Chapter 2

A worldwide perspective on landslide dams

2.1 Introduction

Landslide dams are formed by various kinds of landslides, and occur in differing physiographic settings, ranging from rock slides and avalanches in steep-walled narrow valleys to slumps and flows of sensitive clays in flat river lowlands. They have occurred to heights as great or greater than the world's largest constructed dams.

The earliest recorded landslide dams occurred in Hunan Province in central China in 1737 B.C. when earthquake-triggered landslides dammed the Yi and Lo Rivers (Xue-Cai and An-ning, 1986). Two of the earliest recorded flooding disasters from failure of landslide dams occurred in Switzerland in A.D. 563 (Eisbacher and Clague, 1984) and in Central Java in A.D. 1006 (Holmes, 1965, pp. 485-487). In the disaster in Java, the southwestern part of the cone of Merapi volcano failed as a large rock slide that created a dam behind which a flourishing countryside, famed for its Hindu temples and monuments, was submerged by a deep and extensive lake.

A landslide dam and its impoundment may last for several minutes or for several thousand years, but sooner or later most landslide dams are overtopped by their impounded lakes. Many then fail catastrophically, causing major downstream flooding. Casualties from individual landslide-dam failures have reached into the many thousands. The world's worst recorded landslide-dam disaster occurred when the 1786 Kangding-Louding earthquake in Sichuan Province, China, triggered a huge landslide that dammed the Dadu River. After 10 days, the landslide dam was overtopped and breached; the resulting flood extended 1,400 km downstream and drowned about 100,000 people.

2.2 Types of landslides that form dams

In a study of more than 500 landslide dams worldwide, Costa and Schuster (1991) and Schuster (1995) found that about one half of the dams were caused by rock and earth slumps and slides, about one quarter by debris or mud flows, and about one fifth by rock or debris avalanches. The remaining few have resulted from sensitive-clay failures and rock and earth falls. Often large landslide dams are caused by complex landslides that start as slumps or slides, and deteriorate into rock or debris avalanches. An outstanding example of this process was the 2.8-km^3 rockslide/debris avalanche (the world's largest historic landslide) associated with the 1980 eruption of Mount St. Helens, United States. This high-velocity landslide travelled 24 km down the North Fork Toutle River valley, impounding three large lakes by damming the headwaters and two tributaries of the river.

2.3 Size and geometry of landslide dams

Landslide dams range in height from only a few metres to hundreds of metres. As reported here, the world's largest and highest (550-700 m) historic landslide dam was formed by the 1911 earthquake-triggered 2- to 2.5-billion m^3 Usoi rockslide, which dammed the Murgab River in Tajikistan. Other examples of very large landslide dams are the 1933 earthquake-triggered Deixi dam (255 m high) of the Min River in central China (Li et al., 1986), the 1974 Mayunmarca landslide dam (170 m high) of the Mantaro River in Peru (Hutchinson and Kojan, 1975), and the 1985 Bairaman River landslide dam (200 m high) on the island of New Britain, Papua New Guinea (King et al., 1989).

The cross profiles of the Usoi and Bairaman River landslide dams are compared in figure 1 to that of Oroville Dam, California, one of the world's largest embankment dams. The Usoi dam is nearly twice as high as the world's largest constructed dam, 300 m high Nurek Dam, also in Tajikistan. As indicated in figure 1, landslide dams usually are much wider (dimension parallel to the stream) than embankment dams of the same height, and thus involve considerably larger volumes.

2.4 Modes of failure of landslide dams

A landslide dam differs from an engineered embankment dam by having been formed of a heterogeneous mass of poorly consolidated earth material; in addition, unless modified, landslide dams do not have protected spillways or other outlet structures. Because of the lack of an erosion-resistant outlet, landslide dams commonly fail by overtopping, followed by rapid surface erosion that progresses from the toe of the dam toward the crest. Because of "self armoring" of the eroding outlet (a process involving removal of fine material by the flowing water, leaving coarser, erosion-resistant blocks and fragments to line the channel), a breach often does not erode down to pre-dam channel level.

Landslide dams often are porous. Dams that consist mainly of broken rock often have few fine materials, thus, the voids between the rock blocks and fragments result in high permeability. Dams consisting of soils without much rock are commonly poorly compacted, thus, they, too, can be quite pervious. Resulting seepage through these dams (particularly soil dams) can lead to failure by internal erosion ("piping"). Examples of failure of dams by piping are:

1) the 1966 breach of the landslide dam that had impounded Lake Yashinkul in today's Republic of Kirgizstan 131 years earlier (Glazyrin and

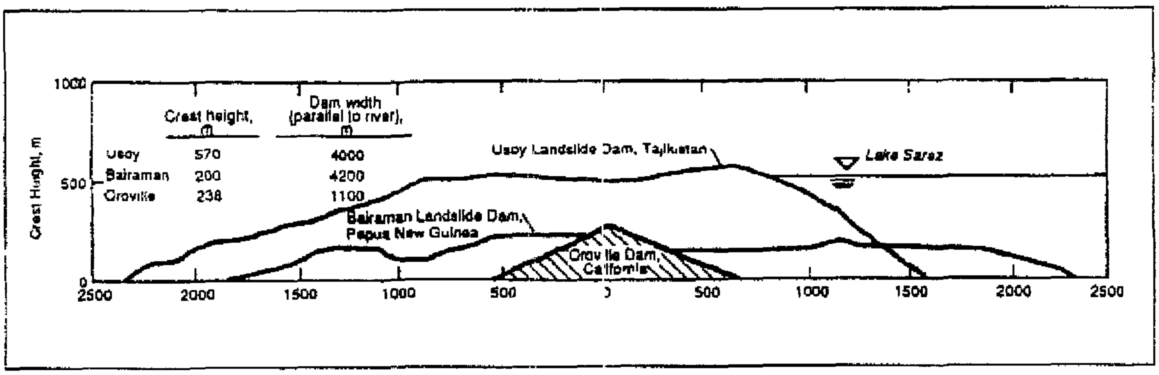

Figure 1. Comparative cross sections (parallel to stream) through the Usoi landslide dam (V.Adushkin, Institute for Dynamics of the Geosphere, Moscow, personal communication), the 1986 Bairaman River landslide dam, Papua New Guinea (King et al., 1989), and the large constructed embankment dam at Oroville, California. Crest heights and dam widths for the three dams are indicated at the left, and the approximate current relative height of the surface of Lake Sarez, the impoundment for the Usoi landslide dam, is shown at the right.

Reyzvikh, 1968; Pushkarenko and Nikitin, 1988); and
2) the 1973 failure of a 90-m-high rock avalanche dam on the Buonamico River in the Province of Calabria, southern Italy (Guerricchio and Melidoro, 1973).

2.5 Longevity of landslide dams

Landslide dams may last for a few minutes or hours, or for thousands of years, depending on many factors, including:
1) volume and rate of water and sediment inflow to the newly formed lake,
2) size and shape of the dam,
3) character of geologic materials comprising the dam, and
4) rates of seepage through the dam.

There are a few known cases in which landslide dams have failed after having been stable for many years. The A.D. 1191 rock-avalanche/debris-flow dam of the Romanche River in alpine France failed after 28 years because of erosion of its downstream face. The failure caused a disastrous flood that destroyed one half of the city of Grenoble (Montandon, 1933). The 1683 landslide dam on the Ojik River, Tochigi Prefecture, Japan, failed after 40 years, causing extensive flood damage downstream. The previously noted 1835 rock- and debris-fall dam that formed Lake Yashinkul on the Tegermach River in the Republic of Kirgizstan failed in 1966 by piping, after having been stable for 133 years (Glazyrin and Reyzvikh, 1968; Pushkarenko and Nikitin, 1988).

In some cases, landslide dams have not been overtopped because inflow to the lake is about equal to losses due to seepage, evaporation, and/or withdrawals for irrigation. The equilibrium shown by Lake Sarez is based on the first two of these factors. Another notable example is Bitang Lake in Qinghai Province, central China, which, because of irrigation, evaporation, and seepage has stabilized at a level considerably below the crest of the landslide dam (Li et al., 1986).

2.6 Floods from landslide dams

Landslide dams create the potential for two very different types of flooding: (1) upstream (backwater) flooding as the lake fills, and (2) downstream flooding due to dam failure. Lake Sarez, as it currently exists, provides an outstanding example of upstream flooding.

Although less common than upstream flooding, downstream flooding due to dam failure is usually more serious. An outstanding example of catastrophic flooding resulted from the 1515 failure of a rock-avalanche blockage of the Brenno River, a tributary of the Tocino River, in southern Switzerland. The flood engulfed the city of Biasca with an explosive surge of water and debris that continued down the Ticino valley for 35 km to Lake Maggiore on the Italian border; about 600 people died in the flood (Montandon, 1933).

2.7 Long-term effects of landslide dams on valley morphology

Landslide dams can affect valley morphology in the following ways:
(1) deposition of lacustrine, alluvial, or deltaic sediments in the reservoir, resulting in changes of stream gradient, surface morphology, and surficial geology upstream from the dam,
(2) formation of shifting channels downstream by introduction of high sediment loads from erosion of the landslide deposits during breaching of the dam, and/or
(3) secondary landsliding along the shore of the reservoir due to reservoir filling or to rapid drawdown when the dam fails. These factors must be considered when siting engineered structures, such as hydroelectric dams, roads, or bridges, in valleys in which landslide dams have occurred or have the potential to occur.

Sediment from landslide dams can significantly influence design and construction of future facilities in a river valley. In the case of the 1941 Tsao-Ling landslide dam on the Chin-Shui-Chi (river), central

Taiwan, thick sediment deposited in the backwater pool behind the dam caused severe siting problems for a proposed power project (Chang, 1984). Because of the 50 m thick deposits, a wide and deep foundation will be necessary if a dam is to be constructed at that site. (Interestingly, earthquake-induced reactivation of the Tsao-Ling landslide dammed the river again in September 1999. As of January 2000, the 50-m-high blockage has not been overtopped). The partial failure in July 1992 of a 100-m-high landslide dam on the Rio Toro (river) in Costa Rica deposited 10 m of sediment at the site of a proposed penstock outlet and powerplant 700 m downstream from the landslide dam (Mora et al., 1993).

Erosion of the stream channel downstream from the dam can adversely affect existing downstream structures, such as hydroelectric plants, bridges, and irrigation works. Such downstream erosion would be expected locally if the Usoi dam were to fail.

Secondary landsliding due to rapid drawdown of the lake after failure of a landslide dam can prove hazardous to any of the aforementioned structures or lifelines along the shore of the lake. For Lake Sarez, this currently poses no significant problem because there is no development along the lake shore

2.8 Engineered control measures for landslide dams

The simplest and most commonly used method of improving stability of a landslide dam has been the construction of protected spillways either across adjacent bedrock abutments or over the crest of the dam An example of a carefully engineered spillway across a landslide dam was constructed by the U.S. Army Corps of Engineers on the Madison Canyon landslide dam, Montana, U.S.A., in 1959. The 75-m-wide spillway was designed for a discharge of 280 m^3/sec and velocities that would only slowly erode the rock sizes that comprised the landslide dam and spillway (Harrison, 1974).

In a few cases, large-scale blasting has been used to excavate new stream channels across landslide dams This technique was used in 1964 to open a channel across a 15-million-m^3 landslide that dammed the Zeravshan River in Tajikistan, upstream from the ancient city of Samarkand (Engineering News-Record, 1964). The dam was 220 m high, 400 m long (across the river), and more than 1800 m wide (parallel to the river) Two blasts, utilizing 250 tons of conventional explosives, excavated 230,000 m^3 of landslide material in forming a 40- to 50-m-deep drainage channel through the blockage.

Other methods of preventing overtopping of landslide dams by stabilizing lake levels include drainage by means of siphon pipes, pump systems, and tunnel outlets and diversions. An excellent example was provided by the stabilization of the level of Spirit Lake, which was impounded by the 1980 Mount St. Helens debris avalanche. As a short-term measure, a system of 20 large pumps, with a maximum total capacity of 5 m^3/sec was used to temporarily prevent overtopping (Sager and Chambers, 1986). The lake was then lowered to its permanent level by means of a 2590-m-long, 3.4-m-diameter gravity-flow tunnel driven through volcanic tuffs and breccias in the right abutment of the dam by the TBM (tunnel-boring-machine) method. A similar procedure was used to stabilize the lake formed by the 1987 damming of the Adda River in northern Italy by the 35-million m^3 Val Pola rock slide/avalanche (Govi, 1989) As a temporary measure, siphons and pumps prevented overtopping. In 1988, Adda River flow was diverted through two bedrock tunnels (6.0 m and 4.2 m in diameter) constructed through the left abutment of the dam (Cambiaghi and Schuster, 1989).

2.9 Beneficial aspects of landslide dams

Not all landslide dams pose hazards, some have proved beneficial to mankind A few landslide dams that have proved to be stable over long periods of time have been used to provide hydroelectric power. Lake Waikaremoana, the largest landslide-dammed lake (volume: 5.2 billion m^3) in New Zealand, is an outstanding example of a landslide-dammed lake that provides water and hydraulic head for production of hydropower. Lake Waikaremoana was impounded about 2,000 years ago by a 2.2-billion-m^3 rockslide (about the same size as the Usoi rockslide), and is still stable (Read et al., 1992).