Paper:

Large Sediment Movement Caused by the Catastrophic Ohya-Kuzure Landslide

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The Ohya-kuzure landslide, one of three largest catastrophic landslides in Japan, is assumed to have been triggered by a strong earthquake and a large-scale debris terrace in a channel downstream from landslide. We verified the time of the landslide's occurrence, its volume, and the amount of sediment supplied to the main river downstream. The landslide's occurrence in 1707 was confirmed by historical documents and earthquake records of sediment disasters. The landslide's size was estimated to be 94 million m^3, from the geomorphic change in the debris terrace. Moreover, it was presumed that 33% of the sediment accumulating as a debris terrace (29 million m^3) was eroded, and that a sediment volume of 17 million m^3 was supplied to the upstream region of the main river. Small-scale debris flows have been triggered recently in the source head of the landslide during heavy annual rainfalls. In 2006, a debris flow in Ichinosawa tributary with the most vigorous debris production and transport in the landslide was recorded during a typhoon. Hydrographs of the debris flow quantified by ultrasonic sensor and hydraulic pressure sensor supplemented video images.

Keywords: large-scale landslide, debris terrace Abe River, sediment transport, earthquake induced landslide

1. Introduction

Strong earthquakes often trigger large-scale landslides causing massive debris disaster, as evidenced in the 2008 M7.2 Iwate-Miyagi Nairiku Earthquake in Japan, the 2008 M 7.9 Wenchuan Earthquake in China, and the 1999 M7.3 Chi-Chi Earthquake in Taiwan. Catastrophic sediment disasters due to earthquakes and triggering large landslide are documented by Usami (1996) [14], but almost no concrete descriptions remain of such large landslide and subsequent sediment movement. The size of collapse, how much sediment moved, and how geographical changes were induced in rivers have rarely quantified. After initial failure, repeated debris production and sediment movement may occur in and around such large landslides. It is necessary to pay attention to a serious sediment disaster that will be caused by coming new earthquake. However, the forecast for the sediment movement is a difficulty to qualitative at present due to the shortage of investigations and studies. Therefore, information on the sediment transport here and elsewhere from large landslides for both managing catchment and developing effective measures against such events is valuable, owing to our apprehension of large earthquake that will definitely hit Japan in the future.

The Ohya-kuzure landslide (Ohya-kuzure) at the Abe River headwaters is one of Japan's three largest catastrophic landslides, presumably triggered by a strong earthquake. The landslide slope is 800 m high and 1800 m wide with an estimated 120 million m^3 volume [4, 5], with sediment extending 5 km downstream, forming Japan's greatest debris terrace. Heavy annual rainfalls have recently triggered several small debris flows in the scar at the head of the landslide [12].

We determined when the initial failure occurred and clarified landslide sediment transport processes based on historical documents. We estimate the landslide's scale based on the debris terrace volume generated downstream in channel. We then clarified the volume of sediment from Ohya-kuzure flowing into the upstream section of Abe River based on cross-sectional terrace profiles. We also review recent debris flow in the Ichinosawa tributary based on data recorded using ultrasonic and hydraulic pressure sensors.

2. Geographical and Local Setting

The deep Abe River rises from the Ohyarei peak 2000 m above sea level and flows 51 km almost straight down to Suruga Bay, passing north-south through Shizuoka City as shown in **Fig. 1**. The Jumaisan tectonic line [10] runs SSE-NNW along the eastern mountains of the Abe River catchment, while the Sasayama tectonic line [10] runs S-N along the vertically eroded gentle flat peaks of the western mountains of the catchment. This area forms typical steep mountainous terrain with a high relief environment of 400-500 m or more. In the west moun-

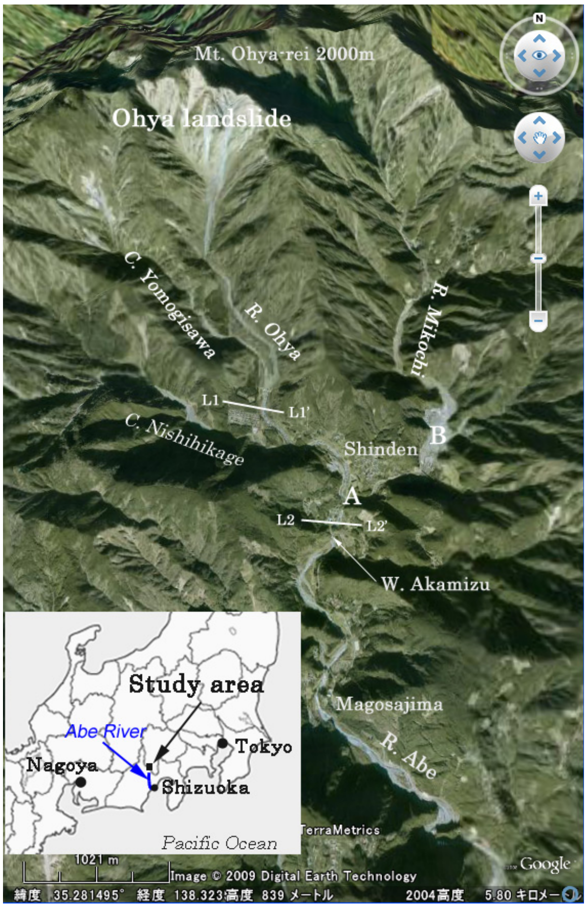

Fig. 1. Showing the around terrain of study area (using Google Earth) 'A' is the river junction of Ohya River and Mikochi River where the landslide dam was formed. 'B' shows that the pond was here in the past.

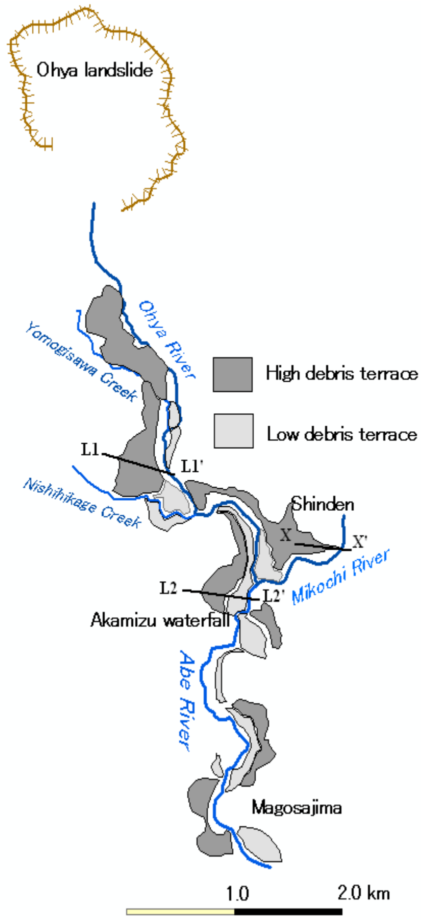

Fig. 2. Map of the distributions of debris terrace generated by Ohya-kuzure.

tain range, gentle and flat peaks persist were formed by vertical erosion, while knick points are formed between steep slopes accompanied by thick debris exfoliated from a steep flank. The geology of the catchment with the Tertiary Setogawa group [10], consisting of sandstone, shale, and their alternating layers is fragile and easily disintegrated into loose fragments by strong tectonic movement. Flooding in this unique geographical area has repeatedly transported large amounts of gravel from upstream, leaving a wider riverbed of thickly accumulated gravel from the middle-lower stream down to the mouth of the Abe River.

The Ohya-kuzure landslide, located in the Abe River headwater in Shizuoka Prefecture as shown in **Fig. 1**, is the largest in sedimentary rock belts in Japan. The Ohya-kuzure landslide is also one of the three major landslides in Japan at 1.8 km^2 in area, 800 m in slope height at the maximum, and approximately 120 million m^3 in landslide volume [5] – the other two being the Tonbiyama landslide at the source of the Jyoganji River in Toyama Prefecture and the Hieda landslide in Otari, Nagano Prefecture [5]. Geology consists of a weak background of fragile weathered bedrock caught between two overthrust faults on the Itoigawa- Shizuoka and the Sasayama tectonic lines [10, 11]. Ohya-kuzure may also have repeatedly formed large failures [11], judging from its high and low debris terraces, as shown in **Fig. 2**. Residents of s Sinden Village showing in **Figs. 1** and **2** immigrated to the terrace in the early stage of Meiji era (1868-1912) [13].

Check dams for controlling erosion have been set up over last 3 decades on the Ohya River that flowing from Ohya-kuzure, together with channel works of 15 ground sills, roughly stabilizing hill slopes, and most sediment discharge has been leveled in channel works. Some slope failures and debris flows of several thousands of cubic meters exist [5, 12], although no sediment has been directly transported into the Abe River. Except for September 24025, 1966, when hourly 130 mm rainfall brought by Typhoon No.26 hit this district and killed 26 people [5].

3. Historical Documents of Ohya-Kuzure

The name of Ohya-kuzure first appeared in historical document in April, 1709 describing "…collapsed ground named Ohya-kuzure, and a lake of 4 km long and 400 m wide located downstream from Ohya-kuzure" [5]. The Mikochi River had already been dammed by Ohya-kuzure sediment discharge and a reservoir generated. It was further reported that "…gold mining operation 500 m up-

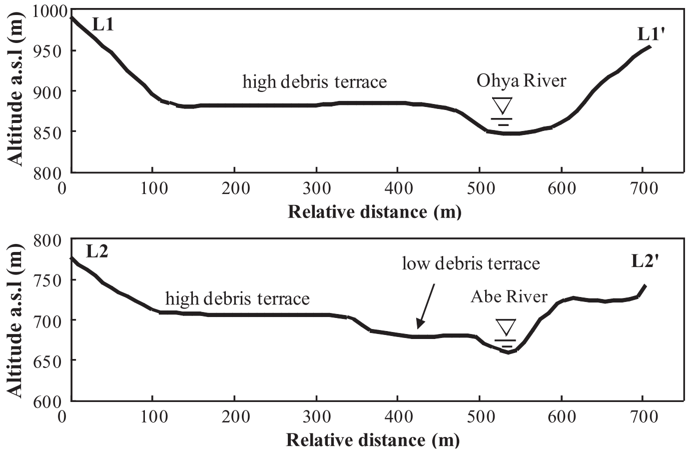

Fig. 3. Representative of cross sections of existent debris terrace in the Ohya River.

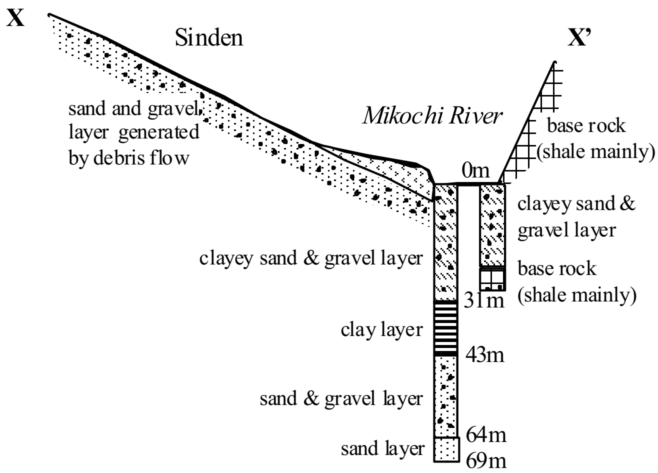

Fig. 4. Section profile proved by the check boring in Mikochi River. Location of X-X' line is shown in **Fig. 2**.

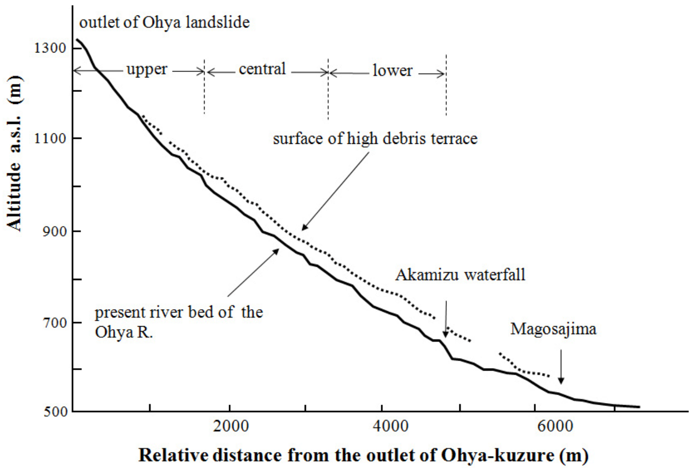

Fig. 5. Comparison of the river bed of Ohya River and surface of high debris terrace.

stream from the junction of the Mikochi and Ohya Rivers was discontinued because the damage to the mining tunnels triggered by the 1703 M8.1 Genroku Earthquake was extremely serious." this was started together with a request to the Suruga magistrate's office for repermission to mine postquake. A 1714 document sent to the office that "many landslides occurred in the upper district and many fallen trees entered the pond" [5].

Ohya-kuzure is understood to have been generated in or before 1709, and no description of significant landslide-triggered damage to the upper Abe River has been found in documents before 1700, despite the 1605 M7.9 Keicho and 1498 M8.2-8.4 Meio quakes that previously hit the Shizuoka region. The 1854 M8.4 Ansei-Tokai Earthquake hitting Shizuoka Prefecture reportedly damage only roads, created many landslips in crop fields, completely destroyed 8 houses, and partially destroyed 23 in Umegashima Village [5]. The strongest earthquake in Japan between 1700 and 1800 was the October 28, 1707, M8.4 Hoei Earthquake, which presumably triggered Ohya-kuzure.

4. Deposit Morphology and its Volume

4.1. Debris Terrace

The Ohya River descends from Ohya-kuzure to join the Mikochi River downstream from Shinden Village and becomes the Abe River. Large-scale debris terraces formed from Magosajima in the Abe River to lower Ohya River, extending 7 km as shown in **Fig. 2** and averaging 300 m width. High and low terrace surfaces formed differed from 20 m to 30 m as shown in **Fig. 3**. The debris terrace in Shinden Village was 500 m wide. Terraces around junctions with other tributaries are generally wider than those far from junctions.

A large pond labeled 'B' in **Fig. 1** formed in the Mikochi River near the Shinden Village around 1870 [13]. Lacustrine (lake-related) and debris-flow sediments were confirmed by drilling near the pond [9]. with boring core sedimentation including clay and sand layers, alternating strata of gravel 31 m deep from the river bed, and a 12-m-thick clay layer underneath as shown in **Fig. 4** that indicates sedimentation may have occurred several times. Massive landslide sediment reaching the steep Ohya River valley immediately after the Hoei Earthquake was transported by floods and debris flow in subsequent rainfall-runoff events.

In the sections shown in **Fig. 5** obtained using a topographic map, comparing the high debris terrace and the river bed on the same axis in the section between the landslide and the nearby Magosajima, suggest that the surface of the high terrace is free of discontinuous geographical features, although discontinuity is seen around the Akamizu waterfall. Generally, sedimentation upstream from the Akamizu waterfall is a randomized phase, but a stratified phase appears to have been created by erosion and sedimentation between the Akamizu waterfall and Magosajima. The debris mass 5 km long originating in the landslide was thus transported through debris flow

Table 1. Sediment volumes generated by Ohya-kuzure unit: million m^3 Locations of upper, central, and lower parts in table are shown in **Fig. 5**.

	Ohya-kuzure to Akamizu. W			total	Akamizu W. to Magosajima
	upper	central	lower		
eroded volume	2.10	10.60	15.90	28.60	8.0
existent volume	9.60	30.11	25.40	65.11	12.0
accumulated volume	11.70	40.70	41.30	93.70	20.0

	Ohya-kuzure to Akamizu. W			total	Akamizu W. to Magosajima
	upper	central	lower		
eroded volume	2.10	10.60	15.90	28.60	8.0
existent volume	9.60	30.11	25.40	65.11	12.0
accumulated volume	11.70	40.70	41.30	93.70	20.0

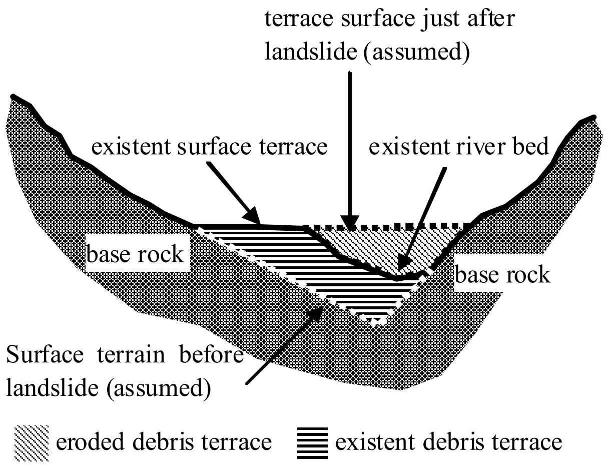

Fig. 6. Schematic illustration for estimation of accumulated and eroded sediment volume.

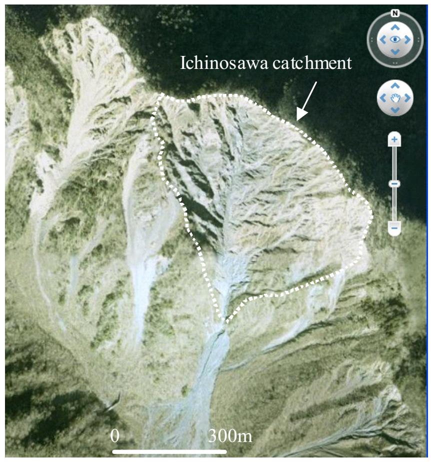

Fig. 7. Location and terrain of Ichinosawa catchment in Ohya-kuzure (using Google Earth).

to the Akamizu waterfall, passing through the Mikochi River junction. Massive sediment created by the landslide generated a debris terrace of 5 km long comparable to the largest debris terrace in Japan.

4.2. Depleted Terrain

We estimate the debris terrace volume based on its cross-section. If the original valley terrain before the landslide is given, the amount of accumulated sediment is estimated assuming that sediment was deposited horizontally in the cross-section at that time. To measure debris terrace volume, cross-sectional lines at 100 to 150 m intervals normal to the channel were arranged on a 1/25,000 scale map.

The volume of deposit was measured using the difference between the existing terrace surface level and the cross-sectional profile of the original river bed before the fill. The flat terrace is assumed to be at the level of the high debris terrace at that time. Note that the terrace surface has been changing continuously with erosion since original deposition. Prelandslide valley terrain is assumed V-shaped, because most terrace-free sections are V-shaped as shown in **Fig. 6**.

Filled sections and areas that should have been eroded afterward in the cross-section are given and filled and eroded sediment volumes evaluated by multiplying them by the cross-sectional line interval, yielding the results in **Table 1**. Upper, central, and lower sections from Ohya-kuzure to the Akamizu waterfall are shown in **Fig. 5**. As stated, accumulated sediment from the Akamizu waterfall to Magosajima is considered secondary, so debris flowing from Ohya-kuzure is estimated at 94 million m^3 – 25 million m^3 less than the total landslide scar volume, i.e., 120 million m^3 as shown by Machida (1959) [4] And limited to from Ohya-kuzure to Akamizu where debris generated by the landslide was deposited directly. Secondary sediment accumulation was observed from the Akamizu waterfall to Magosajima.

Table 1 suggests that the debris terrace created at the landslide in the upper stream has been eroded 20% and that in the lower part eroded by 35%, indicating that the lower part was active. Overall, 33% of the debris terrace at 29 million m^3 has been eroded, with considerable sediment flowing into the Abe River through Magosajima. A sediment flow of 17 million m^3 reached the upper Abe River, as indicated by the remaining 12 million m^3 sediment between the Akamizu waterfall and Magosajima.

5. Local Debris Transport at Present

5.1. General Setting

As shown in **Fig. 7**, a steep valley with the highest sediment yield in the central of Ohya-kuzure is called Ichi-

Fig. 8. Images of the debris flow on 19 July 2006. Debris is flowing down in the white frame.

nosawa, whose catchment features rocky sequences with some high subvertical walls and slopes typically 40-50-. The main geologic unit is tertiary shale and sandstone. Shale is highly shatterable and yields large amounts of silt, whereas sandstone is well jointed, providing many boulders. Most of the slope is bare, occupying 70% of the channel, while vegetation-covered forest, shrubs, and tussocks occupy only 30%. Unconsolidated debris from particles to boulders accumulated on the channel bed, with many talus slopes generated at the slope foot as shown in **Fig. 6**. Large boulders 2-3 m in diameter are also common in channel debris. The debris deposit is several meters thick in some sections. Material produced from the steep bare slope and transport by debris flow has changes debris deposit distribution, with typical channel debris deposit gradients from 28- to 37- and 36- to 38.5- for talus slopes.

5.2. Debris Flow on 19 July 2006

Monitoring included video cameras, ultrasonic sensors, water pressure sensors, and a rain gauge installed in 1999. Continuous video imaging has been obtained since 2003, as shown in **Fig. 8** of debris flow surges on July 19, 2006. Several surge sequences occur during series of rainfall events. Normal clear, mud-free stream flows without abrupt increase in flow depth appeared between surge sequences. The typical debris flow in the upper Ichinosawa catchment is three-phase – precedent flow, main flow and subsequent flow. Precedent flow confirmed as black in video images due to high silty shale concentration appears before surges arrive, with no sudden water-depth increase. Main-phase debris surges are presumably laminar, but the upper layer flows faster than the lower. Thus, gravel in the upper layer sometimes falls in front of the surge as shown in **Fig. 9**.

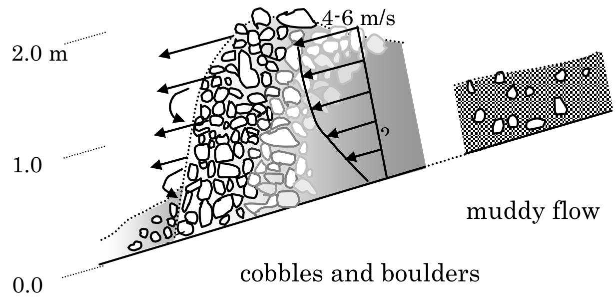

Fig. 9. Schematic diagram of debris flow.

5.3. Debris Flow Surge

Figure 10 shows the flow depth, flow velocity, and discharge determined from video image analysis, with mean surface velocity estimated by multiplying surface velocity by 0.6, suggested by Takahashi (1977) [7, 8]. Discharge was calculated by multiplying cross-sectional debris flow area by mean velocity. As shown in **Fig. 10**, hydraulic properties peak when surges appears in the sequence of flow depth, discharge, and flow velocity. Comparable results were seen in previous studies [2, 3, 6, 8]. Debris

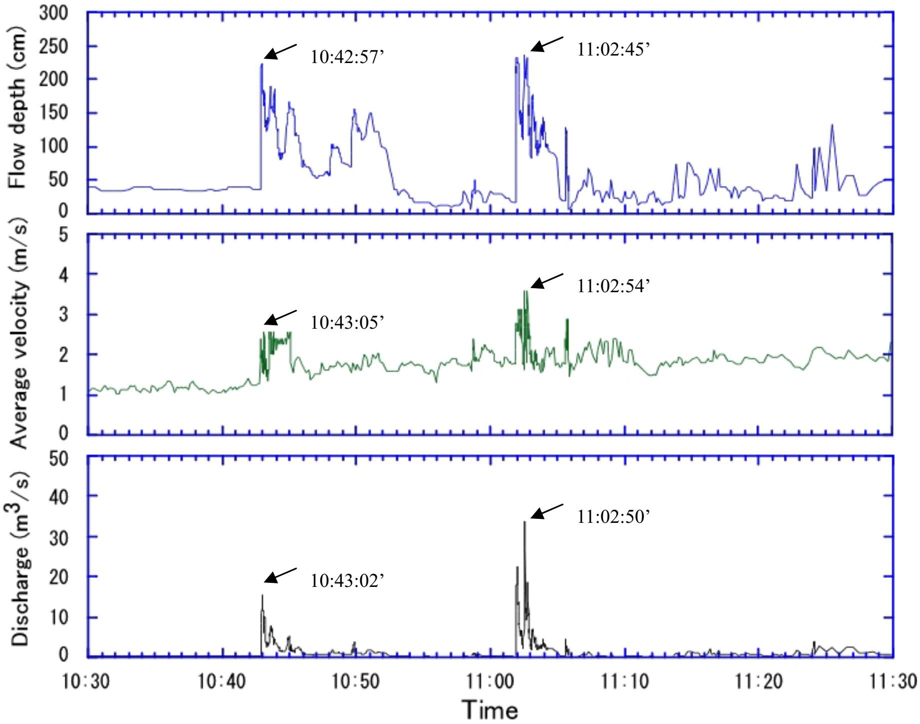

Fig. 10. Changes in flow depth, average velocity, and discharge of debris flow on 19 July 2006.

flow including large amounts of debris and a low average surge velocity of 2.5-3.5 m/s. Total discharge from the first-surge discharge peaking at 15 m^3/s to third-surge discharge peaking at 34 m^3/s was estimated at 2300 m^3.

The peak-to-total discharge relationship during debris flow is plotted in **Fig. 11** together with data from Mt. Yakedake in Nagano Prefecture, Japan [1], where stony debris flow occurs. The debris flow in 2006 is plotted in same position as Mt. Yakedake. Two or three debris flows with similar discharge by downpours in July (Baiu rainy season) and typhoons afterwards occur in each year. Excluding Ichinosawa, no noteworthy sediment production or movement is confirmed in Ohya-kuzure, so recent Ohya-kuzure sediment production is estimated to be 5000 to 10,000 m^3 per year.

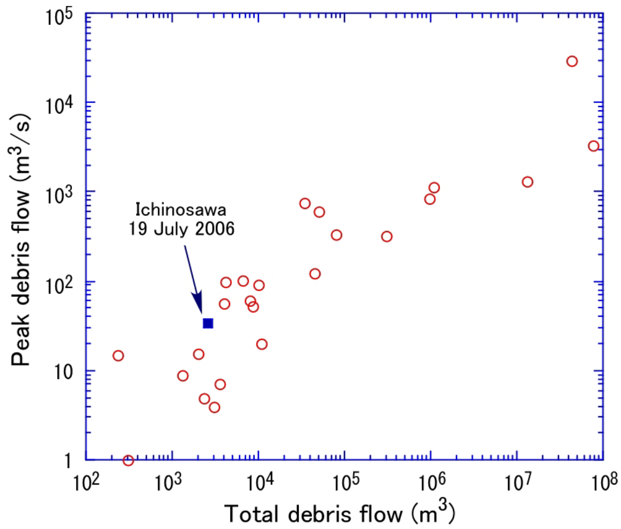

Fig. 11. Logarithmic comparison of debris flow peaks and discharges. The red circles are the data of debris flow obtained in Mt. Yakedake [1].

6. Conclusion

We have concluded that the 1707 Ohya-kuzure landslide was triggered by the Hoei Earthquake and that debris produced by it was 94 million m^3 downstream from Ohya-kuzure, generating Japan's largest debris terrace, with 29 million m^3 of sediment – 33% of the debris terrace – eroded from direct accumulation, with 17 million m^3 of this flowing into the upper Abe River during subsequent events.

Check dams for controlling Ohya River erosion and channel work such as 15 ground sills in Ohya-kuzure have reduced sediment disasters to where sediment supply has remained relatively stable over the last 30 years. Most sediment movement is leveled in channel work, although slope failures and debris flow of several thousands of cubic meters occur in Ohya-kuzure. Based on obtained debris flow data in Ichinosawa where sediment production is most active, annual sediment production in Ohya-kuzure is 5,000 to 10,000 m^3.

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