EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 85 NUMBER 15
13 APRIL 2004
PAGES 145–156

Landslides and Debris Flows Strike Kyushu, Japan

PAGES 145, 151

On 20 July 2003, several damaging landslides and debris flows in southern Kyushu, Japan, attracted international attention and resulted in one of the most major natural disasters of recent years. Large amounts of rain fell on 19 and 20 July as a Baiu front passing over the Sea of Japan met a high-pressure zone moving up from the southeast over the Pacific Ocean. Altogether, 21 lives were lost due to the sediment disasters, and more than 240 homes were either damaged or destroyed and flooding. Nevertheless, such natural disasters occur frequently in Japan. In summer 1993, 121 people were killed by landslides and debris flows within an area of unwelded pyroclastic flow deposits (known as Shirasu) in the Kagoshima Bay area of Kyushu. Thus, local residents generally acknowledge their potential exposure to these hazards, but risk and vulnerability issues may be clouded by inadequate warnings and scientific knowledge, socio-economic factors, and the general feeling that local and national governments are overly protective.

Natural hazard analysis and mitigation are often plagued by misperceptions, both technological and sociological [*Alexander*, 2000]. In the case of these recent disasters, several misperceptions that were apparently held by government agencies, media, and residents were noted related to the history of landslides and debris flows, triggering thresholds for rainfall, susceptibility of weathered volcanic rocks to landslides, the extent of the mass movements, and the effectiveness of structural control measures. Our investigation addresses these misperceptions and offers some insights and suggestions to improve current prediction, control, and mitigation measures.

July 2003 Landslides and Debris Flows

Initial news reports following the 20 July storm suggested that only a few slope failures occurred. While all fatalities occurred in two debris flows in Minamata (Hogawachi and Fukagawa) and a landslide in Hishikari (Table 1), damage by mass movements was widespread in southern Kyushu. Thirty-seven landslides were identified in the most affected areas of Minamata (4 km^2) and 14 in Hishikari (2 km^2), respectively.

Almost all landslides in the Minamata-Hishikara region were underlain by weathered andesite, tuff-breccia, and tuff, and the slope gradients of 20 inspected landslides were generally less steep (initiation zone 20–38°), compared to earlier failure sites in landslide-prone Shirasu deposits in southern Kyushu [*Shimokawa*, 1984]. As the 20 July landslides moved downslope, they accumulated water, and those that entered stream channels generally evolved into debris flows. Except for one very small "piping failure" near the fatal landslide in Hishikari, all landslides appeared to be triggered by the rapid buildup of pore water pressure in fractures and interstices of the weathered andesite (above the more compact volcanic bedrock), or at the soil-bedrock interface (where bedrock was not highly weathered). Clearly, the nature and connectivity of the heterogeneous pore structure of the regolith were important factors related to slope stability [*Sidle et al.*, 2001].

None of the debris flows that were examined in the channels appeared to initiate as debris flows, nor did they rapidly convert from landslides to debris flows as has been suggested in other studies [*Fannin and Rollerson*, 1993; *Iverson et al.*, 1997]. Step-like features and residual trees in the upper portion of landslides clearly indicate that these failures initiated as debris slides or avalanches (Figure 1). Landslides that occurred in weathered bedrock were obviously deeper (4–9 m deep; Figure 1a) than those that failed at the soil-bedrock interface (1–3 m; Figure 1b). Deeper landslides typically traveled further downslope if gradients were steep, and they often developed into debris flows. Of the inspected landslides, only three did not mobilize > 35 m; in these, lithology of both the failed and underlying material was very impermeable, hydrothermally altered volcanics. Shallow landslides constituted the majority of all failures.

Rainfall intensities during the 2- and 6-hour periods up to and including the time of landslides at Hishikari and Minamata were very intense—53 and 89 mm h^{-1}, respectively (Figure 2). Total storm precipitation prior to failure was very high at Hishikari (< 337 mm; ≈3.5 km west of the fatal landslide), but not extraordinary in Minamata (< 265 mm; ≈2 km from the two major debris flows). Moderate rainfall occurred at Hishikari and Minamata on the day prior to the disasters and antecedent 10-day rainfall was only 75 and 70 mm, respectively. In contrast to these rainfall patterns, the summer 1993 storms in Kagoshima that triggered widespread landsliding in Shirasu deposits were of similar size, but antecedent rainfall was almost an order of magnitude higher [*Jitousono et al.*, 1995]. While some 1993 storms had periods of high intensity, few approached the 2-hour intensity at Minamata.

The Disasters at Minamata (Hogawachi Area) and Hishikari

The landslide and resultant debris flow at Hogawachi in Minamata was the largest and most damaging of the 20 July disasters (Table 1). The debris flow occurred only 4.3 hours into the rainstorm (4:20 a.m.), but during the period of highest intensity (Figure 2). A moderate-sized, 4–9-m-deep debris avalanche triggered the debris flow ~1.5 km upslope of where the casualties occurred (Figure 1a). The debris flow began once the landslide entered the channel; no fluid deposits occurred along the lower flanks of the landslide. The landslide that triggered the debris flow initiated in weathered andesite (dipping downslope at 16°) underlain by rather impermeable tuff-breccia; gradient of the slope that failed was 20° near the top and 40° in the lower section. During the intense rainfall, pore water pressure likely developed at the base of the weathered andesite within the limited space in the fractures and interstices. Almost no subsurface water exfiltrated from the exposed bedrock one week after the landslide, attesting to the rapid accretion of pore pressure in this weathered regolith during the storm. This probable scenario of rapid pore pressure accretion and subsequent slope failure is in contrast to theoretically derived responses in homogeneous regoliths, which suggest that thin regoliths become unstable during short-term, high-intensity storms, while deeper regoliths fail during prolonged storms of moderate intensity [e.g., *Haneberg*, 1991; *Iverson*, 2000].

The Minamata debris flow traveled the full length of the channel and entered the Hogawachi River where it terminated due to the abrupt junction angle (≈85°) (Figure 1a). In addition to sediment inputs from other smaller landslides, the debris flow entrained a lot of material as it moved down the valley, transporting many

---

BY ROY C. SIDLE AND MASAHIRO CHIGIRA

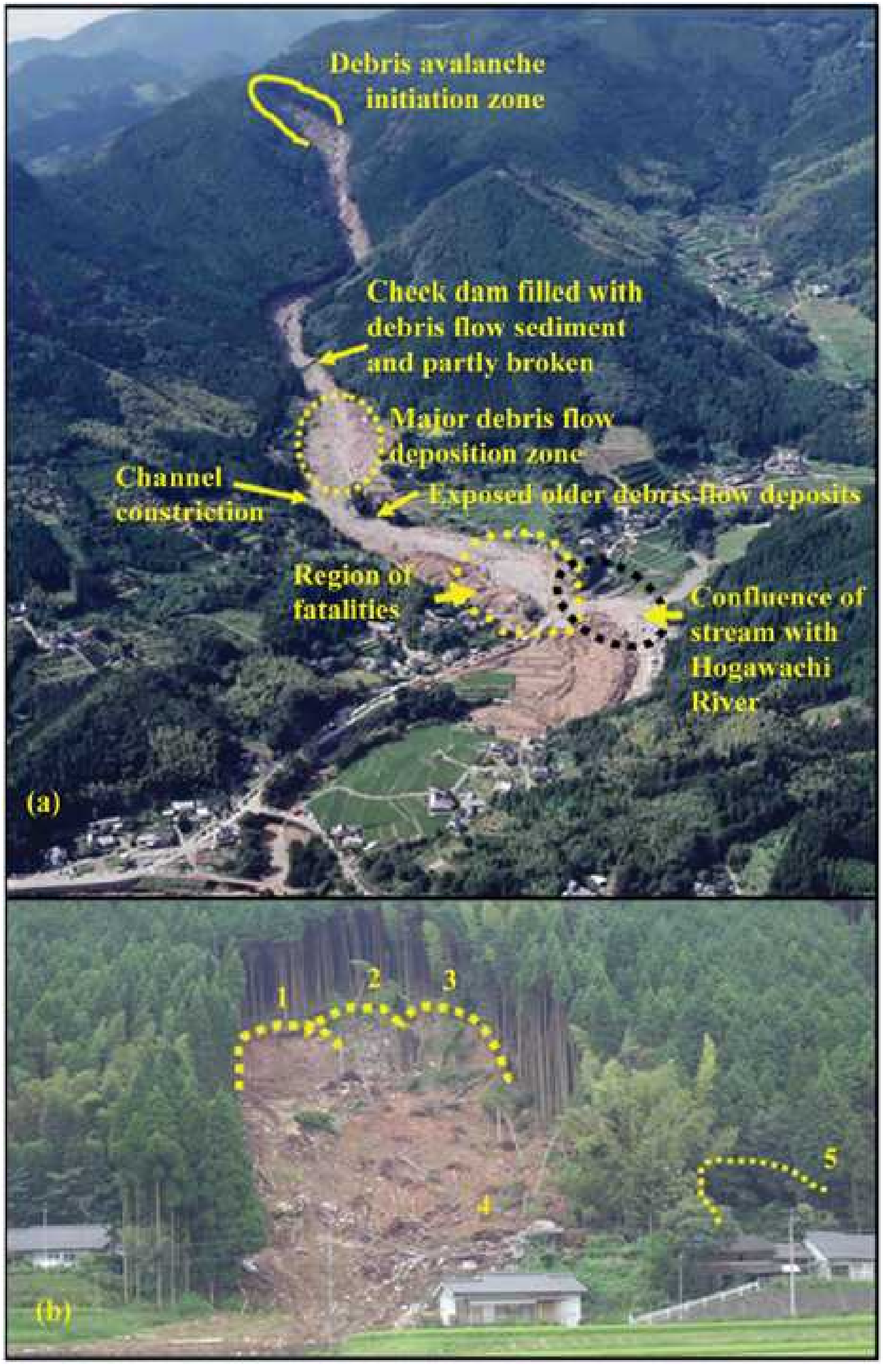

Fig. 1. The 20 July 2003 sediment disasters in Kyushu, Japan: (a) Deep landslide/debris flow at Minamata; (b) More shallower and smaller landslide at Hishikari. A home was destroyed at site #4; a small landslide severely damaged a nearby home (site #5).

times the initial landslide volume. Along this route, several major depositional areas were observed just upstream of channel constrictions. The largest deposit was in a rather steep reach (8–10°) about 350 m upstream from the river junction (Figure 1a). While both tributary junction angle and channel gradient strongly affect debris flow run-out distance [*Benda and Cundy*, 1990], it is clear that channel constrictions or valley pinching also influence deposition; such pinching may have reduced the extent of this debris flow.

While this disaster at Minamata was extraordinary in terms of its consequences, this size of debris flow is not rare based on sediment records and hydrogeomorphic evidence. By examining incisions (≈350 m upstream from the confluence of Hogawachi River) in channel sediments exposed by the recent debris flow, two previous large debris flows were discovered (Figure 3). The upper, more recent debris flow appeared to be the larger of the two. This deposit was 8 m thick in places, but usually > 3 m thick. The matrix was largely comprised of poorly sorted cobbles and boulders, with a mean diameter (D_{50}) of 70 mm and a D_{90} of 220 mm. Based on the estimated age of the largest tree growing on the upper deposit, the debris flow occurred about 80 years ago. The lower debris flow deposit was not completely exposed in the recent incision; it contained a larger percentage of fines and smaller boulders (Figure 3). Thus, contrary to news reports, evidence existed of previous and potentially damaging debris flows in this valley. Large (> 1 m diameter), andesite boulders rounded due to spheroidal weathering were observed in previous debris flow deposits, as well as in the 2002 debris flow, not only near the front [*Coussot and Meunier*, 1996], but also several hundred meters upstream; these may have contributed to the long run-out distance.

Three check dams were found along the path of the debris flow, as well as extensive areas of concrete bank reinforcements. The largest of these dams (≈600 upstream of Hogawachi River) was completely filled with recent debris flow material, the upper structure was broken in places, and a large vertical crack developed (Figure 1a). If the dam had ruptured, the downstream damage could have been worse. The other two dams located upstream were smaller and were designed more as channel grade leveling structures; these were both severely damaged. Intense scouring was evident just downstream of all dams, indicating that when the debris flow overtopped the dams, a high amount of energy was transferred downstream. Overall, the three dams probably did not increase the severity of the debris flow disaster, but they likely had no ameliorative effect. Concrete bank reinforcements along the channel were completely inundated by the debris flow and, in many cases, broken and transported downstream. While none of these structures were designed to contain this size of debris flow, their existence may have contributed to a false sense of security of residents in the valley.

The disastrous landslide in Hishikari town occurred at 8:30 a.m. on 20 July, 7.5 hours into the rainstorm during the period of maximum intensity (Figure 2, Table 1). The upper portion of this landslide appeared to occur in three parts: the left side failed first, followed by the middle portion, and finally the right side of the slope (see scars 1, 2, and 3, respectively, in Figure 1b). Each landslide may have progressively triggered the neighboring failure in rapid succession as evidenced by the scouring and deposition at the site. The soil was 2–3 m deep and underlain by hydrothermally altered andesite and tuff breccia. In places, the rock was weak, highly fractured, clayey, and variable in structure. The first debris avalanche initiated about 10 m downslope of the landslide scarp, probably triggered by outflow along the impermeable rock contact. Compared to the deeper landslide at Hogawachi in Minamata, the accretion of pore water pressure occurred more slowly along the shallower failure plane at Hishikari. Two mechanisms are proposed: infiltration through the wet and porous forest soil mantle, and ex-filtration of subsurface water from fractures in bedrock during the prolonged storm. Water flowing on top of the altered rock on a dry day more than a week after the initial failure attests to these slower infiltration and ex-filtration processes. The landslide converged into a small debris flow that flowed 103 m into a paddy field. Slope angle near the top of the landslide was 31–32°; overall steepness of the landslide/debris flow complex was 19°.

Evidence of past landslide activity at the Hishikari site consists of tilted and curved trees and an old landslide scar upslope of the recent failure. Furthermore, a geomorphic hollow exists immediately above the left side of the failure; thus, it is a concentration zone for subsurface water.

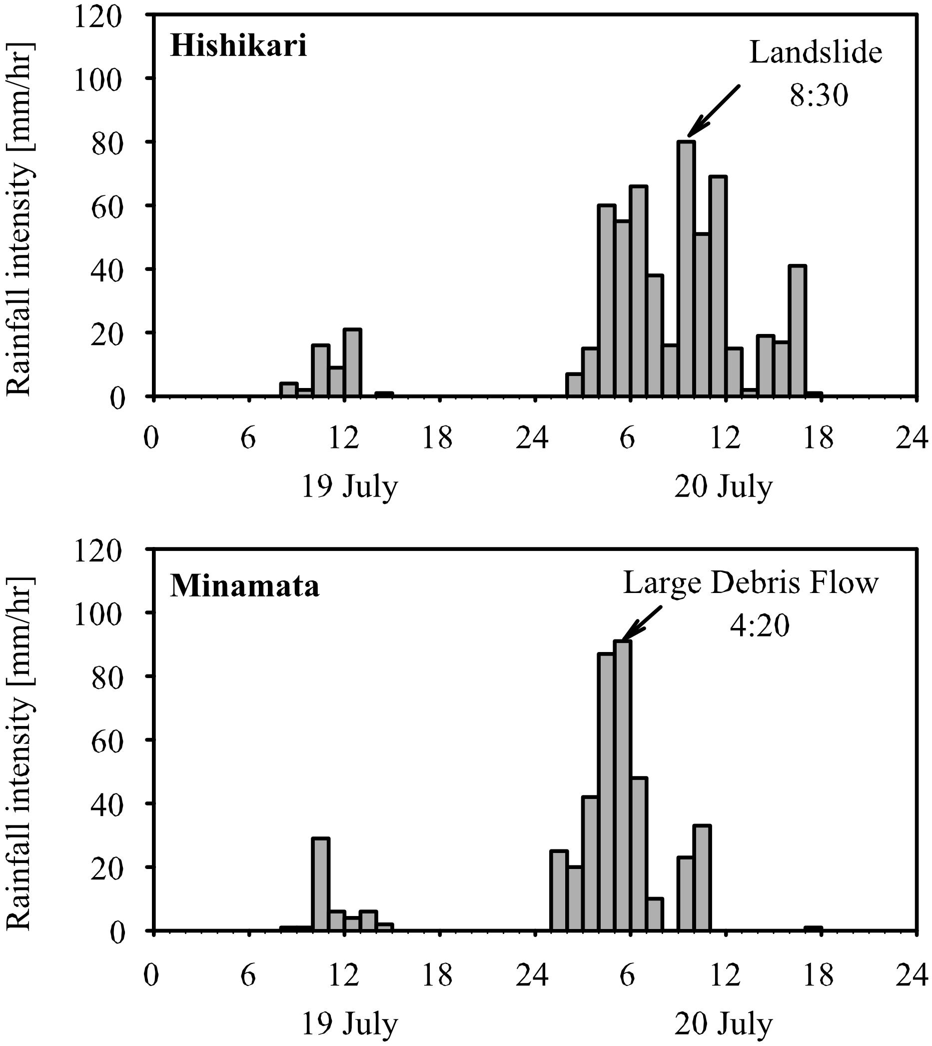

Fig. 2. Rainfall near the Hishikari and Minimata landslide/debris flow sites on 19 and 20 July 2003 is shown; time of landslide/debris flow initiation is noted.

Knowledge Gained from Disasters

The investigation following the 20 July disasters in southern Kyushu provides insight into landslide initiation mechanisms, debris flow run-out patterns, influences of land management and erosion control measures, and potential improvements in mitigation strategies. First, tuff-breccia overlain by weathered andesite appears susceptible to landsliding in this region, particularly during high-intensity rain events during which pore water pressure can rapidly develop in bedrock fractures and interstices.

Widespread landsliding in similar lithological sequences has been noted around Nagasaki, but the lithology-hydrology interactions have not been clarified [*Nishiyama and Chigira*, 2002]. In general, weathered andesite underlying moderately steep (from 20–38°) slopes is not typically recognized by land developers and government agencies as being highly unstable compared to the much steeper Shirasu hillslopes in the region. In stark contrast to the Minamata and Hishikari slope failures that occurred during the highest rainfall intensity, many of the 1993 landslides in Shirasu terrain initiated several hours after the storm peak [*Jitousono et al.*, 1995]. Thus, there was less warning time for the 2003 disasters, especially at Minamata. Although the most intense cells of the July 2003 storm struck a different region than the 1993 storms, some Shirasu terrain near Hishikari experienced heavy rain. The fact that landslides on steep Shirasu slopes were essentially absent during this 2003 storm could be explained by such different antecedent and triggering rainfall conditions.

Thus, it is necessary to account for lithology in the development of regional rainfall thresholds. Shirasu deposits, while known to be very susceptible to landslides, appear to require similar or larger total amounts of rainfall and much higher levels of antecedent rainfall (but not necessarily such high intensity) as triggering conditions due to the low permeability of the weathered material and its larger and more uniform porosity [*Chigira and Yokoyama*, 2002]. Second, debris flow run-out appeared to be influenced by the permeability of failed material, rounded boulders, and valley constrictions. It appears that channel constrictions could be used together with other morphometric attributes to estimate debris flow run-out. Such findings should be useful in planning structural control measures—that is, constructing large-scale channel restrictions that allow some of the debris flow to pass but promote upstream deposition of larger materials.

Many small landslides were observed along road cuts; engineering works along roads were often ineffective in preventing such landslides.

In Hishikari, plantation terraces may have contributed to landslide initiation by concentrating water (site #5, Figure 1b). Structural erosion control measures proved ineffective in mitigating debris flow damage, and in some cases may have actually exacerbated the damage due to partial collapse. Engineers must carefully weigh the structural integrity of debris check dams in view of episodic geomorphic phenomena. If past geomorphic evidence of debris flows is used with unstable site indicators, lives and investments can be saved by leaving the most hazardous sites undeveloped.

References

Alexander, D. (2000), *Confronting Catastrophe*, 282 pp., Oxford University Press, U.K.

Benda, L. E., and T. W. Cundy (1990), Predicting depositions of debris flows in mountain channels, *Can. Geotech. J.*, 27, 409–417.

Chigira, M., and O. Yokoyama (2002), Weathering profiles and landslide of ignimbrite, in *Proceedings of the 9th Conf. of the International Association for Engineering Geology and the Environment (IAEG)*, pp. 1780–1784, IAEG, Paris, France.

Coussot, P., and M. Meunier (1996), Recognition, classification and mechanical description of debris flows, *Earth-Science Rev.*, *40*, 209–227.

Fannin, R. J., and T. P. Rollerson (1993), Debris flows: Some physical characteristics and behaviour, *Can. Geotech. J.*, *30*, 71–81.

Haneberg, W. C. (1991), Pore pressure diffusion and the hydrologic response of nearly saturated, thin landslide deposits to rainfall, *J. Geol.*, *99*, 886–892.

Iverson, R. M. (2000), Landslide triggering by rainfall infiltration, *Water Resour. Res. 36(7)*, 1879–1910.

Iverson, R. M., M. E. Reid, and R. G. LaHusen (1997), Debris-flow mobilization from landslides, *Ann. Rev. Earth Planet. Sci.*, *25*, 85–138.

Jitousono, T., E. Shimokawa, I. Miura, M. Matsumoto, and S. Kato (1995), The rainfall and outbreaks of landslides and debris flows caused by heavy rain in 1993, in *The investigations of disaster in Kagoshima by heavy rain in 1993, Report 2*, Kagoshima University, Japan.

Nishiyama, K., and M. Chigira (2002), Geological features of slope failures due to 1982 heavy rainfall disaster in Nagasaki, Japan, *Annuals of the Disaster Prevention Research Institute*, *45B*, 47–59 (in Japanese).

Shimokawa, E. (1984), A natural recovery process of vegetation on landslide scars and landslide periodicity in forested drainage basins, in *Proceedings of the Symposium on the Effects of Forest Land Use on Erosion and Slope Stability*, pp. 99–107, East-West Center, Honolulu, Hawaii.

Sidle, R. C., S. Noguchi, Y. Tsuboyama, and K. Laursen (2001), A conceptual model of preferential flow systems in forested hillslopes: Evidence of self-organization, *Hydrol. Process.*, *15*, 1675–1692.

Author Information

Roy C. Sidle and Masahiro Chigira, Disaster Prevention Research Institute, Kyoto University, Geohazards Division, Gokasho, Uji, Japan

Fig. 3. Two previous debris flows exposed in the incision made by the 20 July 2003 debris flow at Minamata; boundary between the two debris flows is shown; older (lower) debris flow appears less damaging (more fines in the consolidated matrix).

Table 1. Characteristics, Triggering Rainfall Conditions, and Damage Related to the Three Landslides/Debris Flows in Southern Kyushu, Japan, that Inflicted Casualties on 20 July 2003.

Site of landslide/debris flow	*Landslide volume[1] (m^3)*	*Total Rain[2] (mm)*	*Maximum 1-h rain intensity ($mm\ h^{-1}$)*	*Debris flow runout distance[3] (m)*	*Homes destroyed*	*Number of people killed*
Minamata (Hogawachi)	26,000	< 265	91	1700 m	13	15
Minamata (Fukagawa)	370[*]	< 265	91	340 m	5	4
Hishikari	7000	< 337	80	103 m	1	2

[1] the volume of the landslide that triggered the debris flow
[2] including the 1-h interval during which the landslide occurred (thus <)
[3] measured from the low portion of the initiating landslide
[*] estimated from air photos