

THE FORMATION AND FAILURE OF LANDSLIDE DAMS: AN APPROACH TO RISK ASSESSMENT

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INTRODUCTION

Building on the work of COSTA (1988), COSTA & SCHUSTER (1988, 1991), recent work has attempted to quantify aspects of the formation and failure of landslide dams (e.g., CASAGLI & ERMINI, 1999; ERMINI & CASAGLI, 2003; KORUP, 2004). Together with our growing knowledge of landslide magnitude and frequency distributions (e.g., HUNGR *et alii*, 1999; GUZZETTI *et alii*, 2003; DUSSAUGE *et alii*, 2003) at spatial and temporal scales, this work forms a promising basis for a first approximation to quantitative risk assessment for both landslide dam formation and landslide dam failure. Drawing also on recent work in the risk assessment of built dams, it is the objective of this paper to explore this basis and to present preliminary results for the formation and failure of landslide dams and their destructive effects.

This work focuses on landslides resulting from rock slope failure and includes landslide dams resulting from rock avalanches, rockslides, and rockfall in non-volcanic environments. It does not include landslides and landslide dams resulting from major and partial sector collapse of volcanoes (see CAPRA, this volume).

The present discussion focuses exclusively on the risk to human life. It builds on recent investigations of life-loss due to floods (e.g., GRAHAM, 1999; JONKMAN *et alii*, 2002, 2003; McLELLAND & BOWLES, 2002), earthquakes (SAMARDJIEVA & BADAL, 2002) and landslides (EVANS, 2003) in exploring life-loss models for landslide dam formation and failure.

THE RATE OF LANDSLIDE DAM FORMATION

Rockslope failure in the landscape does not necessarily lead to landslide dam formation. Factors favouring the development of landslide dams are geometry of valley in relation to geometry and volume of debris, characteristics of landslide debris, and discharge of dammed river.

The global record of large twentieth century non-volcanic rock avalanches (1900-2000) over a threshold volume of $20 \times 10^6 \text{ m}^3$ is well known (EVANS, in press). There are 37 in total, equivalent to a major ($>20 \times 10^6 \text{ m}^3$) rock avalanche every 2.75 years, an annual frequency of 0.36. Their magnitude and frequency relations plot in a robust power law (Figure 1) where $F = 151384.5V^{-0.77}$. Of this total,

19 (51%) rock avalanches formed significant landslide dammed lakes (COSTA & SCHUSTER, 1991 and other references), a global landslide dam formation rate of 1 per 5.36 years equivalent to an annual frequency of 0.18.

Similar statistics may be assembled and analysed for mountain regions, administrative areas or individual watersheds.

MAGNITUDE AND FREQUENCY OF IMPOUNDMENT VOLUME

Impoundment volume is an important variable in landslide and artificial dam hazard assessment since breach discharge is directly related to outburst volume (EVANS, 1986; COSTA, 1988; COSTA & SCHUSTER, 1988; WALDER & O'CONNOR, 1997). The release of a very large impoundment volume may be expected to be highly catastrophic as in the case of the 1841 Indus Flood, Pakistan, in which approximately 10^9 m^3 of water was released (HEWITT, 1968) with effects famously described in contemporary reports, summarized by MASON (1929). The largest impoundment volume ($17 \times 10^9 \text{ m}^3$) in the data set is Lake Sarez, Tajikistan, which was formed by the earthquake-triggered Usoy landslide in 1911 (e.g., SCHUSTER, 2002; SCHUSTER & ALFORD, 2004). Impoundment volume is a function of dam geometry and volume, valley physiography and watershed characteristics (e.g., CASAGLI & ERMINI, 1999; KORUP, 2004).

The magnitude and frequency of volumes of the landslide dams formed in the twentieth century by rock avalanches over the threshold volume noted above may be analysed in a similar manner as in Figure 1. Because of the uncertainty of estimating impoundment volumes only those above a threshold impoundment volume of $40 \times 10^6 \text{ m}^3$ have been plotted in Figure 1. 11 events fulfill this criterion. Their magnitude and frequency characteristics form a clear power law relationship where $F = 103.4EV^{-0.39}$. Note that the exponent is -0.39 compared to that of -0.77 for the rock avalanche/rockslide data.

These impoundment volumes indicate that landslide dams that impound $40 \times 10^9 \text{ m}^3$ or greater, form roughly every 10 years, globally. Landslide dams that impound ca. 10^9 m^3 appear to occur every 50 years, while impoundments of ca. 10^{10} m^3 may occur with a frequency of roughly a century. As is detailed below these are significant impoundment volumes when examined in the light of breaching scenarios.

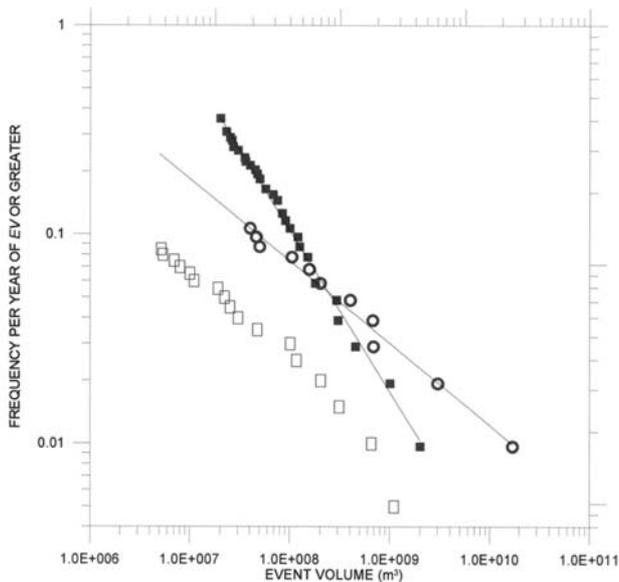


Figure 1 - Magnitude and frequency plot of (a) rock avalanches (volume equal to or greater than $20 \times 10^6 \text{ m}^3$) which occurred around the world 1900-2000 (solid black squares, $n=37$), (b) volume of landslide lakes (volume equal to or greater than $40 \times 10^6 \text{ m}^3$; open circles, $n=11$) impounded by 11 events in (a), and (c) major outburst floods from the failure of artificial dams 1800-2000 (open squares; $n=25$)

THE RATE OF LANDSLIDE DAM FAILURE

Landslide dams fail by a variety of processes including overtopping, piping, overtopping by a landslide-generated wave, slope failure of upstream or downstream face, and the effects of human activity, usually an 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 (e.g., HEIM, 1932).

Again using the twentieth century data set, of the 19 landslide dams formed by the rock avalanches/rockslides over the threshold volume of $20 \times 10^6 \text{ m}^3$, 9 (47%) failed (or partially failed) catastrophically, a rate of 1 per 11.3 years globally, equivalent to an annual frequency of 0.08. Time to failure varied from 7 (Diexi) days to 3435 (Tsao-Ling 2) days and released impoundment volumes ranged from $40 \times 10^6 \text{ m}^3$ to $3000 \times 10^6 \text{ m}^3$. Significant loss of life (deaths > 100) only occurred in two of these released events, i.e. Diexi (2423) and Tsao Ling 2 (154).

There are some cases of landslide dams failing in the twentieth century that were formed many centuries before in historical or even prehistoric time. An example of this delayed catastrophic failure is the breach and outburst from Lago Cari Lauquen in the Patagonian Andes of Argentina. In 1914, failure of a paleo-landslide dam released $1.5 \times 10^9 \text{ m}^3$ into the Rio Colorado valley causing widespread damage and the loss of about 300 lives (HERMANN *et alii*, 2004). This outburst volume is comparable to the largest release from the failure of a landslide dam in the twentieth century, i.e. the 2000

failure of the Jigong landslide dam. The dam formed and failed in Tibet, China, releasing ca. $3 \times 10^9 \text{ m}^3$ of impounded water. The flood/debris flood traveled up to 500 km downstream and reached the main channel of the Brahmaputra River in northern India. It caused 94 deaths, made 50,000 homeless in Arunachal Pradesh and Assam, destroyed 20 bridges, and caused more than USD 25 M of damage in India alone (SHANG *et alii*, 2003; ZHOU *et alii*, 2003).

COMPARISONS WITH THE FAILURE OF ARTIFICIAL DAMS

To compare the magnitude and effects of these outburst events from landslide dams, floods resulting from the failure of artificial dams were reviewed from a number of sources including JANSEN (1980), COSTA (1988) and ICOLD (1995)⁽¹⁾. The largest impoundment release recorded is probably the flood which resulted from the intentional destruction of the Dniestrostroy dam, on the Dnieper River, Ukraine, during the Second World War. The volume released was in the order of 10^9 m^3 (VOGEL, 1984). The downstream effects are not well documented. The second largest is the 1960 overtopping failure of the Oros Dam, Brazil, during its construction (Figure 2). This event released about $660 \times 10^6 \text{ m}^3$ of water was released into the Jaguaribe River within 34 hours (ICOLD, 1973). Major loss of life was avoided by warning and evacuation of 100000 people from downstream communities.

The 2000 Yigong landslide dam release event is thus larger than the largest documented release from the failure of an artificial dam. Only 7 release volumes from the failure of artificial dams are in excess of the $40 \times 10^6 \text{ m}^3$ threshold adopted above; 3 of these events were due to military action in the Second World War. It is noted that several present day artificial impoundments exceed a storage capacity of 10^{10} m^3 .

FACTORS CONTROLLING LIFE LOSS IN DAM-FAILURE FLOODS

The catastrophic breaching of landslide dams has resulted in significant natural disasters (e.g., MONTADON, 1933; EISBACHER & CLAGUE, 1984; BONNARD, this volume). Indeed, the most catastrophic landslide disaster in history occurred in 1786 as a result of the breach-

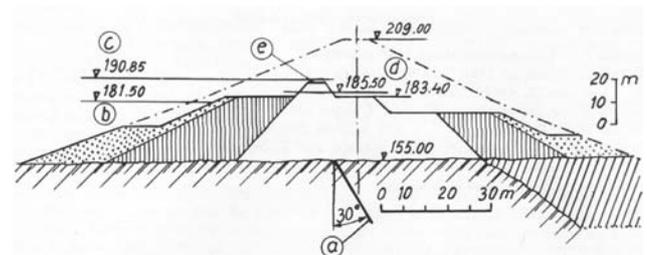


Figure 2 - Cross-section of Oros Dam, northeast Brazil, showing stage of construction when catastrophic overtopping (at pool el. 190.85 m) took place in 1960 during exceptionally heavy rains. Height of dam at failure was 35.8 m. About $660 \times 10^6 \text{ m}^3$ of water was released into the Jaguaribe River (after ICOLD, 1973)

ing of a landslide dam on the Dadu River, China. The death toll has been estimated to be 100000 (LI & WANG, 1992; DAI *et alii*, 2005).

A detailed analysis of the factors controlling the destructive effects of dam failure floods is beyond the scope of this paper. Comprehensive analyses and reviews of life loss models may be found in recent work by GRAHAM (1999) and MCCLELLAND & BOWLES (2002). Generally, the magnitude of the death toll are a function of outburst volume (and associated variables of peak discharge), the velocity of breaching which determines the shape of the breach hydrograph, the attenuation characteristics of the downstream flood and associated velocity decay, the height and velocity of the downstream flood wave (controlled by such factors as geomorphology of the flood path), and the nature of materials entrained in the flood waters (e.g., trees). Destructive effects are also a function of human factors such as warning time of dam failure, population density, time of day and time of year, resilience of structures to destruction, and other human-social factors (GRAHAM, 1999).

In a review of loss of life from dam failures in the United States from 1960-1998, GRAHAM (1999) found that 88% of the fatalities were caused by the failure of dams less than 15 m high. Further, 75% of the deaths were caused by the failure of dams with drainage areas less than 26 km². 50% of the deaths occurred 4.8 km or less from the failed dam. More than 99% of the fatalities occurred 24 km from the dam that failed. The level of destruction of small magnitude events evident in this data is reflected to some extent in the failure of small natural dams. In the case of the Malpa rockfalls, for example, which occurred in the Kumaun Himalaya of India in 1998, rockfalls dammed a steep watershed and the resulting dam-break debris flow overwhelmed Malpa Village claiming the lives of 221 people (PAUL *et alii*, 2000).

TOWARDS A LANDSLIDE DAM FAILURE DAMAGE INDEX

EVANS (2003) proposed the Landslide Destructive Index (LDI), an attempt to link the magnitude of landslides and their destructiveness. The LDI is defined in Equation 3 as the ratio of loss per unit volume of the damaging landslide in question.

$$LDI_{vol} = L/V \tag{1}$$

where L is loss and V is landslide volume measured in cubic metres. Loss can be measured in terms of mortality, monetary cost, damaged dwellings, and other measures of loss. In this paper loss is measured in deaths. In this case LDI is a function of the population density of the area struck by the landslide. The LDI tends to 1 in the case of small rockfalls.

To illustrate the application of the LDI, EVANS (2003) examined losses in terms of landslide deaths in the Canadian fatal landslide record and major single-event landslides from other parts of the world. A plot of LDI v. landslide volume (Figure 3) shows a negative power-law relationship in which LDI is scaled to landslide volume (V) by Equation 2.

$$LDI = aV^b \tag{2}$$

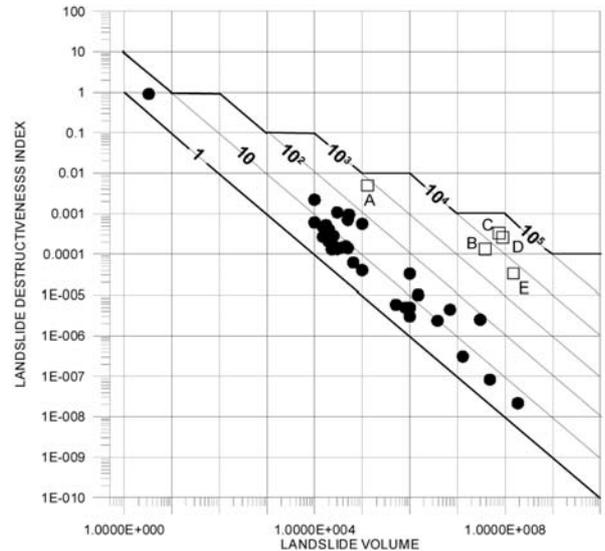


Figure 3 - Plot of Landslide Destructiveness Index (LDI_{vol}) based on Equation 1 v. Landslide Volume (V) for Canadian landslide events (filled circles). Also included are data points for some highly destructive landslides from other parts of the world (open squares) as follows (dates in brackets); A - Las Colinas, El Salvador (2001); B - Kelud, Indonesia (1919); C - Huascaran, Peru (1970); D - Nevado del Ruiz, Colombia (1985); E - Mont Granier, France (1248). Diagonal lines show loci of equal number of deaths from 1 to 105 fatalities (modified from EVANS, 2003)

where V is volume of deposit in m³, where a is a constant and b ~ -1 (Figure 3). The relationship is inverse showing that small magnitude-high frequency landslides are more destructive on a per unit volume basis than larger, less frequent events.

EVANS (2003) mapped out the landslide destructiveness space (Figure 3). A lower limit of 1 death per event establishes the lower boundary of the plot envelope. A series of parallel lines with a spacing of one log. cycle may be plotted to the right of the lower boundary (Figure 3). These correspond to 10, 10², deaths and so on to a maximum of 10⁵ deaths. As suggested by EVANS (2003), 105 is approaching the maximum credible death toll in a single event landslide. The upper boundary can thus be approximated as seen in Figure 3. The lower and upper boundary thus defines a landslide destructiveness space.

Figure 3 is a plot of destructiveness for catastrophic landslides from which no escape is possible and assumes that vulnerability is equal to susceptibility and that no resistance exists in the system. Some of the most destructive landslides in the global historical record plot near the upper boundary of the landslide destructiveness space (Figure 3) suggesting that this first approximation to an upper boundary is quite realistic.

A similar approach was utilized in developing an Event Destructive Index (EDI) for the failure of artificial dams and landslide dams. EDI is defined in terms of event volume and deaths resulting from the event (Eq. 3)

$$EDI_{vol} = L/EV \tag{3}$$

where L is loss and V is event volume, in this case outburst volume, measured in cubic metres.

Data on release volume and casualties were collected from a number of sources (e.g., JANSEN, 1980; COSTA, 1988; ICOLD, 1995) and values of the EDI and V were plotted on Figure 3 (see Figure 4). The data for artificial dam failure events plot within the landslide destructiveness space (Figure 4). Dam failure events are thus comparable to landslide events in terms of destructiveness. For the failure of landslide dams, the points for the 1933 Diexi event is plotted as are the upper and lower bounds for the Great Indus Flood of 1841.

CONCLUSIONS

An approach to the risk assessment of the formation and failure of landslide dams is suggested. Not all rockslides form landslide dams that impound significant lakes. Of the 37 rockslides (with volumes over $20 \times 10^6 \text{ m}^3$) that occurred around the world during the period 1900-2000, 51% formed significant landslide-dammed lakes.

The magnitude and frequency of these impoundment volumes equal to or greater than $40 \times 10^6 \text{ m}^3$ form a robust power law. 47% of landslide dams failed or partially failed. Outburst volumes ranged from 40 to $3000 \times 10^6 \text{ m}^3$, the largest being the 2000 Yigong landslide dam failure, Tibet which devastated areas in the upper Brahmaputra in northern India. Comparisons with the magnitude of outburst volumes resulting from the failure of artificial dams indicate that the Yigong outburst flood is greater than any documented release from an artificial dam failure, which is about 10^9 m^3 .

Landslide dam failures have resulted in a number of major natural disasters including the 1786 Dadu River disaster.

Finally, a landslide dam failure damage index was developed and shows that event destructiveness (loss of life per unit volume of the event) is inversely related to event volume. It provides a tem-

REFERENCES

- BROWN C.A. & GRAHAM W.J. (1988) - *Assessing the threat to life from dam failure*, Water Resources Bulletin, **24**: 1303-1309.
- CASAGLI N. & ERMINI L. (1999) - *Geomorphic analysis of landslide dams in the northern Appennines*. Trans. Japanese Geomorph. Union, **20**: 219-249.
- COSTA J.E. (1988) - *Floods from dam failures*. In V.R. Baker, R.C. Kochel & P.C. Patton (eds.) Flood Geomorphology New York, John Wiley and Sons, pp. 439-463.
- COSTA J.E. & SCHUSTER R.L. (1988) - *The formation and failure of natural dams*. GSA Bulletin, **100**: 1054-1068.
- COSTA J.E. & SCHUSTER R.L. (1991) - *Documented historical landslide dams from around the world*. United States Geological Survey Open-File Report 91-239, 486 p.
- DAI F.C., LEE C.F., DENG J.H. & THAM L.G. (2005) - *The 1786 earthquake-triggered landslide dam and subsequent dam-break flood on the Dadu River, south-western China*. Geomorphology, **65**: 205-221.
- DEKAY M.L. & MCCLELLAND G.H. (1993) - *Predicting loss of life in cases of dam failure and flash flood*. Risk Analysis, **13**: 193-205.
- DUSSUAGE C., GRASSO J-R. & HELMSTETTER A. (2003) - *Statistical analysis of rockfall volume distributions: implications for rockfall dynamics*. Journal of Geophysical Res., **108**: B26, 2286.
- EISBACHER G.H. & CLAGUE J.J. (1984) - *Destructive mass movements in high mountains: hazard and management*. Geol. Surv. Can., Paper 84-16, 230 pp
- ERMINI L. & CASAGLI N. (2003) - *Prediction of the behaviour of landslide dams using a geomorphological dimensionless index*. Earth Surface Processes and Landforms, **28**: 31-47.

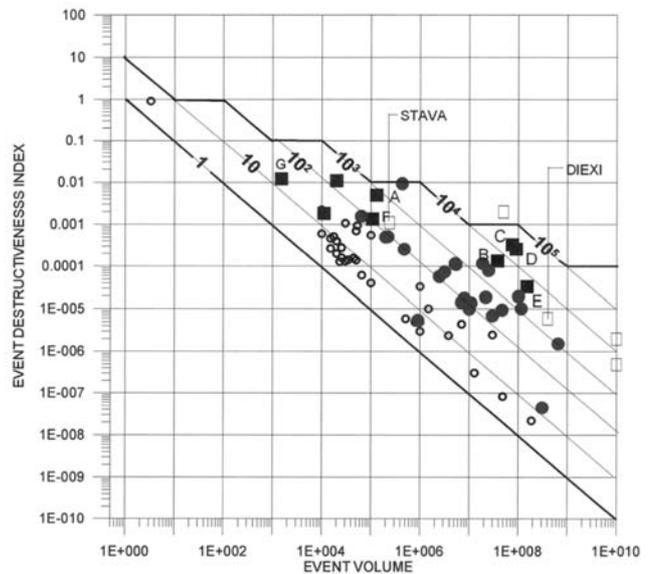


Figure 4 - Plot of Event Destructiveness Index (EDI), calculated using Eq. 3, v. Event Volume (EV) for fatalities from floods resulting from the failure of artificial dams (black dots; n=37). Data for the 1985 Stava tailings dam failure is plotted as is the 1933 Diexi landslide dam failure (open squares). The two open squares at event volume of 10^9 m^3 are upper and lower bound estimates for the 1841 Indus Flood resulting from the bursting of a landslide dam. Other data are for landslides (Fig. 3)

plate for estimating life loss from landslide dam failures linking the magnitude and frequency of landslide dam formation and failure, to such factors as the density of the vulnerable population.

(1) a table of these data and a full reference list is available from the author

THE FORMATION AND FAILURE OF LANDSLIDE DAMS: AN APPROACH TO RISK ASSESSMENT

- EVANS S.G. (1986) - *The maximum discharge of outburst floods caused by the breaching of man-made and natural dams*. Canadian Geotechnical Journal, **23**: 385-387.
- EVANS S.G. (2003) - *Characterising landslide risk in Canada*. Proceedings, 3rd Canadian Conference on Geotechnique and Natural Hazards, Edmonton, Canadian Geotechnical Society, pp. 35-50.
- EVANS S.G. (2006) - *Single-event landslides resulting from massive rock slope failure: characterizing their frequency and impact on society*. In EVANS S.G., SCARASCIA-MUGNOZZA G., STROM A. & HERMANN R. (eds.) Landslides from Massive Rock Slope Failure. NATO Advanced Workshop, Celano, Italy. Science Series, Springer, Dordrecht.
- GRAHAM W.J. (1999) - *A procedure for estimating loss of life caused by dam failure*. U.S. Bureau of Reclamation, Dam Safety Office, Report DSO-99-06, 44 p.
- GUZZETTI F., REICHENBACH P. & WIECZOREK G.F. (2003) - *Rockfall hazard and risk assessment in the Yosemite valley, California, USA*. Natural Hazards and Earth System Sciences, **3**: 491-503.
- HEIM A. (1932) - *Bergsturz und Menschenleben, Zurich*. Fretz and Wasmuth Verlag, 218 pp.
- HERMANN R.L., NAUMANN R., FOLGUERA A. & PAGENKOPF A. (2004) - *Sedimentologic analyses of deposits of a historic landslide dam failure in Barrancas valley causing the catastrophic 1914 Rio Colorado flood, northern Patagonia, Argentina*. Proc. 9th Int. Symp. on Landslides, Rio de Janeiro, Brazil, Balkema, Rotterdam, **2**: 1439-1445.
- HEWITT K. (1968) - *Records of natural damming and related events in the Upper Indus basin, Indus*. Jo. of Water Power Dev. Auth., **10**: 11-19.
- HUNGR O., EVANS S.G. & HAZZARD J. (1999) - *Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia*. Canadian Geotechnical Journal, **36**: 224-238.
- JANSEN R.B. (1980) - *Dams and Public Safety*. U.S. Department of the Interior, 332 pp.
- International Commission on Large Dams (ICOLD) (1973) - *Lesson from dam incidents*. Paris, ICOLD, 201 pp.
- International Commission on Large Dams (ICOLD) (1995) - *Dam Failures - Statistical Analysis*. Bulletin 99, 73 pp.
- JONKMAN S.N., VAN GELDER P.H.A.J.M. & VRILING J.K. (2002) - *Loss of life models for sea and river floods*. In Flood Defence 2002. New York, Science Press, p. 196-206.
- JONKMAN S.N., VAN GELDER P.H.A.J.M. & VRILING J.K. (2003) - *An overview of quantitative risk measures for loss of life and economic damage*. Journal Hazardous Materials, **99**: 1-30.
- KORUP O. (2004) - *Geomorphometric characteristics of New Zealand landslide dams*. Engineering Geology, **73**: 13-35.
- LI T. & WANG S. (1992) - *Landslide hazards and their mitigation in China*. Beijing, Science Press, 84 pp.
- MACDONALD T.C. & LANGRIDGE-MONOPOLIS J. (1984) - *Breaching characteristics of dam failures*. Journal of Hydraulic Eng., **110**: 567-586.
- MASON K. (1929) - *Indus Floods and Shyok Glaciers*. Himalayan Journal **1**: 10-29.
- MCCLELLAND D.M. & BOWLES D.S. (2002) - *Estimating life loss for dam safety risk assessment-a review and new approach*. U.S. Army Corps of Engineers, IWR Report 02-R-3, 403 pp.
- MONTADON F. (1933) - *Chronologie des grands éboulements alpins du début de l'ère chrétienne à nos jours*. Matériaux pour l'étude des calamités, **32**: 271-340.
- PAUL S.K., BARTARYA S.K., RAUTELA P. & MAHAJAN A.K. (2000) - *Catastrophic mass movement of 1998 monsoons at Malpa in Kali valley, Kumuan Himalaya (India)*. Geomorphology, **35**: 169-180.
- SAMARDJIEVA E. & BADAL J. (2002) - *Estimation of the expected number of casualties caused by strong earthquakes*. Bull. Seismol. Soc. America, **92**: 2310-2322.
- SCHUSTER R.L. (2002) - *Usoi landslide dam, southeastern Tajikistan*. Proc. Int. Symp. on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage, Kyoto, Japan; 489-505.
- SCHUSTER R.L. & ALFORD D. (2004) - *Usoi landslide dam and Lake Sarez, Pamir Mountains, Tajikistan*. Env. and Eng. Geosci., **10**: 151-168.
- SHANG Y., YANG Z., LI L., LIU D., LIAO Q. & WANG Y. (2003) - *A super-large landslide in Tibet in 2000: background, occurrence, disaster, and origin*. Geomorphology, **54**: 225-243.
- VOGEL A. (1984) - *Failures of masonry and concrete dams in Europe*. Proc. Int. Conf. on Safety of Dams, Coimbra, p. 45-54. Rotterdam, Balkema, 45-54.
- WALDER J.S. & O'CONNOR J.E. (1997) - *Methods for predicting peak discharge of floods caused by the failure of natural and constructed earthen dams*. Water Res. Research, **33**: 2337-2348.
- ZHOU C.H., YUE Z.Q., LEE C.F., ZHU B.Q. & WANG Z.H. (2001) - *Satellite image analysis of a huge landslide at Yi Gong, Tibet, China*. Quat. Journal Eng. Geol. and Hydrogeol., **34**: 325-332.