfall from December 2005 to November 2006 were 3,531 mm and 238 mm, respectively.

3. METHODS

The area of interest is the source of the Jeneberang River as shown in Fig. 1. The authors acquired multi-temporal satellite images to clarify the erosion processes of the collapsed mass of the gigantic landslide. Two kinds of satellite data were used in this study. One was very high-spatial resolution images for viewing the erosion processes in detail, and the other was satellite images for making digital elevation models (DEMs).

(1) Analysis by satellite images

The very high-spatial resolution images were obtained by QuickBird. Pan-sharpened images were used to view the erosion processes in detail, such as gully erosion on the landslide deposit. The pan-sharpened images were created by combining two products, 1-m resolution panchromatic images and 2.5-m resolution multispectral images. The pan-sharpened image was orthographically projected through matching the DEM as mentioned below.

Revegetation processes were analyzed using the QuickBird images. First, unsupervised classifications were applied to the multi-temporal color composite images acquired in 2004, and the sediment-covered areas were clearly abstracted. The shadow parts of the sediment-covered areas were purged because it is impossible to evaluate vegetation cover in the shadow. The abstracted sediment-covered areas were obtained for the other two images acquired in 2005 and 2006 in the same manner.

The normalized difference of vegetation index (NDVI) is a non-linear transformation of the visible (red) and near-infrared bands of satellite information. NDVI is defined as the difference between the visible (red) and near-infrared (nir) bands, over their sum. The NDVI is an alternative measure of vegetation

Table 1 Satellite images used in this study

Date of data acquisition	Name of satellite/sensor	Spatial resolution of image	Remarks
July 7, 2001	ASTER	15 m	Stereo-pair to generate 15-m DEM
Oct. 13, 2004 Nov. 2, 2004	SPOT-5	5 m	Stereo-pair to generate 5-m DEM
Sept. 6, 2004	QuickBird	2.5 m	Pan-sharpened
June 16, 2005	QuickBird	2.5 m	Pan-sharpened
Sept. 20, 2005 Sept. 26, 2005	SPOT-5	5 m	Stereo-pair to generate 5-m DEM
July 7, 2006	QuickBird	2.5 m	Pan-sharpened
Aug. 4, 2006 Aug. 29, 2006	SPOT-5	5 m	Stereo-pair to generate 5-m DEM

amount and condition. It is associated with vegetation canopy characteristics such as biomass, leaf area index and percentage of vegetation cover. Inside the abstracted sediment-covered area, NDVI is calculated to show quantitatively the degree of revegetation of the deposit as follows:

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (1)$$

NIR: reflection of near infra-red spectrum
RED: reflection of red spectrum

(2) Quantitative analysis of topographic changes through DEMs obtained by satellite images

DEMs were generated through pairs of satellite images as shown in Table 1. The pair of images for making a DEM of the pre-slide topography of the source area of the Jeneberang River was obtained by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) mounted on the TERRA platform. The other pairs for making DEMs of the post-slide topography were obtained by the HRG camera mounted on the Satellite Probatoire d'Observation de la Terre 5 (SPOT5). These DEMs are very useful for areas where there is little topographic data. Indeed, they have already been used to identify drastic topographic changes in previous studies (Fujisada et al. 2005 and Tsutsui et al. 2007). The authors clarified the differences between the multi-temporal DEMs to assess quantitatively the topographic changes caused by the post-landslide erosion processes.

4. TOPOGRAPHIC CHANGE REVEALED BY COMPARISON OF MULTI-TEMPORAL DEMS

(1) Topographic change by the gigantic landslide

Figure 2 shows satellite views of the source area of the Jeneberang River. In the figure, satellite images a) and b) show the area where the collapsed sediment deposited. The area of the deposit extends up to 7 km from the caldera wall which collapsed. The deposit area in 2004 was 7.77 km^2 and is defined as the area of interest, AOI, here. Comparison of the DEM in

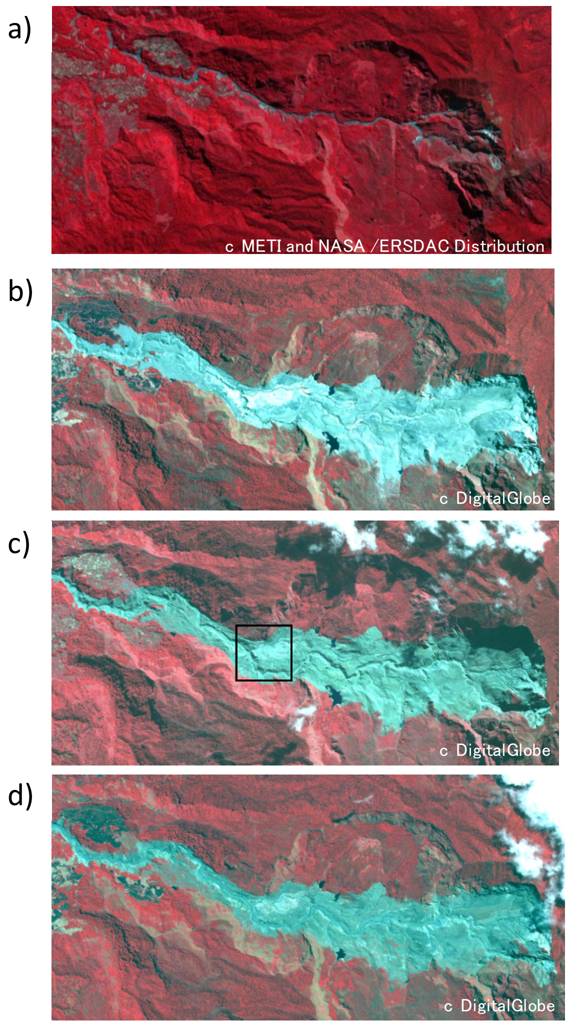

Fig.2 Satellite images before and after the gigantic landslide. The square shows where Photo 1 was taken.
a) Satellite image acquired on July 7, 2001; b) Satellite image acquired on September 6, 2004; c) Satellite image acquired on June 16, 2005; d) Satellite image acquired on July 7, 2006

Photo 1 Oblique view of the exit of the caldera of Mt. Bawakaraeng. This photo was taken in 2005.

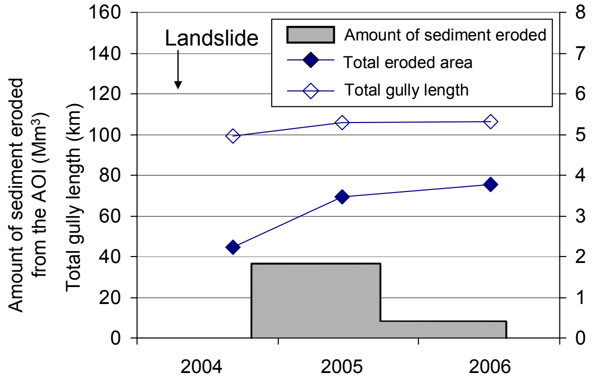

Fig.4 Temporal change in the total gully length, total eroded area and amount of sediment eroded from the AOI

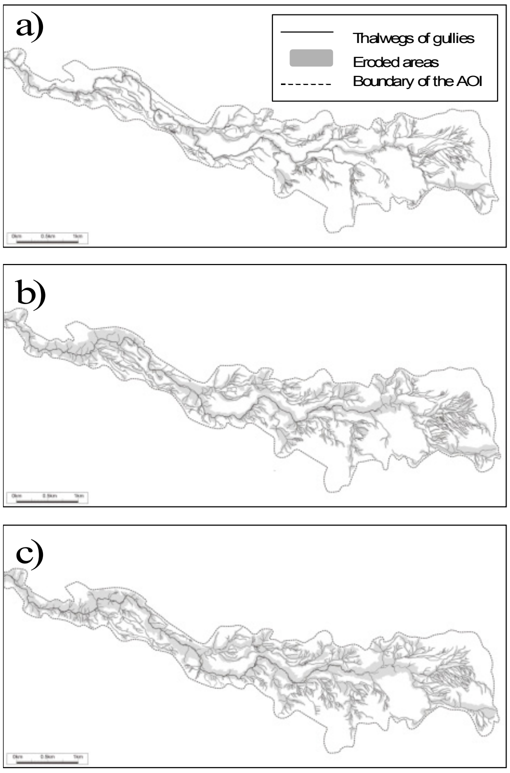

Fig.3 Distribution of eroded areas in the AOI in a) September 2004, b) June 2005, and c) July 2006.

2001 and that in 2004 after the landslide shows that the original river bed of the Jeneberang River rose by up to 140 m. Photo 1 shows an oblique view of the deposit at the exit of the Bawakaraeng caldera. According to the DEM comparison, the total amount of degradation in the AOI, namely the sediment volume of the landslide, was calculated to be about 190 million m^3.

(2) Topographic change after the gigantic landslide

The satellite images in Fig. 2 show the extent of the deposit caused by the gigantic landslide in March 2004 and the development of gullies on the deposit. Figure 3 shows the development of eroded area. Even in September 2004, a considerable part of the AOI had already been eroded, and in particular, many gullies had developed. In the following years, although a few gullies have become slightly longer, they mainly became wider especially from September 2004 to June 2005. From June 2005 to July 2006, the increase in eroded area was much smaller than that in the preceding period (Fig. 4). As of July 2006, 34% of the surface area of the deposit of the gigantic landslide had undergone severe erosion, especially gully erosion.

Figure 4 also shows the amount of sediment eroded away from the AOI to the downstream for the two periods, from October/November 2004 to September 2005 and from September 2005 to August 2006. The amount of sediment eroded was obtained by differentiating the DEMs made from SPOT stereo-images (Table 1). For the first period, 36.263 million m3 of sediment was eroded away from the area of interest while 8.337 million m3 of sediment was eroded in the second period. Part of the gully bed was found to have degraded by up to 60 m in the first period. The amount of sediment eroded during the study period corresponds to about 23% of the sediment volume of the gigantic landslide. As shown in Fig. 3, however, since the deposit had been already eroded to some extent as of September 2004, the total amount of sediment eroded to date seems to be more.

(3) Revegetation of the deposit of the 2004 gigantic caldera collapse of Mt. Bawakaraeng

Figure 5 shows the NDVI maps within the AOI. Bright areas mean those where the NDVI values are high. In 2004, almost no vegetation is found inside the AOI. In 2005, remarkable revegetation occurred on the edge of the AOI, and the bright areas grew forward in 2006. The arrow in Fig. 5 marks the area shown in Photo 2. This photo was taken on October 16, 2006 from the right bank of the Jeneberang River. Thin vegetation is seen on the deposits of the gigantic landslide in 2004. Within the revegetated area shown in Fig. 5 and more

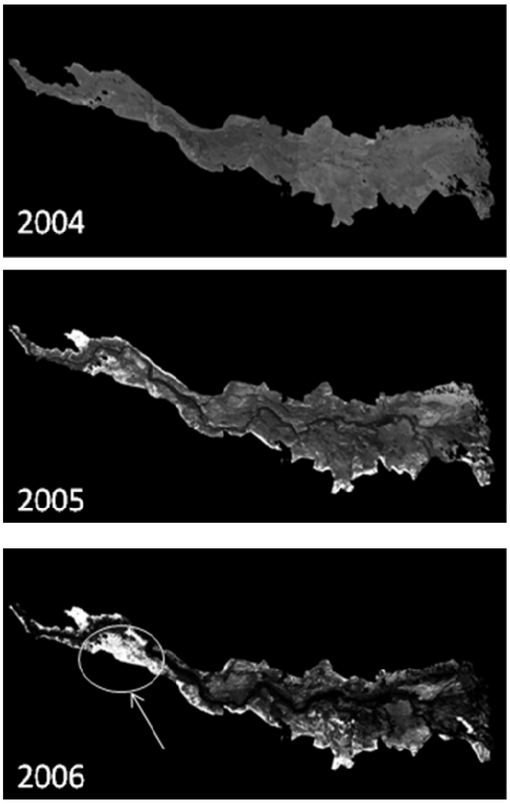

Fig.5 Revegetation in the AOI. The white circle shows the area where Photo 2 was taken in 2006.

Photo 2 Revegetation on the deposit (Photo taken on-site on October 16, 2006)

precisely in Photo 2, the average NDVI value was calculated to be 0.159. Within the revegetated area shown in Fig. 5 and more precisely in Photo 2, the average NDVI value was calculated to be 0.159. If we set the threshold between revegetated ground and bare ground to be this value, the proportion of the revegetated area in 2005 and 2006 is obtained as 10.2% and 14.3% of the entire AOI, respectively. Even such a sparse vegetation just like shown in Photo 2 had occupied only 14% of the AOI as of 2006. It means that 86 % of the AOI remained bare.

5. DISCUSSION

Use The sediment yield from the landslide deposit was very large compared to the results of previous studies conducted on active volcanoes. Regarding erosion, the processes observed at Mt. Bawakaraeng were erosion processes of “virgin land”. This kind of erosion process can be observed after volcanic eruptions. Table 2 compares the annual specific sediment yield obtained in this study with those obtained from slopes of other volcanoes which were almost erosion-free before the eruptions. This table shows that the specific sediment yields observed in post-eruption volcanoes are very similar to those obtained in this study. The values of the annual specific sediment yield can be considered to be the annual average depth of erosion in meters. In these examples, including this study, therefore, as much annual erosion occurs as annual precipitation. Even if we assume that all the precipitation had discharged as water flow, water flow has to transport almost as much sediment as itself. For instance, the annual sediment yield of 1.1 Mm^3/km^2 in the period 2005–2006 at Mt. Bawakaraeng was considered to be transported by water flow generated by the rainfall of 3531 mm, that is 3.531 Mm^3/km^2. In general, the annual amount of water flow should be smaller than that of rainwater, so it could mean that the sediment removed was transported in a very dense volumetric sediment concentration, C, that is $C = 1.1\ Mm^3 / (1.1\ Mm^3 + 3.531\ Mm^3) = 0.24\ (m^3/m^3)$. This value is considered to be the minimum value because all the rainwater is now assumed to discharge without any evaporation or infiltration loss. In general, the volumetric sediment concentration for a hyper-concentrated flow and debris flow is considered to be 0.2–0.6 and more than 0.6, respectively (Beverage and Cullbertson, 1964). The sediment discharged from this catchment, therefore, should be transported by hyper-concentrated flows or debris flows.

According to personal communication with Mr. Takeshi Watanabe, no artificial structure was installed within the AOI during the study period. In addition, satellite images of the landslide deposit showed that

Table 2 Annual specific sediment yield measured at post-eruption volcanoes

Site	Type of eroded sediment	Annual specific sediment yield ($Mm^3/km^2/yr$)	Annual precipitation (mm/yr)	References	Remarks
Mt. Merapi (Indonesia)	Pyroclastic flow deposit	1.4	4385	Kaneko et.al(2001)	
Mt. Pinatubo (Philippines)	Pyroclastic flow deposit	3.9	2200	Hirose and Inoue(1999)	
Mt. Oyama (Japan)	Ash fall deposit and old scoria	0.82	?	Tagata et. al(2005)	
Mt. Bawakaraeng (Indonesia)	Landslide deposit	4.7 1.1	? 3531	This study	The upper-line figures for the period 2004-2005. The lower for that of 2005 -

there was no remarkable revegetation on the landslide deposit. Still 86 % of the AOI remained bare, while around 36 million m^3 of sediment discharge from the AOI in 2005 was drastically decreased to around 8 million m^3 in 2006. Mizuyama and Miyamoto mentioned that the long-term temporal change in the sediment discharge from post-eruption volcanoes could be governed by revegetation processes. In the case of this study, however, it seems that the temporal change in the eroded sediment has not yet been controlled by revegetation processes, at least during the study period. The drastic decrease in the sediment discharge should have occurred independently of such external factors but dependently on some internal factors such as a kind of intrinsic negative feedback process of gully erosion. As shown in Fig. 3, gullies were widened greatly, which is likely to decrease the depth and velocity of a given water flow. This would result in less erosion for the next flood. Nishida (1998) pointed out that further erosion could cause armoring of the gully bed, which would then decrease the erosion rate. This is also one hypothesis for the possible intrinsic negative feedback processes. This issue should be further studied in future.

6. CONCLUDING REMARKS

In this study, the temporal changes in gully erosion and sediment yield from the huge amount of deposit of the gigantic landslide in 2004 were quantitatively shown by analyzing satellite images. The following were clarified. 1) The sediment volume of the gigantic landslide was estimated to be 190 million m3. 2) The total amount of sediment eroded from the deposit of the gigantic landslide was about 36 million m3 in the period of 2004-2005 and about 8.3 million m3 in 2005-2006. As of July 2006, 34% of the surface area of the deposit of the gigantic landslide had undergone severe erosion, especially gully erosion. 3) Unlike long-term temporal changes in erosion rate in other cases, the temporal changes observed in this study seem to be free from revegetation processes. The decrease in the sediment yield should have occurred independently of such external factors but dependently on some internal factors such as a kind of intrinsic negative feedback process of gully erosion.

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