STATISTICAL CHARACTERISTICS AND STABILITY INDEX (SI) OF LARGE-SIZED LANDSLIDE DAMS AROUND THE WORLD

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ABSTRACT

In the last few decades, landslide dams have received greater attention of researchers, as they have caused loss to property and human lives. Over 261 large-sized landslide dams from different countries of the world with volume greater than 1 x 105 m^3 have been reviewed for this study. The data collected for this study shows that 58% of the catastrophic landslides were triggered by earthquakes and 21 % by rainfall, revealing that earthquake and rainfall are the two major triggers, accounting for 75% of large-sized landslide dams. These land-slides were most frequent during last two decades (1990-2010) throughout the world. The mean landslide dam volume of the studied cases was 53.39 x 10^6 m^3 with mean dam height of 71.98 m, while the mean lake volume was found to be 156.62 x 10^6 m^3. Failure of these large landslide dams pose a severe threat to the property and people living downstream, hence immediate attention is required to deal with this problem. A stability index (SI) has been derived on the basis on 59 large-sized landslide dams (out of the 261 dams) with complete parametric information.

Keywords: *Landslide dam, longevity, statistical characteristics, landslide frequency, classification.*

1. INTRODUCTION

Landslide dams are hazardous land forms. Mostly due to climatic changes, human activities, and frequent earthquakes, landslides have become common occurrences. It requires quick predictions and accurate measures to mitigate the effect of such hazards. In mountainous areas, landslides are the second most destructive natural hazard after earthquake (Li, et al., 1999; U.S. Geological Survey, 2000). Many researchers have devotedly studied landslide dams (e.g., Costa and Schuster, 1991; Korup, 2006; Ermili and Casagali, 2003), however there remains a need for building comprehensive database on large-sized landslide dams in order to pave way for subsequent studies in a systematic manner.

A set of 261 cases has been reviewed in this paper, comprising of a data-set of 59 large-sized landslide dams with complete information about their landslide volume, dam height, length, width, volume, and life span. There exists well established relationship between earthquake size (magnitude) and the probability of large landslides (Keefer, 1994). Empirical evidence compiled by Keefer (1999) suggests that coseismic triggering of landslide volumes in the order of 10^9 m^3 would require an earthquake of magnitude M>8. Due to their large volumes, rock avalanches usually have clearly defined source areas, easily identified by large scars or arcuate depressions on hillslopes (Hewitt, 2002; Ballantyne and Stone, 2004; Mitchell, et al., 2007).

In terms of size, there seems to be no difference between earthquake-induced landslides and those triggered by rainfall. Baoping Wen, et al. (2004) suggested that in terms of lithology and geological structures, rainfall-induced landslides occurred more often in soils with slip surfaces along the soilrock contacts. Moreover, it is more likely to occur in the stratified rocks with contrast in competency in which slip surfaces occurr along bedding planes. While earthquake-induced landslides were more prevalent in stratified competent rocks in which slip surfaces occurred along cross-bedding joints.

As data for these landslide dams were collected from a wide variety of sources, the detailed information may varies. But the assessment has been made primarily on major characteristics. The comparison of all these large-sized landslide dams have also been made, on the basis of their impact factors, frequencies, runout, velocities, horizontal and vertical distances, failure modes, runout behavior, and other important aspects. A statistical assessment and distribution of all landslides has been made and compared in this paper.

2. DATASET OF CATASTROPHIC LANDSLIDES

Large-sized landslide dams are defined in this paper as having volume of more than 1 x 10^5 m^3 and are among the most significant geological hazards. The data presented in this paper is collected from different published papers and from authors' own observations. A subset of 59 large-sized landslide dams with complete information about landslide volume, dam height, dam length, dam width, dam volume, lake volume and dam life span, has been used to calculate the stability of the large-sized landslide dams (Table-1).

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Table-1: Dataset of 59 of Large-sized landslide Dams used for Calculating Stability Index

Country	Landslide volume (m^3)	Dam height (m)	Dam lengt h (m)	Dam width (m)	Dam volume (m^3)	Lake volume (m^3)	Dam life span (days)	Stability Index (SI)
Canada	15000000	25	274	880	6028000	65000000	1.8	Unstable
China	150000000	255	400	1300	132600000	400000000	7	Unstable
Ecuador	1800000	56	60	300	1008000	3600000	24	Unstable
Hungary	5000000	90	100	400	3600000	150000	stabled	Stable
Indonesia	100000	10	30	200	60000	100000	16	Unstable
Italy	21000000	90	400	700	25200000	7500000	31	Unstable
Italy	35000000	33	2700	550	49005000	22000000	stabled	Stable
Japan	1500000	38	110	350	1463000	2000000	6	Unstable
Japan	25000000	90	900	500	40500000	150000000	20	Unstable
Japan	230000	10	100	200	200000	37000	stabled	Stable
Japan	3200000	55	500	230	6325000	3100000	stabled	Stable
Japan	1200000	48	250	300	3600000	16000000	110	Unstable
Japan	1600000	10	130	400	520000	390000	0.2	Unstable
Japan	23000000	18	100	450	810000	780000	0.04	Unstable
Japan	26000000	80	300	700	16800000	40000000	17	Unstable
Japan	36000000	10	150	150	225000	560000	0.1	Unstable
Japan	2500000	50	180	300	2700000	1600000	0.7	Unstable
Japan	8800000	25	160	300	1200000	920000	0.2	Unstable
Japan	3600000	15	130	130	253500	1300000	0.02	Unstable
Japan	4400000	25	130	250	812500	110000	stabled	Stable
Japan	610000	15	50	180	135000	1300000	stabled	Stable
Japan	5400000	140	400	180	10080000	26000000	6	Unstable
Japan	22000000	36	50	170	306000	10000000	stabled	Stable
Japan	1500000	60	250	250	3750000	6400000	1	Unstable
Japan	4400000	20	200	250	1000000	1300000	0.4	Unstable
Japan	6600000	80	300	350	8400000	12000000	22	Unstable
Japan	3400000	100	400	150	6000000	2300000	10	Unstable
Japan	2700000	25	200	250	1250000	1800000	0.4	Unstable
Japan	300000	20	120	160	384000	400000	0.4	Unstable
Japan	1400000	75	350	125	3281250	9000000	1.5	Unstable
Japan	4900000	70	200	450	6300000	1700000	22	Unstable
Japan	20000000	190	600	500	57000000	38000000	5	Unstable
Japan	300000	20	50	170	170000	350000	50	Unstable
Japan	120000000	30	500	650	9750000	4700000	stabled	Stable
Japan	4000000	80	250	330	6600000	75000000	3	Unstable

continue...

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Japan	150000000	110	600	200	13200000	2600000	59	Unstable
Japan	150000000	125	600	700	52500000	27000000	12	Unstable
Japan	640000	10	80	100	80000	47000	0.01	Unstable
Japan	460000	40	100	200	800000	270000	68	Unstable
Japan	5200000	60	300	350	6300000	17000000	67	Unstable
Nepal	12000000	8	300	300	720000	2400000	0.08	Unstable
Nepal	3000000	8	300	200	480000	1500000	0.08	Unstable
Papua New Guinea	200000000	200	1000	3000	600000000	50000000	489	Stable
Papua New Guinea	150000000	50	500	1000	25000000	2100000	stabled	Stable
Papua New Guinea	2000000	45	100	200	900000	1000000	stabled	Stable
Papua New Guinea	600000	30	100	300	900000	280000	19	Unstable
Papua New Guinea	5000000	50	200	500	5000000	2000000	stabled	Stable
Papua New Guinea	15000000	3	100	300	90000	100000	731	Stable
Peru	3500000	133	250	580	19285000	301000000	73	Unstable
Peru	1600000000	160	1000	3800	608000000	670000000	42	Unstable
U.S.S.R	2000000000	800	1000	1000	800000000	16000000000	stabled	Stable
United States	1100000	13.5	75	400	405000	1700000	0.05	Unstable
United States	1900000	15	75	500	562500	2700000	0.25	Unstable
United States	1900000	15	75	500	562500	2700000	0.25	Unstable
United States	6000000	9	60	200	108000	290000	stabled	Stable
United States	1700000	3	30	150	13500	53000	105	Unstable
United States	22000000	63	200	450	5670000	78000000	stabled	Stable
United States	2800000000	4.5	975	425	1864687.5	2470000	644	Stable
Yugoslavia	200000000	20	150	700	2100000	500000	stabled	Stable

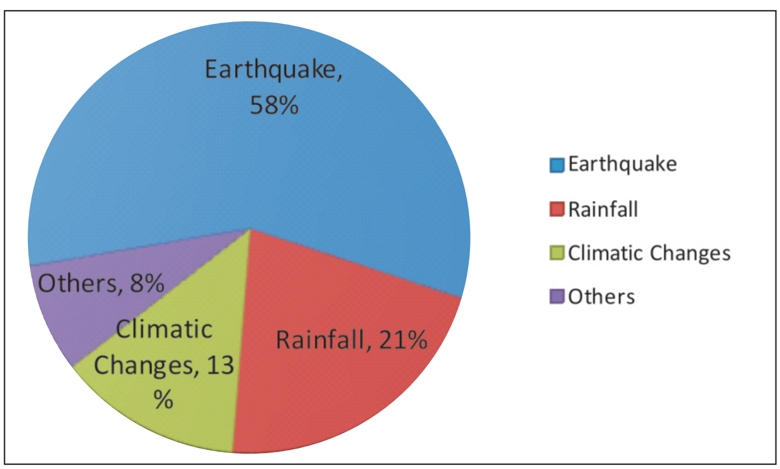


Figure-1: Comparison and frequency of different triggering factors (261 dams)

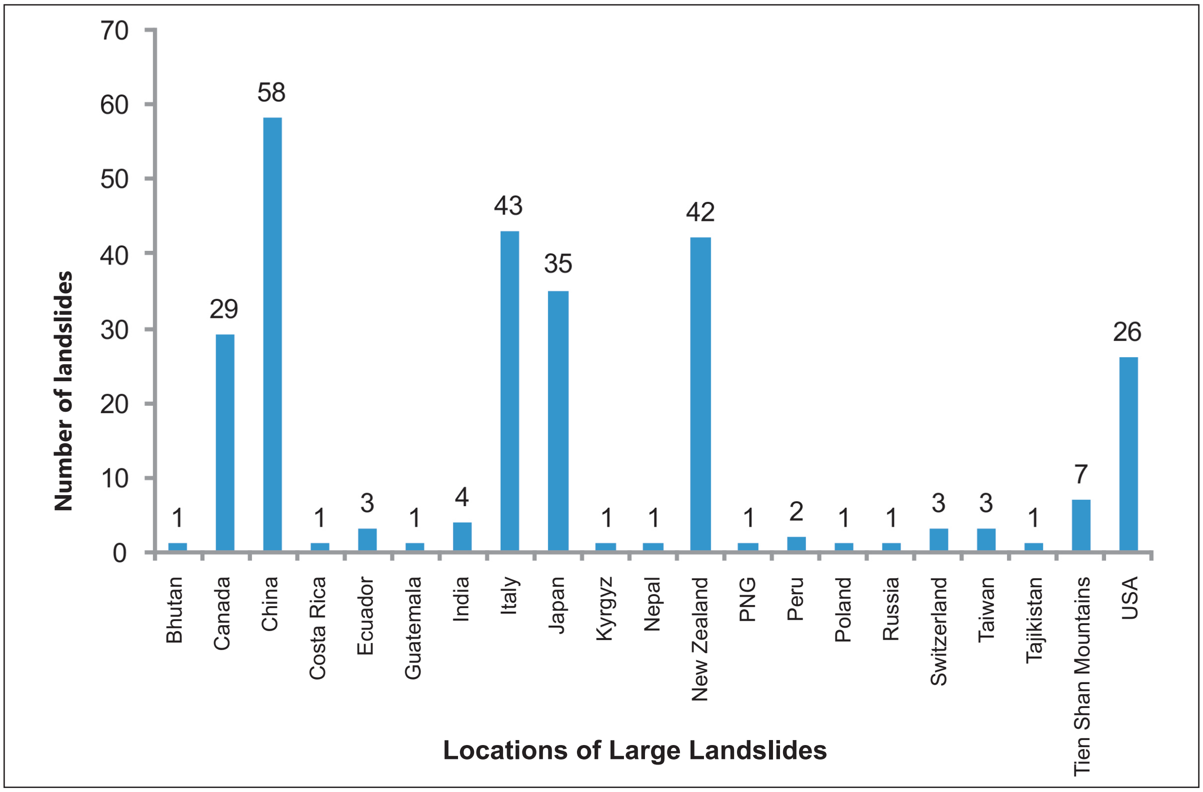


Figure-2: Large-sized landslide dams distribution around the World (261 dams)

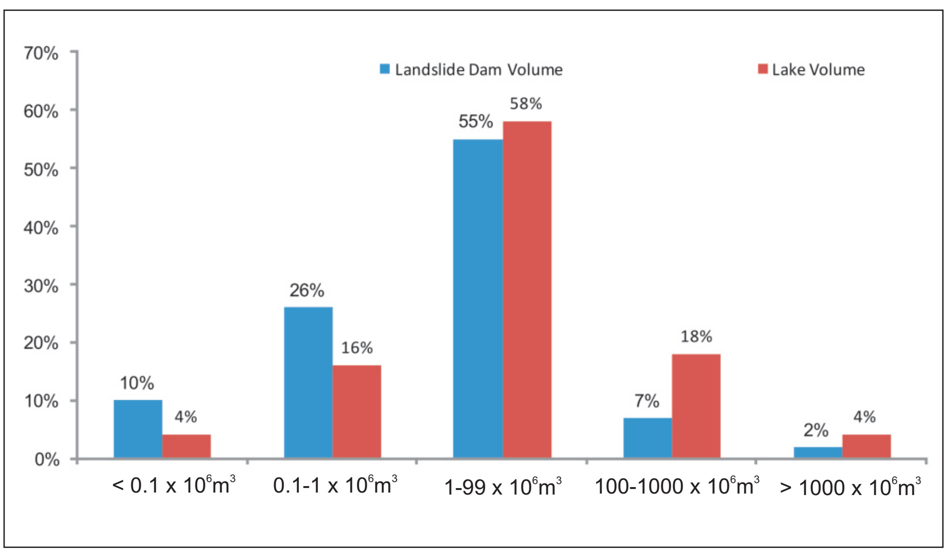
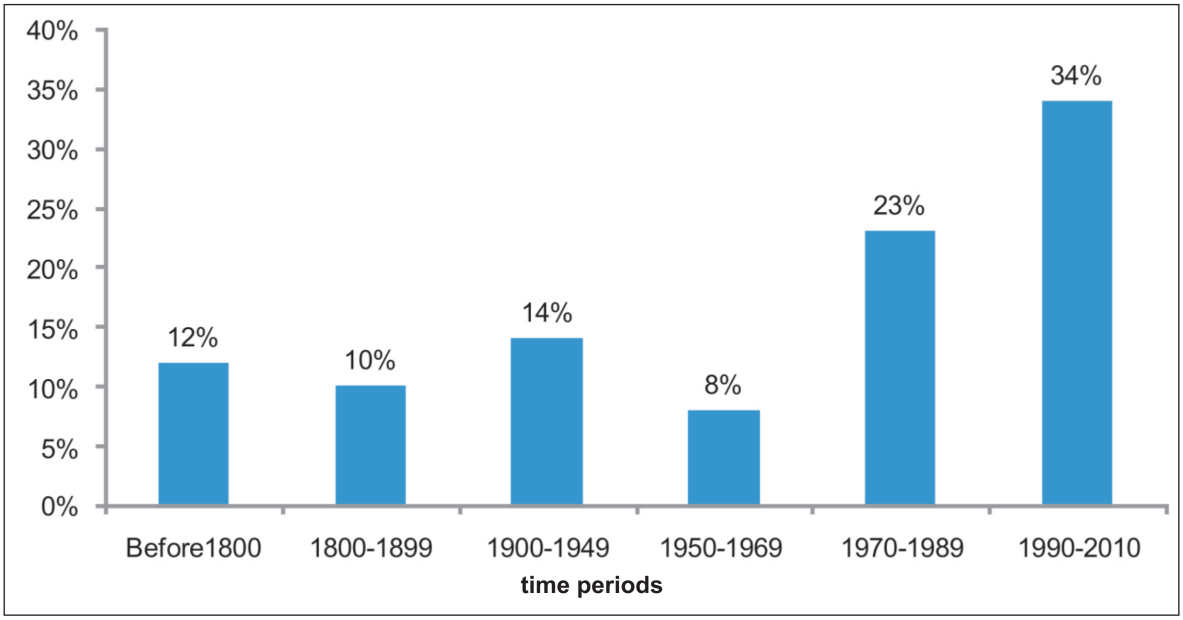


Figure-3: Comparison of landslide dam volume with the lake volume (261 dams)

3. CHARACTERISTIC ANALYSIS OF THE LARGE-SIZED LANDSLIDE

The data set of 261 large-size landslide dams show that such dams are controlled by a number of physiographical factors. Some of the most import factors are discussed as follows:



Figire-4: Time and frequency distribution of large-sized landslide dams around the World (261 dams)

3.1 Type of Landslides

Baoping, Wen, et al. (2004) stated that when landslide frequency and their kinematic parameters are correlated with slope geometry, it is observed that (a) slide-type landslides have been active on slopes with gradients between 10°C and 35°C, and heights between 100 and 1,000 m; (b) two slide-flow-type landslides occurred on slopes with about the same gradients (33° and 34°) and heights between 320 and 450 m; and (c) flow-type landslides seemed to occur at slopes steeper than 36° and higher than 300 m. Different researchers gave their own classifications for landslides on the basis of movement behavior (e.g, Baoping Wen, et al. 2004). As the data in this paper is collected from different sources, keeping in mind the original characteristics of the landslides, six types have been noted: (i) rock-avalanche; (ii) flows; (iii) rock-slide; (iv) flow-slide; (v) complex slides (mixture of different type movements); and (vi) slides. Among 122 known cases with known movement type, 45% were rock-slides, 3% were flows, 17% were rock-avalanches, 17% were flow-slides, 11% were slides, and 7% were complex slides (Figure-6).

3.2 Landslide triggers

Earthquakes and the rainfall are the two major triggering factors for all the large-sized landslide dams with some other minor triggers (Figure-1). There are clear, well-documented relationships between earthquake size and the probability of large landslides (Keefer, 1994). In terms of size, there seems to be no difference between earthquake-induced landslides and those triggered by rainfall. Out of the cases in which triggers of the large-sized landslide dams were known, 58% large-sized landslide dams were triggered by earthquakes, 21% by rainfall, 13% by physio-clamatic factors and 8% by other minor factors, like bank erosion, loading and undercutting, and human activities (Figure-5). It has also been observed that rainfall related large-sized landslide dams mostly occur in soil and loosed strata, while earthquake-triggered landslide dams occur due to the large rocky landslides.

3.3 Landslides distribution and volume

The study data reveals that China has most number of large-size landslide dams (58). Other countries having such dams include: Italy (43), New Zealand (42), Japan (35), Canada (29), USA (26), Tien Shan Mountains (7), India (4), Peru (2), Taiwan (3), Ecuador (3), Bhutan (1), Papua New Guinea (1), Switzerland (3), Kyrgyz (1), Tajikistan (1), Poland (1), Costa Rica (1), Nepal (1), Russia (1), and Guatemala (1), as given in Figure-2.

In 10% cases of large-size land slide dams (out of 261), the dam volume was less the 0.1×10^6 m^3, in 26% cases the volume was about $0.1\text{-}1 \times 10^6$ m^3, in 55% cases the volume was about $1\text{-}99 \times 10^6 m^3$, in 7 %

cases the volume was about 100-1000 x 10^6 m^3 and only in 2% cases it exceeded the size of 1000 x 10^6 m^3 (Figure-3). This assessment shows that in 90% cases the volume of landside dams was greater than 1 x 10^5 m^3. According to the present data, mean landslide dam volume was 53.39 x 10^6 m^3, while the maximum mean dam height was recorded to be 71.98 m and the mean lake volume was calculated to be 156.62 x 10^6 m^3, with highest landslide frequency during the period of 1970s and 1980s for large-sized landslide dams from all over the world.

3.4 Occurrence time and frequency of landslides

According to the statistical calculations, 12% landslides have occurred before 1800, 10% occurred from 1800 to 1899, 14% occurred from 1900 to 1949, 8% occurred in the period of 1950-1969, 23% occurred in the period of 1970-1989, and 34% between 1990 and 2010 time period (Figure-4).

This data shows that only a few large-sized landslide dams have occurred before 1800, but it can be assumed that there may be too much data missing for that period. But it can also be noted that for the period between 1800 to 1970 there was also not too much frequency of creation of landslide of dams, if we calculate the frequency on the basis of 20-year period gap for that phase, then it would be 2.57 for every 20-year period. The frequency of landslides during the period 1970 to 1989 was 23% among all the studied cases; 34% large-sized landslide dams occurred in the period from 1990 to 2010. Current statistics show that large-sized landslide dams have an increasing trend (Figure-4).

From these assessments it can be concluded that the large-sized landslide dams frequency was the highest during last two decades from 1990 and 2010 all around the World.

3.5 Relationship with active tectonics

A hypothesis of a palaeoseismic origin for a rock-slope failure needs to be supported by evidence such as proximity to active faults, occurrence of modern analogues, limiting equilibrium back analyses and demonstrated synchroneity of failure with fault rupture (Crozier, et al., 1995). It has been observed that maximum percentages of the slide triggered by earthquakes are centered along or very near to an active fault zone. The locations of the giant landslides are very close to the major fault zones in China, particularly the active earthquake zones (Baoping Wen, et al. 2004). Baoping Wen, et al. (2004) stated that tectonic imposed controls on landslides occur in three ways: (1) creating favorable terrains; (2) providing sufficient landslide-prone materials, such as highly fractured and weak rocks; and (3) extra driving force of seismic activity. In this study, 58% dams were triggered by earthquake, and among these, maximum lie within or near the active fault zone.

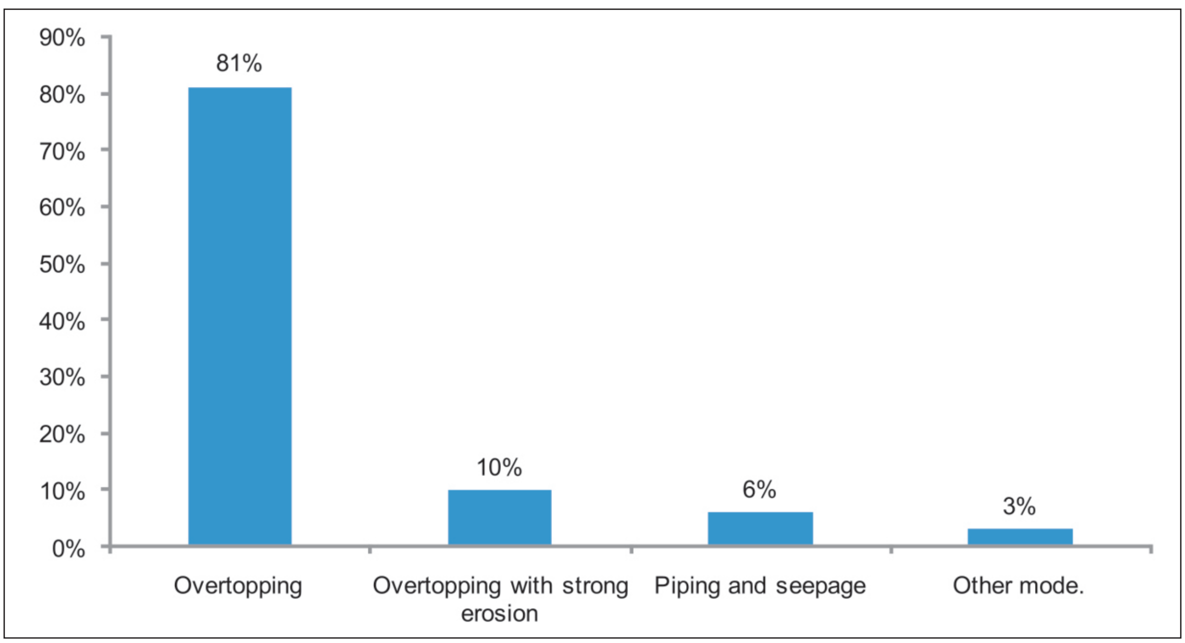


Figure-5: Different modes of failure (261 dams)

4. DISCUSSION ON THE LARGE-SIZED LANDSLIDE DAMS

Landslides may obstruct river flow and result in creating landslide dams. Such phenomena have occurred in many tectonically active regions of the world (Swanson, et al., 1986; Costa and Schuster, 1988; Casagli and Ermini, 1999; Ermini and Casagli, 2003; Korup, 2004). It is a fact that not all but most of the large-sized landslides make landslide dams once they occurred. Of the 37 rockslides (with volumes over 20 x 10^6 m^3) that occurred around the world during the period 1900-2000, 51% formed significant landslide-dammed lakes (Evans, 2006). Failure of these dams may pose severe threat to downstream property and human lives. The catastrophic breaching of landslide dams has resulted in significant natural disasters (Montadon, 1933; Eisbacher & Clague, 1984). The release of a very large impoundment volume can be expected to be highly catastrophic as in the case of the 1841 Indus flood in Pakistan, in which approximately 10^9 m^3 of water was released (Hewitt, 1968) with effects described in contemporary reports, summarized by Mason (1929).

4.1 Formation and Failure

Most of the large landslides occuring in the vicinity of a river may obstruct flow and results in landslide dams that may persist from few minutes to hundreds of years, depending upon lithologic, parametric, and topographic conditions of the blockage. Such phenomena have occurred in many tectonically active regions of the world (Swanson, et al., 1986; Costa and Schuster, 1988; Casagli and Ermini, 1999; Ermini and Casagli, 2003; Korup, 2004). In 4% cases the lake volume was less than 0.1 x 10^6 m^3, in 16% cases the lake volume was about 0.1-1x 10^6 m^3, in 58% cases volume was about 1-99 x 10^6 m^3, in 18% cases volume was about 100-999 x 10^6 m^3, while only in 4% cases the volume exceeded limit of more than 1000 x 10^6 m^3 (Figure-3). Of the 37 rockslides (with volumes over 20 x 10^6 m^3) that occurred around the world during the period 1900-2000, 51% formed significant landslide-dammed lakes (Evans, 2006). From this investigation, it is clear that in 96% cases the volumes of lakes were greater than 1 x 10^5 m^3. The very low percentage (4%) of the smaller lakes shows that they were only formed in rare cases due to less resistance offered by the small landslide volume against the river flow.

Failure of landslide dams may include overtopping, piping, slope failure of upstream or downstream face, overtopping by a landslide-generated wave and the effects of human activity (usually as a result of attempt to excavate a spillway over the debris dam). Not all landslide dams are unstable or have failure potential, indeed some landslide dams have been utilized as foundations for artificial storage dams or for sites of power generation (Evans, 2006; Heim, 1932). Keeping in view the original data for all landslides, possible failure modes of landslide dams were divided into four types: (i) overtopping, (ii) overtopping with strong erosion, (iii) piping and seepage, and (iv) any other failure mode. Out of the dams with known failure modes the 81% dams failed by overtopping, 10% by overtopping with strong bank erosion, 6% by piping and seepage, and 3% by other different modes of failures, like progressive failure, etc. (Figure-5).

A statistical assessment and distribution of all landslides has been made and compared. The mean dam volume was 53.39 x 10^6 m^3 with the maximum mean dam height of 71.98 m and the mean lake volume was calculated to be 156.62 x 10^6 m^3, which is the highest landslide frequency during the last two decades after 1990 for large-sized landslide dams from all over the world.

4.2 Landslide Dams Stability Index (SI)

Some researchers have also performed the dam stability assessment using different geomorphic parameters but not exclusively on large-sized dams (Canuti, et al., 1998; Casagli and Ermini, 1999; Ermini and Casagli, 2003; Pirocchi, 1992; Swanson, et al., 1986). All of the these researchers used the ratio of the following parameters to find out the stability of the dams:

- The dam volume is considered as the main stabilizing factor since it controls the dam's weight.
- The water-shed area is considered as the main stabilizing factor since it controls the channel discharge and stream power, and indirectly the dam shape.
- The dam height is main stabilizing factor since it controls both overtopping and piping failure mechanisms.

Casagli and Ermini (1999) and Canuti, et al. (1998) defined the blockage index (BI), using this parameter for a preliminary forecast of blockage evolution:

$$BI = \log (V_d/A_b)$$

where, V_d is the landslide dam volume (m^3) and A_b the catchment area (km^2). From the results obtained, the

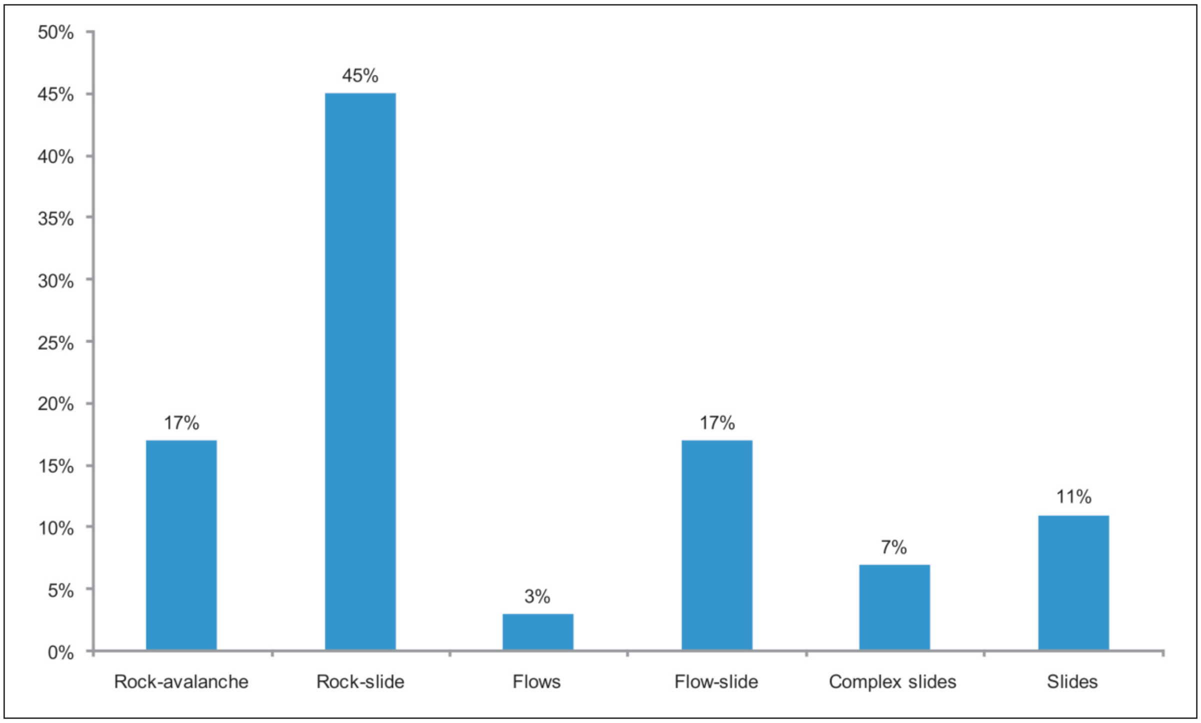


Figure-6: Comparison of different type movements of landslides (261 dams)

authors propose that a lower boundary for cases of complete dam formation can be given by BI = 3 and an upper boundary for failed dams by BI = 5, while a lower boundary for stable dams by BI = 4.

Ermini and Casagli (2003) did an attempt to improve this model on a relativity larger number of landslide dams by setting up a new index. All the case histories collected were ranked in the two main evolution classes: Stable & Unstable. The relationship used in this classification is known as dimensionless blockage index (DBI):

$$DBI = \log (A_b \times H_d / V_d)$$

where, H_d represents dam height, V_d landslide dam volume and A_b catchment area. DBI<2.5 represents the stability domain, DBI between 2.5-3.08 represents the uncertain domain, while DBI > 3.08 represents the instability domain.

In this study, we used three additional variables: lake volume, landslide volume and dam height, as they are considered the most important factors in dam failure mechanism. A detailed data set of 59 large-sized landslide dams (Costa and Schuster, 1991) with complete information about landslide volume, dam height, dam length, dam width, dam volume, lake volume and dam life span (Table-1) has been used to calculate the stability of the large-sized landslide dams. It is mathematically represented as follows:

$$SI = \ln((V_l/V_d) \times (H_d/L_d))$$

where, SI is the stability index, In is natural log, V_l is lake volume, V_d is dam volume, H_d is dam height and L_d is dam length. According to stability index (SI), if the SI value is -2.9 or less, the dam will be considered stable, otherwise it will be consider as unstable. But if the landslide volume and dam volume ratio is 2:5 or greater, then non-zero positive SI values will also be considered as stable (Table-1).

Possible improvements in this empirical model could be made by using other variables and more comprehensive data. Lithology of the dam area can play a more important role in improving and resetting a new accurate and precise model, for which the efforts by the scientific community are required. A basic classification related to dam's stability is proposed as follows:

4.3 Landslide dam types

On the basis of classification proposed by Costa and Schuster (1988), following five types out of the six dam types were found (type-V was absent). These types are not mutually exclusive. A landslide could be Type-II, Type-III, and Type-IV or other types at the same time. The failure mechanism, evolution process, and the stability analysis of landslide dams are very complex (Costa and Schuster, 1988). The available data shows that 1% were Type-I dams, 47% were Type- II dams, 16% were Type-III dams, and 3% were Type-IV dams, 3% were Type-VI dams. Whereas, there were also dams that were the combination of two types, that is, 15% represented Type-I and II combined, and 15% represented Type-II and III combined. This shows that Type I, II and III are most common dam types, with more than 75% making Type-II and/or Type-III dams.

5. SUMMARY AND CONCLUSIONS

A data set of 261 large-sized landslide dams was collected and reviewed carefully in order to make a comprehensive assessment. Based on the data-set, statistical characteristics (lithologies, relation with tectonics, types of movement, triggers, volumes, frequencies, failure modes and special distribution) of landslides have been investigated. Maximum of landslides were located in China (58), 43 in Italy, 42 in New Zealand, 35 in Japan, 29 in Canada, and a small number was in other different countries. The highest frequency of the occurrence of landslide dams was observed during the last two decades (1990-2010).

A data set of 261 large-size landslide dams was reviewed under 20 headings (name, location, time of occurrence, dam dimensions, H/L ratio, volumes, material, triggers, types of movement, failure modes, dammed river, etc.). A subset of 59 large-sized landslide dams (Costa and Schuster, 1991) comprising landslide volume, dam height, dam length, dam width, dam volume, lake volume and dam life span was studied in detail in order to find out the stability (SI) of these dams. According to the available data, the mean landslide dam volume was 53.39 x 10^6 m^3, with the maximum mean dam height of 71.98 m and the mean lake volume of 156.62 x 10^6 m^3. Most of large-sized landslide dams were triggered by earthquakes (58%) followed by those triggered by rainfall (21%). While the dam failure in most of the cases was observed due to overtopping (81%).

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