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LANDSLIDE DAMS - PROCESSES, RISK AND MITIGATION

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Edited by Robert L. Schuster

# **LANDSLIDE DAMS: PROCESSES, RISK, AND MITIGATION**

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## LANDSLIDE DAMS IN JAPAN

Frederick J. Swanson<sup>1</sup>, Norio Oyagi<sup>2</sup>, and Masaki Tominaga<sup>2</sup>

## ABSTRACT

Damming of rivers by landslides is common in Japan because widespread unstable slopes and narrow valleys exist in conjunction with frequent hydrologic, volcanic, and seismic landslide triggering events. Landslides that dam rivers can be broadly classed as fast (>1.5 m/day) and slow (<1.5 m/day). Fast landslides are further distinguished by the extent of valley floor receiving landslide deposits. Slow landslides are differentiated in terms of location of the basal shear zone in relation to the stream channel. Different landslide types have differing effects on frequency and extent of damming and upstream and downstream flooding.

## INTRODUCTION

A variety of factors combine to make landslide dams a widespread natural phenomenon of substantial social importance in Japan. Active tectonism has led to high relief and structurally weak rocks. Numerous tall volcanoes are composed of unstable, hydrothermally altered rocks that are susceptible to large landslides triggered with or without volcanic activity (Ui, 1983). Earthquakes and heavy precipitation caused by a variety of meteorological conditions (Tominaga, 1985) also initiate landsliding. Effects of landslide dams on people are aggravated by high population densities and numerous villages even in the narrow, mountain valleys that are common in Japan. Studies of landslide dams in Japan are facilitated by extensive documentation, but the natural behavior of such blockages is commonly obscured by immediate, intensive modification to reduce the hazards of debris flows and upstream and downstream flooding.

In this paper we use the term "landslide" in a general sense to include slope movements with velocities ranging from slow (1.5 m/yr to 1.5 m/mo) to extremely rapid (>3 m/sec), based on classification of velocity by Varnes (1978). Landslides slower than 1.5 m/yr seldom cause any type of damming. More specific terminology for slope movements follows that of Varnes (1978).

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The objectives of this paper are: (1) to define general classes of landslide-channel interactions that can lead to flooding in upstream and, in many cases, downstream areas; (2) to describe these classes of landslide damming events using examples from Japan; (3) to speculate on the type of flooding and debris flows likely to result from different types of damming events; (4) to evaluate some factors controlling the lifetime of the dams; and (5) to consider the relative frequency of occurrence of the different classes of landslide-channel interactions.

#### CLASSES OF LANDSLIDE-CHANNEL INTERACTIONS LEADING TO DAMMING

The interactions between landslides and channels can be broadly classified based on several geometric considerations, including the size of landslides relative to the receiving valley floor. A classification system is useful for identifying the local and downstream effects of landslide dams in geologic terranes with distinctive valley floor geometries and landslide characteristics (size distribution, velocity).

Landslides are differentiated here as fast (>1.5 m/day) or slow (<1.5 m/day). Slow landslides are divided into three classes based on location of the toe of the basal shear zone relative to river channel: (1) toe of the basal shear zone upslope of channel, (2) toe of the basal shear zone in channel, and (3) basal shear zone extending beneath the channel to emerge on the opposite side of the channel (Figure 1). The term "basal shear zone" refers to both the surface of rupture and the surface of separation defined by Varnes (1978). Fast landslides are classified by the volume of landslide material delivered to the valley floor relative to valley width (Figure 2). Types of slow landslides include earthflows, earth slump, and earth block slide. Fast landslides are typically slides and flows, rock falls, and complex combinations of these types.

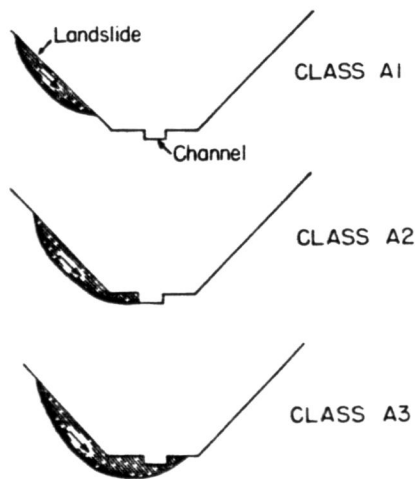


Figure 1. Classification of relation between basal shear zone of slow landslides and river channel.

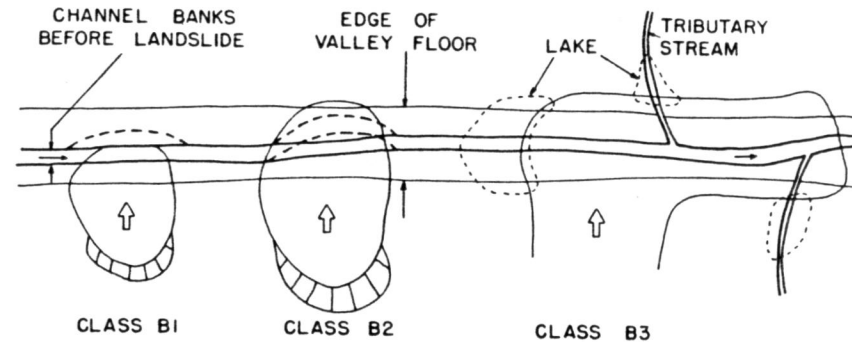


Figure 2. Generalized sketch of relation between volume of fast landslides and width of valley floor.

The following is a classification system based on these considerations.

#### A. Slow landslides

##### A1. Basal shear zone emerges at ground surface upslope of channel

In this case, the slow landslide does not impinge directly on the channel, but delivery of colluvium to the channel may occur by one or more smaller, rapid, secondary slope movements, such as debris avalanches. If damming occurs, it would be considered under other classes described below.

##### A2. Basal shear zone emerges in the channel

Intersection of the basal shear zones of slow landslides and stream channels is common. Channel constriction by landslide movement can lead to impoundment of water in upstream areas. In narrow, landslide-constricted valleys, channels are commonly bordered by landslide colluvium on one bank and bedrock on the other. Channel damming in these sites may be temporary because the unconsolidated landslide debris is readily eroded. In other cases, such as the Slumgullion landslide in Colorado, U.S.A., landslide movement may push a stream up the opposite valley slope where the stream becomes stabilized as it flows over bedrock (Schuster, 1985).

Channel response can be considered in terms of a channel constriction ratio:

$$\text{Annual constriction ratio} = \frac{\text{speed of landslide toe}}{\text{channel width}}$$

which expresses toe velocity in terms of proportion of channel width (Swanson et al., 1985). Based on field observations in Oregon, U.S.A., annual constriction ratios of more than 100 appear to be required for development of lakes, even temporarily during floods.

## A3. Basal shear zone emerges on far side of channel

The basal shear zone of a landslide may extend entirely beneath the channel of a river which crosses the lower end of the landslide. Landslide movement in this situation, termed "kawagoe-ryukigensho" by Yamaguchi and Takeuchi (1968), can result in an upstream backwater effect from upward movement of the streambed. The channel is cut entirely in alluvium and landslide material. Flooding of downstream areas is unlikely because abrupt release of a large volume of water is limited by the small storage capacity behind such dams and perhaps by the low erodibility of landslide debris exposed in the river bed.

## B. Rapid landslides

## B1. Landslides small in relation to width of valley floor

Landslides which only partially cross valley floors typically cause only minor damming. In the minimal case where landslide debris does not fully occupy the bankfull channel, the river remains in the same channel and the impoundment is very small and of short duration. Landslides large enough to occupy the channel completely divert flow over adjacent floodplain and, possibly, terrace areas. The relocated channel may cut into old alluvium rather than landslide colluvium. The volume of water collected behind the dam varies in relation to dam height, channel gradient, and width of the floor of the dammed valley. The volume of impounded water in this class of landslide-river interaction is not likely to be large because it is limited by the low height of the dam.

## B2. Landslide deposits spanning valley floor

A landslide delivering a volume of colluvium large enough to cross the valley floor, but not large enough to occupy an extended length of valley floor, typically produces a single impoundment. This occurs by landslide movement from the valley wall or by debris flow or debris avalanche movement down a tributary channel. Water impounded by the dam may flood broad areas upstream and may eventually flow over the unconsolidated landslide debris, in some cases leading to dam failure and widespread downstream flooding.

## B3. Landslide deposits covering the valley floor over a valley length much greater than the width

Landslide deposits can occupy a valley floor over a distance of hundreds to thousands of meters and, in so doing, dam not only the main channel but also a series of tributary streams. Consequently, more than one lake may be formed by damming. Additional ponds may form on the landslide surface; however, we disregard ponds on landslide surfaces in this discussion. Streams draining the lakes and the landslide surface flow on the loose landslide debris or at the contact with the valley wall. Volumes of impounded water are very large where dams are high and the geometry of the valley floor provides a large storage capacity. As such dams are overtopped and fail, large discharges of water flow over the unconsolidated landslide deposits and commonly produce debris flows.

## LANDSLIDE DAMS IN JAPAN

Case Examples - Simple, Individual Landslide Dams

## A1. Slow landslides with basal shear zone emerging at ground surface upslope of channel

We know of no examples in Japan of this class of landslide-channel interaction that resulted in damming except where the ultimate delivery of landslide debris to the channel was rapid. This is considered below in discussions of fast landslides.

## A2. Slow landslides with basal shear zone emerging in channel

We know of no documented examples of this class of landslide damming in Japan. Since such dams and associated lakes would have very short lifetimes and pose little flood threat to downstream areas, they have not been documented. Documentation of landslide dams in Japan focuses on large, rapid landslides where extensive engineering works have been carried out.

## A3. Slow landslides with basal shear zone passing beneath the channel and emerging on the far side of the valley

Kamenose (Osaka Prefecture), Shorinzan (Gunma Prefecture), Kujumidai (Nagano Prefecture), and Yachi (Akita Prefecture) (Figure 3) are landslides where at least part of the toe of the basal shear zone reaches the ground surface on the side of the river opposite the main sliding mass. Slow movement has been monitored at each of the landslides, and extensive control measures have been underway for some years.

Not all of these landslides have caused flooding, but 20-36 m of upward movement of the bed of the Yamato River where it flowed over the Toge Unit of the Kamenose landslide (Figure 4) led to flooding in upstream areas (Ministry of Construction, 1980). This episode of movement, which occurred between November 1931 and July 1932, destroyed a railroad tunnel, damaged a national highway, and flooded 200 ha of farmland and villages. Maximum upward movement rate was 38.5 cm/day. Horizontal movement totaled 40.7 to 53 m at a maximum rate of 53.2 cm/day. Over a six-month period ending in November 1932,  $1.87 \times 10^6 \text{ m}^3$  of material was excavated in a government project to maintain the channel and prevent flooding. There is no report of downstream flooding. Several incidents of flooding along the Usui River caused by upward movement of the river bed by the Shorinzan landslide have also occurred since movement began in 1890.

## B1. Fast landslides with deposits not crossing the valley floor

This class of landslide-channel interaction is common, particularly where rivers have eroded the toe of a slope, decreasing its stability. Wada (Nara Prefecture) and Onishiyama (Nagano Prefecture) landslides are examples of landslide debris just reaching the far channel bank and of its extending just to the base of the opposite side of the valley (Figure 5).

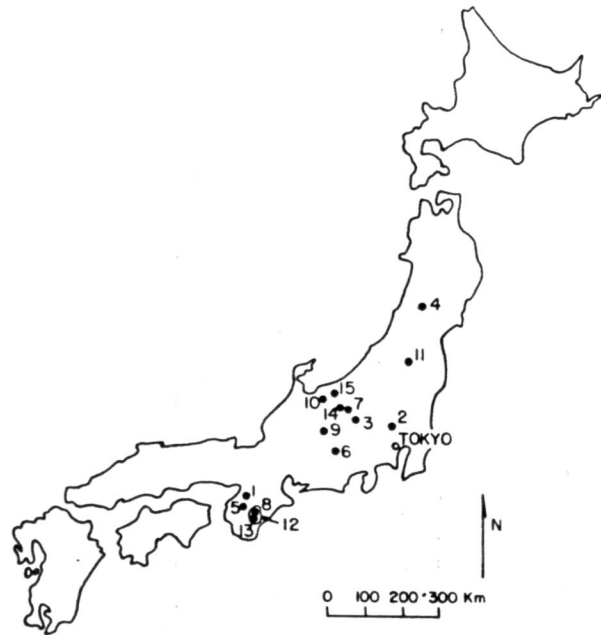


Figure 3. Map showing locations of landslides referred to in the text and figures. 1. Kamenose, 2. Shorinzan, 3. Kujumidai, 4. Yachi, 5. Wada, 6. Onishiyama, 7. Kokuzo, 8. Nakayama, 9. Ontake, 10. Hieda, 11. Bandai, 12. Totsu River basin, 13. Shigesato, 14. Yanaku Pond, 15. Ozuchiyama.

In late July and early August 1982, as Typhoon 10 passed over west central Honshu, rainfall exceeded 500 mm in some areas. In the vicinity of the Wada landslide, rainfall for a 26-hour period beginning at 2000 hours on August 2 was greater than 180 mm (Fujita et al., 1983; Yonetani et al., 1983). Earlier rainfall led to incipient slope movement indicated by ground cracks first noticed on July 14. Two large, rapid landslides occurred on August 4. About  $7.0 \times 10^5 \text{ m}^3$  of landslide material moved downslope, of which approximately  $1.2 \times 10^5 \text{ m}^3$  entered, but did not completely fill, the Niu River channel. A village in the upstream area was partially flooded, but within a few days the channel was reopened by excavation of a narrow artificial channel that was enlarged further by river erosion. Dikes and other channel control structures prevented lateral movement of the river channel across the valley floor. No downstream flooding occurred because the volume of impounded water was small and it was released over several days.

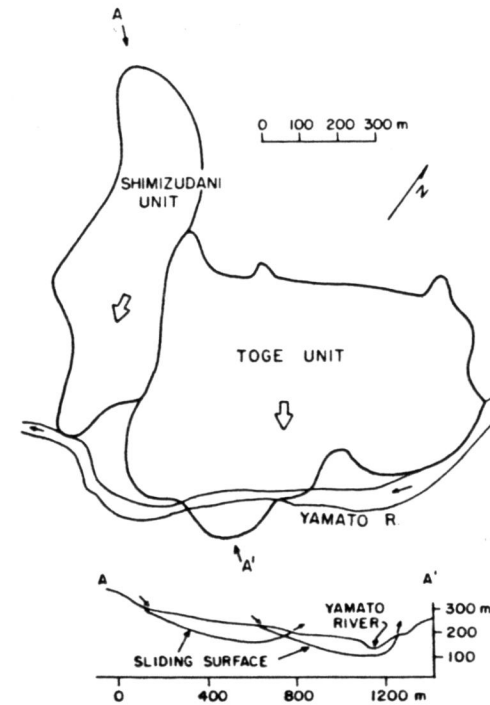


Figure 4. Map of Kamenose landslide, showing Toge and Shimizudani Units, and cross section (adapted from Ministry of Construction, 1980). Large arrow indicates direction of landslide movement.

On June 29, 1961, after an extended period of heavy rainfall, the  $3.0 \times 10^6 \text{ m}^3$  Onishiyama landslide collapsed into the Koshibu River and spread about  $2.4 \times 10^6 \text{ m}^3$  of material 500 m across the valley floor, just reaching the opposite side of the valley (R. Tsunaki, personal communication, 1985). Within a few days the river cut a new channel through the landslide dam and older floodplain deposits, but not before houses and fields were flooded in upstream areas.

## B2. Fast landslides spanning valley floor

Japan experiences many large landslides that cover the full width of the valley floor and create dams with sufficient water-storage capacity to cause major downstream flooding at the time of dam failure. This class of landslide damming includes both direct delivery from slope to channel [for example, Kokuzo landslide (Nagano Prefecture) and Nakayama landslide (Nara Prefecture)] and movement of large debris flows or debris avalanches down tributary channels before blocking a main stem channel [for example, Ontake landslide (Nagano Prefecture) and Mount Hieda landslides and debris flows into the Ura River (Nagano Prefecture)].

The Kokuzo landslide occurred during the Zenkoji earthquake of March 24, 1847, which triggered more than 43,000 landslides and other

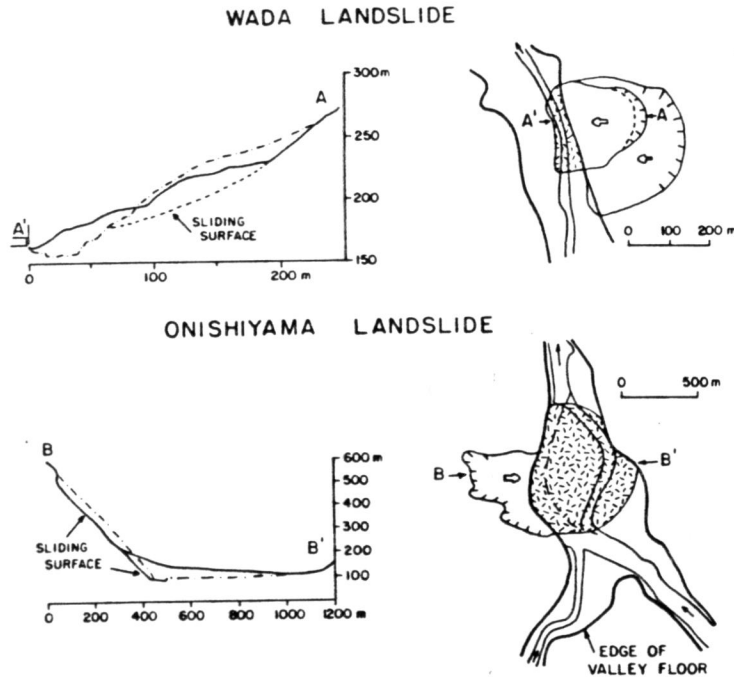


Figure 5. Map and cross section of Wada (Yonetani et al., 1983) and map of Onishiyama landslides (R. Tsunaki, Ministry of Construction, Tokushima, Japan, pers. comm.). Shaded area denotes landslide deposit on valley floor, dashed line shows channel location before shifting to location marked by the solid line. Large arrows indicate direction of landslide movement.

slope failures in the Nagano area (Nishizawa and Chiba, 1979; Itoh, 1983). At least eight large landslides formed dams on the main channels of the Sai River and its major tributaries. The  $2 \times 10^6 \text{ m}^3$  Kokuzo landslide formed a dam 100 m high on the Sai River, flooding upstream areas along the river for a distance of 23.25 km (Itoh, 1983). Some excavation of the dam was carried out for about one week after its formation, but then the work was abandoned because of hazardous working conditions. Heavy rainfall on April 8-9 led to flow over the dam the following day. This water was ponded by another landslide dam formed by the earthquake 3 km downstream at Fukikura village. Complete failure of both dams on April 13, 1847, sent a wall of water rushing downstream, flooding about 30 villages and an area of about  $150 \text{ km}^2$  in the vicinity of Nagano City. More than 24,000 houses were damaged, but only 26 people were killed, because local government officials had warned of the impending flood and most people had evacuated to higher ground. Dams in this event

with known lifetimes failed in 4 days (2 cases), 17 days (1 case), 19 days (2 cases), and 4 months (1 case).

B3. Large, fast landslides covering the valley floor over a length much greater than width

Damming of rivers by very large landslides can produce multiple lakes. This is common at active volcanoes (Ui, 1983; Siebert, 1984) because of high local relief, an abundance of wet, hydrothermally altered, poorly consolidated debris, and the opportunity for triggering by volcanic activity and earthquakes. An eruption-triggered debris avalanche led to the most notable, historical example of a very large landslide in Japan which occurred on July 15, 1888, at Bandai volcano (Fukushima Prefecture). About  $1.5 \text{ km}^3$  of the summit of Mount Bandai collapsed and flowed as a rapid debris avalanche northward up the Nagase River valley (Figure 6), burying about  $70 \text{ km}^2$  of the valley and killing 461 inhabitants (Sekiya and Kikuchi, 1889; Nakamura, 1978). The debris avalanche deposit blocked several branches of the Nagase River, forming Osuzawa, Hibara, Onogawa, and Akimoto Lakes in the mouths of dammed tributary streams. Because the newly formed lake basins had large capacities and contributing drainage basins were not large (40 to  $110 \text{ km}^2$  each), the lake basins filled with water over a period of many months. Hibara Village was abandoned on February 17, 1889, "on account of the encroachment of the new lake" (Sekiya and Kikuchi, 1889, p. 139). By May 1889, Osuzawa and Hibara Lakes had grown and merged into one large lake, now called Lake Hibara.

Sekiya and Kikuchi (1889) document several floods in downstream areas as lakes filled and overflowed the landslide dams. On October 7, 1888, "the new lake Akimoto rushed out cutting through the mudfield, after a heavy rain-storm. In the lower course of the river Nagase, the water level suddenly rose '9 ft' (2.7 m) above the ground, causing great uneasiness among the people" (Sekiya and Kikuchi, 1889, p. 139). On April 13, 1889, "a large portion of Onogawa Lake was suddenly drained, and the torrent of water rushed through the mud-field, carrying mud, pebbles, and boulders to the lower levels" (Sekiya and Kikuchi, 1889, p. 134). This may have been a debris flow. Drainage of the lake in response to natural channel incision slowed abruptly as a lag concentration of large boulders armored the channel. Onogawa remains a lake of about 156 ha surface area.

Damage in downstream areas caused by these discharge events was limited by the sparse population in the area and the short length (11 km) of the Nagase River between the lower end of the landslide deposit and Inawashiro Lake. Inawashiro Lake, which was dammed by a much earlier landslide on the southwest side of Mount Bandai, is large enough to attenuate the peak of such floods and debris flows farther downstream (Figure 6).

#### Complex Landslide-Channel Interactions

Although many of these cases of landslide damming fit within single classes of landslide damming events, complex landslide-channel

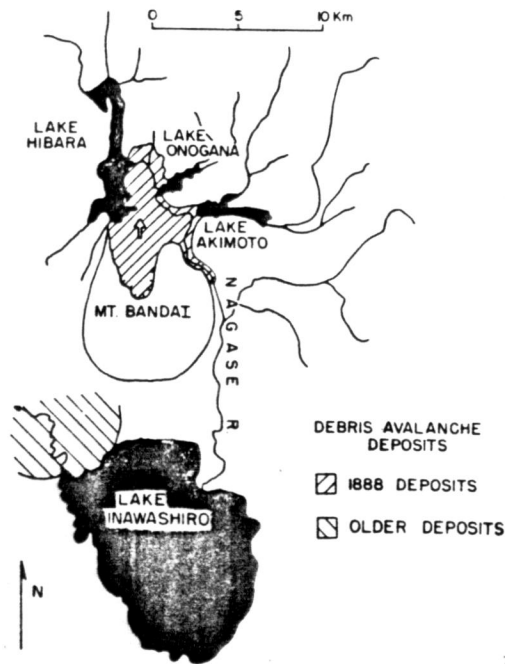


Figure 6. Map of Mount Bandai and vicinity, showing debris avalanche deposits and associated lakes. Large arrow indicates direction of landslide movement.

interactions are also common. Both the Yachi (Sasaki, 1985) and Kamenose (Ministry of Construction, 1980) landslides, for example, are composed of several blocks with different potential effects on the river channel. The rivers flow over blocks of these complex landslides where the basal shear zone extends beneath the river (Class A3). In these cases, accelerated landslide movement would raise the level of the river bed and impound water upstream. Other landslide blocks move laterally into the channel and temporarily block the stream by channel constriction (Class A2), leading to debris flows or floods downstream upon release of the water. Such an event was reported in the late 1940's at Iwaigawa village, 10 km downstream of the Yachi landslide (Sasaki, 1985). In the case of the Kamenose landslide (Figure 4), upward movement of the bed of the Yamato River by the Toge Unit produced upstream flooding in 1931-1932. This was followed in 1951 by reactivation of the Shimizudani Unit, which "was threatening to move into the Yamato River" (Ministry of Construction, 1980, p. 5). Damming by channel constriction was prevented by excavation and slope stabilization works.

#### Considerations of Groups of Landslide Dams

Most studies of landslide damming of rivers in Japan have centered on

case studies of individual landslides; however, some useful insights arise from analyzing groups of landslide dams. Here we consider analysis of: (1) a landslide-triggering event that produced multiple dams; (2) the relations among landslide volume, drainage area above the dam, and lifetime of the lake; and (3) the relative abundance of different classes of landslide-damming events.

#### A Landslide-Triggering Event Producing Multiple Dams

Most publications and reports about landslide dams deal with single dams where engineering stabilization works are prescribed or documented. Indeed, many dams occur as isolated events. One indication of the highly favorable conditions for landslide damming in Japan are the examples of numerous dams formed by single triggering events. Multiple landslide dams in the Totsu River flood disaster of August 1889 in Nara Prefecture (Figure 3) are documented in detailed hand-written records. A period of heavy rainfall triggered more than 1100 rapid landslides. Landslides greater than 90 m in length and 90 m in width occurred at 247 locations, producing 53 dams within the narrow valleys of a 1100 km<sup>2</sup> portion of the Totsu River basin (Chiba, 1975; Kagose, 1976; Fujita, 1983). These dams completely crossed the valley floor and formed individual lakes on the main channel that received the landslide debris (Class B2). The dams formed over a 70-hour period, and most had lifetimes of up to a few days. Local villagers attempted to excavate some of the dams; however, natural processes, such as flooding in August and September, removed much of the channel-damming debris. The only lake surviving today is Shigesato Lake, a pond in a 32 ha drainage basin dammed by a landslide with a volume of approximately  $1 \times 10^6$  m<sup>3</sup>.

#### Lifetime of Dams and Lakes

Landslide dams and the lakes they impound may have lifetimes ranging from minutes to millenia. The lifetime of a dam is determined by the time necessary to develop conditions leading to dam failure. For dams that do not fail, the lifetime of the lake is controlled by the rate of sediment accumulation. Dam failure may result from overflow and subsequent channel incision, piping, or mass slope failure of the dam.

The lifetime of a lake behind a landslide dam is controlled in part by the interaction of fluvial and landslide factors. The relationship among landslide volume, watershed area above the dam, and dam lifetime has been examined in a very cursory way by Swanson et al. (1985) who plotted these relationships for nine examples from Japan. We add the Onishiyama, Shigesato, and Ozuchiyama landslide dams to this analysis and observe the general relationship of short-lived dams occurring where smaller landslides entered rivers draining larger basins (Figure 7). It is unlikely that there is a single threshold relationship between landslide volume and watershed area that determines potential for dam failure because many other factors are important, including the slope of the dam surface and the size distribution, hence erodibility, of landslide debris.

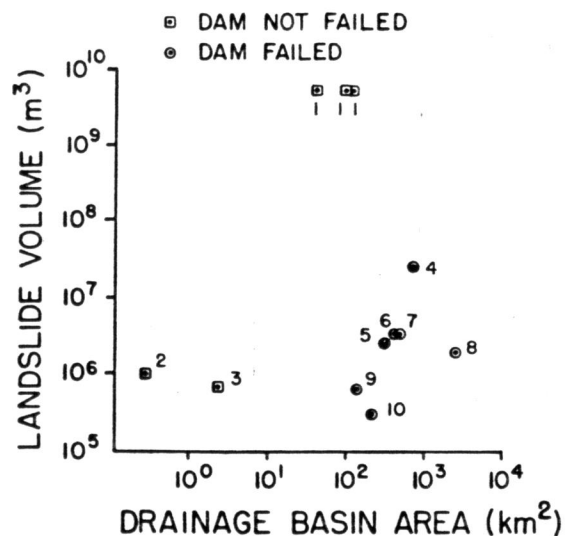


Figure 7. Distribution of long- and short-term landslide dams in relation to landslide volume and drainage basin area above the dam. Sites: 1. Bandai, 2. Shigesato, 3. Yanaku Pond, 4. Kamenose, 5. Onishiyama, 6. Hieda, 7. Nakayama, 8. Kokuzo, 9. Wada, 10. Ozuchiyama. Locations shown in Figure 3.

Even where dams may maintain lakes for many years, flooding or debris flows may occur when the dam is first overtopped, as observed at Bandai volcano. Channel incision and associated drop in lake level of several tens of meters may release a large volume of water rapidly before the channel is armored by a lag concentration of large particles. However, observations from the 1889 flood of the Totsu River basin and the low number of long-term, landslide-dammed lakes in Japan indicate that most landslide dams fail completely in the first few large floods.

#### Relative Abundance of Classes of Landslide Dams

The relative importance of different classes of landslide damming can be inferred from examination of a large sample of such events. Unfortunately, because a list of landslide-damming events has not been compiled systematically, we must rely on interpretations of other field observations to judge the relative frequency of landslide damming types. Lateral constriction of channels (Class A2) by slow moving landslides is common, but damming and flooding associated with this type of hillslope-channel interaction are very rare. Upward movement of channels by landslides (Class A3) is quite uncommon, and not all landslides of this type dam rivers.

Rapid landslides are the most common cause of landslide dams. Landslides with volumes in the range of  $1 \times 10^4$  to  $1 \times 10^6 \text{ m}^3$  commonly divert a channel across floodplain and terrace areas (Class B1). Larger landslides, which are likely to produce class B2 or B3 landslide-channel interactions, are less common but may have a greater tendency to dam channels. The very large landslides that produce multiple lakes are not very common, but they may have the greatest capability to form large, long-lived lakes.

#### CONCLUSIONS

Landslide dams commonly block rivers in Japan because of conditions favoring large-scale landsliding and the wide distribution of narrow valleys conducive to damming. Landslide dams can be classified in terms of slow ( $<1.5 \text{ m/day}$ ) landslides, the location of the basal shear zone relative to the river channel; and fast ( $>1.5 \text{ m/day}$ ) landslides, the volume of landslide material in relation to valley floor width. The potential magnitude of upstream and downstream flooding varies among the classes of landslide-damming conditions.

The lifetime of landslide-dammed lakes is determined in part by dam stability. In general, small landslides entering large channels produce dams with short lifetimes. Landslides that are large relative to the channel and valley floor receiving the deposits are more likely to produce dams with long lifetimes. According to the available record of landslide-damming throughout Japan and in the Totsu River flood of 1889, dams of short duration appear to be much more common than long-lived dams.

#### ACKNOWLEDGMENTS

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