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GLOBAL LOSSES FROM LANDSLIDES ASSOCIATED WITH DAMS AND RESERVOIRS

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ABSTRACT

The 1963 Vajont disaster represents by far the largest landside-related accident associated with a dam or reservoir in recorded history. Since then, those involved in planning and constructing large dams and reservoirs have taken measures to ensure that this event is not repeated. In general this has been successful, with no events with losses on a similar scale. However, landslides have continued to present a substantial challenge to those involved in the design and construction of large dams. In the first part of this paper, a brief review is provided of the impacts of landslides on dam projects, highlighting that although losses of life from landslides on reservoir banks have been low, mass movements have frequently caused problems for dam foundations and abutments. Unidentified landslides or areas of potential instability have required very expensive mitigation works when identified after dam construction had started, and they have caused substantial environmental impacts. The second part of this paper examines losses of life from landslides associated with dams and reservoirs in the period 2003-2012 inclusive. It is shown that during this time 500 lives have been lost in landslides associated with dams and reservoirs in 37 separate events. Almost all of these landslides have occurred in East and South Asia, with the majority affecting India and China. These landslides have mostly killed people involved in the construction of dams, either at construction sites or in landslides affecting workers' accommodation. In the mountainous regions of Asia, a very large number of dam construction projects are proposed, planned or under construction. This suggests that losses will continue to rise in the years ahead unless substantial measures are taken to address the causes.

Key words: *landslide, dam, reservoir, precipitation, loss*

INTRODUCTION

The 1963 Vajont landslide represents the most important example of a dam-related landslide that caused loss of life. Whilst details about the mechanisms of failure remain controversial, the failure sequence and causes are well-documented, as are the consequences of the wave generated by the landslide when it entered the reservoir (Paronuzzi & Bolla, 2012). There is little doubt that this event changed the ways in which landslide hazards associated with dams have been perceived and managed, and there has been no subsequent dam-related event of this scale, despite many large dam construction projects in high mountain areas. Nonetheless, landslides associated with dams continue to cause both loss of life and high levels of economic cost. In summarizing the main causes of failure of large dams, Singh (1996) noted that 10% of collapses result from slides of earth, rock and/or ice from the flanks of the lake. Thus, this remains a problem that requires further work. This paper presents a review of recent landslide events associated with dams and reservoirs worldwide, with a focus on those that cause fatalities, drawing upon information from both the literature and the Durham Fatal Landslide Database (DFLD). It shows that landslide-induced losses remain unacceptably high, although in recent years the majority of fatalities have been associated with mass movements during the construction phase of the dam. As there are plans to build large numbers of dams in high mountain areas in the coming years, greater attention will need to be paid on the mitigation of landslide hazards if losses are not to increase.

PERSPECTIVES ON RESERVOIR-INDUCED LANDSLIDES

Schuster (1979) reviewed landslides induced by reservoirs, noting that the failure of slopes into lakes can induce the following hazards:

(1) Water waves that can cause local damage along the reservoir shoreline and, if overtopping occurs, to structures downstream of the dam;

(2) Damage to the dam itself and to its associated infrastructure;

(3) Loss of storage capacity;

(4) Delays to the construction of the project.

In addition, landslides on the flanks of reservoirs can cause environmental problems, such as the loss of ecosystem services. Landslides impact upon dam construction and operation at all phases of such a project (Fig. 1), but the greatest impacts usually occur in the construction and commissioning/impoundment phases of a project. Thus, for example, in a review of 254 examples in which landslides had generated substantial problems at dam sites around the world, Schuster (2006) found that 78 had suffered from ground movement of either an abutment or the dam foundations. However, he cited only five examples in which post-construction landslide movement had threatened the integrity of the dam itself, and noted that such cases are fortunately very rare. Landslides on the flanks of reservoirs are much more common though, and the peak of activity usually occurs during initial impoundment and shortly thereafter, although activity can continue for long periods of time. Finally, landslides during the decommissioning of a dam site are rarely considered but can be very important. The change in the stress state can destabilise the flanks for the reservoir and sediment impounded behind the dam can become unstable, forming mudflows.

Dam project phase	Examples of potential landslide impacts
Site preparation	Damage to haul road infrastructure, damage to dam site. landslides in quarries, landslides on spoil heaps, landslides at workers' camps
Dam construction	Damage to haul road infrastructure, failure of abutments, failure of foundations, loss of tunnels, landslides in quarries, landslides on spoil heaps, landslides at workers' camps
Commissioning / impoundment	Damage to access roads, failure of dam foundations, failure of reservoir flanks
Day-to-day operation	Damage to access roads, failure of dam foundations, failure of reservoir flanks
Decommissioning	Failure of reservoir flanks, draw-down landslides

Fig. 1 - A summary of the landslide impacts associated with each phase of a major dam project

COSTS OF DAM-RELATED LANDSLIDE DISASTERS PRIOR TO 1963

Although Vajont remains the best-known example of a landslide associated with the construction of an artificial dam, there is a number of documented examples of previous events in the literature. Four key events are reviewed here, demonstrating the high costs associated with landslides at dam sites.

AN EARLY MASS FATALITY EVENT: THE 1864 DALE DYKE DAM FAILURE NEAR TO SHEFFIELD, ENGLAND

The collapse of the Dale Dyke Dam on the River Loxley, upstream of Sheffield, England in 1864 caused very high levels of loss, including about 250 fatalities and £324,000 (the equivalent of \$50 million in 2012 values) of direct economic costs. The city of Sheffield and surrounding areas were flooded by the resulting deluge. The inquest into the event heard conflicting evidence about the likely cause of the failure, but evidence was presented that the failure may have been the result of a landslide that affected the toe of the embankment. Evidence was presented to the jury that the flank of the dam was subject to landslide-related deformation prior to the collapse. A landslide remains a likely possible cause of the collapse, although Binnie (1978) argued that the failure may have been due to fracturing in the clay core of the dam.

AN EXAMPLE OF UNANTICPATED LANDSLIDE IMPACTS: THE 1941 TO 1953 GRAND COULEE DAM LANDSLIDES

The Grand Coullee Dam on the Columbia River in Washington State, USA was completed in 1942 toprovide both irrigation and hydroelectric power. The resultant lake is exceptionally long (232 km), such that some landsliding was expected. However, Jones *et alii* (1961) documented a much higher level of landslide activity than had been anticipated, with about 500 landslides being observed in the period between 1941 and 1953. Of these, 245 occurred during the reservoir-filling period. Subsequent landslides were mostly associated with periods in which the water level was drawn down, supplemented by some associated with heavy rainfall. Schuster (1979) noted that although the total volume of landslide movement is probably 50 - 100 million m3, economic losses have not been high and there has been no loss of life. His is attributed to: a. the comparably small size of the individual failures; b. the low population density of the reservoir banks; and c. careful landslide management.

AN EXAMPLE OF A SMALL-SCALE, LANDSLIDE-INDUCED DAM COLLAPSE WITH HIGH CONSEQUENCE: THE 1955 ATENQUIQUE VOLCANICLASTIC DEBRIS FLOW AT NEVADO DE COLIMA, MEXICO

On 16th October 1955, a volcanic debris flow struck the town of Atenquique in Mexico (Saucedo *et alii,* 2008), triggered by three days of sustained rainfall. The lahar originated as a series of multiple landslides on the flanks of the Nevado de Colima volcano, which coalesced within a steep series of ravines, probably increasing in volume through entrainment of basal materials within the channels. Downstream, about 1 km prior to reaching the town of Atenquique, the lahar encountered a 60,000 m^3 water storage reservoir, which appears to have failed instantaneously. At 10:45 in the morning, the town was struck by the debris flow, which by this stage is thought to have had a frontal height of 8-9 m. The landslide destroyed several houses, a school, the local church, four bridges and a paper factory. In total 23 people lives were lost.

AN EXAMPLE OF A VERY EXPENSIVE LANDSLIDE MITIGATION PROGRAMME: THE CLYDE DAM LANDSLIDES IN NEW ZEALAND, 1989-1993

The Clyde Dam is an important 432 MW run-of-the-river HEP scheme on the Clutha River in South Island, New Zealand. During construction of the project, 17 large prehistoric landslides were identified on the flanks of the Cromwell Gorge, which was to be impounded by the dam. Some of these landslides were unusually large – for example with thicknesses of in excess of 150 m and in one case a volume of over 1 km^3 (Macfarlane, 2009) To ensure the stability of the flanks of the reservoir, a major programme of engineering works was undertaken, involving buttressing (Fig. 2a), drainage (pumped and gravity), and infiltration protection (Fig. 2b). It is estimated that the costs of the landslide stabilisation and monitoring programme were US$300 million (the equivalent of $470 million in 2012 values).

AN EXAMPLE OF A LANDSLIDE INDUCING SUBSTANTIAL WATER QUALITY ISSUES IN A WATER SUPPLY RESERVOIR PROJECT: THE SHIHMEN RESERVOIR IN TAIWAN

The Shihmen Dam in Taiwan, which was completed in 1964, is located in Taoyuan County of northern Taiwan, primarily for drinking water supply, irrigation and flood defence purposes. Since construction the catchment area of the dam has suffered from a very significant landslide problem (Fig. 3), which has led to

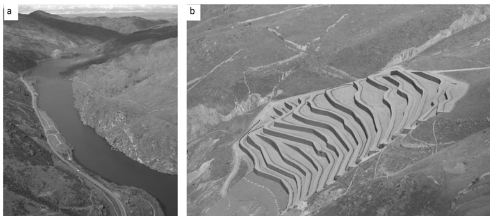

Fig. 2 - Two oblique aerial views of the Clyde Dam landslide mitigation works: a. A toe buttress on the Brewery Creek landslide (landslide volume = 80 million m^3); b. The innovative infiltration protection structure on the Cainmur landslide

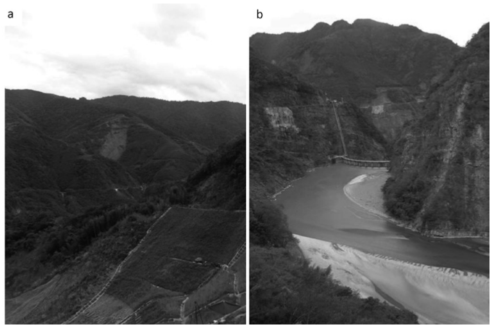

Fig. 3 - Two views of the Shihmen Dam landslide catchment. a) A landslide located on the catchment valley walls); b. One of the many sediment check dams upstream of the main reservoir, constructed to retain sediment released by landslides. In this case the storage capacity of the check dam is now fully infilled

large volumes of sediment entering the reservoir. In consequence, the storage volume of the reservoir has been reduced from 0.309 to 0.210 km^3. Considerable effort has been expended in trying to manage the landslides and to trap sediment before it enters the lake with, for example, over 120 large-scale check dams. In 2007, one of these failed, releasing 10 million m3 of sediment. The high suspended sediment level in the lake has also caused a deterioration of water quality due to the effects of eutrophication and turbidity (Ku *et alii,* 2009). As a result a series of very expensive mitigation programmes have been required.

As these examples show, the impacts of landslides on dam and reservoir projects are highly complex and varied. For example, even small-scale dams can be responsible for substantial loss of life when they are affected by landslides. In addition, landslides can inflict high unanticipated economic costs to large-scale dam and reservoir projects, often causing cost over-runs and delays to completion dates. In many of the examples examined in detail by Schuster (2006), the remediation costs were very high - for example, the 80 m high Tablachaca Dam in Peru was constructed in 1972 on an ancient rockslide. In the late 1970s the landslide, which formed the right abutment of the dam, began to move. A complex set of remediation structures, including an earth berm at the toe, rock anchors and drainage tunnels, were constructed at an estimated cost of US$40 million (the equivalent of $84 million in 2012 values). There are many similarly expensive impacts on dam and reservoir projects.

Finally, landslides can have substantial intangible costs as well, for example damaging the recreational value of the banks of the reservoir, as well as being responsible in some cases for significant deterioration of water quality through turbidity and eutrophication, which can require extremely expensive mitigation schemes. Thus, the impact of landslides is commonly under-estimated in large-scale dam and reservoir projects. However, it is also the case that the costs of landslides are generally under-estimated in both financial and life terms.

GLOBAL LANDSLIDE FATALITIES 2004-2011

Petley (2012a) used the DFLD to investigate losses associated with non-seismic landslides in the period 2004-2010, reporting a total 2620 fatality-inducing landslides that caused a total of 32,322 recorded deaths. Although this is an order of magnitude higher than had been previously reported, this total is likely to underestimate the total losses by a small degree (probably 10-20%). The methodology used to collect this data is described in detail in Petley *et alii* (2005) and Petley (2012a and 2012b), but in brief involves the use of newswire data, technical reports, official datasets and scientific papers to track the occurrence of fatality-inducing landslides on a global basis. The dataset includes all mass movements commonly classified as landslides, including rockfalls and debris flows, but not including snow and ice avalanches.

Here, an updated dataset is presented, with losses for an additional year (2011), such that the dataset spans the period 2004-2011 inclusive. In this period 35,287 landslide-induced fatalities were recorded in 3,059 non-seismic events, representing an average of 4,411 fatalities per year. Once seismically-induced landslides are included in the total, the number of landslide-induced fatalities increases to 84,341 (i.e. an average of 10,543 per annum), with this data being dominated by the landslides associated with the 2005 Kashmir and 2008 Wenchuan (Sichuan) earthquakes. Figure 4

presents the distribution of non-seismically-induced landslide induced fatalities in the period 2004-2011; as noted by Petley (2012a) the global landslide distribution in the DFLD dataset is strongly heterogeneous, with the majority of landslides occurring in South,

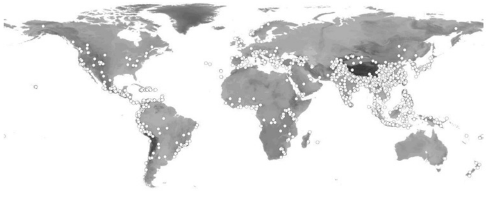

Fig. 4 - The distribution of non-seismic fatality-inducing landslides from 2004 to 2011, projected onto a digital elevation model. Each dot represents a single landslide that caused one or more deaths

Fig. 5 - The distribution of major dams worldwide as recorded in the GRanD dams database (Lehner et alii, 2013)

South-East and East Asia, with the southern edge of the Himalayas representing the largest global hotspot for landslide events. Other hotspots can be found in for example Central and parts of South America and in the Caribbean. Most landslide hotspots in the DFLD dataset are in poorer countries.

It is interesting to compare the distribution shown on Fig. 4 with the distribution of large dams worldwide. Figure 5 shows the distribution of large dams as mapped by the Global Reservoir and Dam (GRanD) database version 1 (2012) (Lehner *et alii,* 2013). This dataset provides compiles reservoirs with a storage capacity of > 0.1 km³. This version of the database contains records of 6,862 reservoirs worldwide with a storage volume of >0.1 km³. In Fig. 6, dams constructed since 1990 are shown. It is notable that in this period the numbers of large dams completed in North America and Northern Europe was low, with significant numbers being built in Asia and Southern Europe.

In Fig. 7 the distribution of very large reservoirs (storage volume greeter than 1 km³) is shown, superimposed on top of the distribution of fatality-inducing landslides for the period 2004-2011 as per Fig. 4. Note that in most of the world these very large dams are located in areas with comparatively low landslide incidence in the DFLD dataset. However, in Asia these very large dam / reservoir projects are generally located in areas with high rates of fatality-inducing landslide occurrence, suggesting a different level of landslide hazard associated with these programmes in this region.

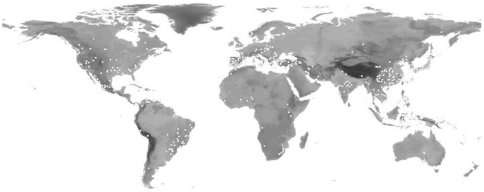

Fig. 6 - The distribution of major dams worldwide constructed since 1990 as recorded in the GRanD dams database (Lehner et alii, 2013). Note the comparatively large number that have been constructed in Asia and in S Europe

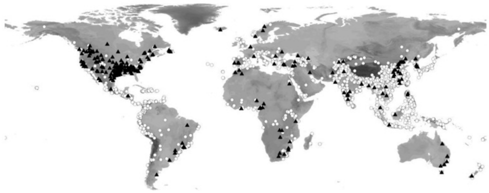

Fig. 7 - The distribution of non-seismic fatality-inducing landslides from 2004 to 2011 (open circles) and major dams (reservoir capacity >1 km³, black triangles) from the GRanD dams database (v1 2012, Lehner et alii, 2013), projected onto a digital elevation model

FATALITIES ASSOCIATED WITH DAMS AND RESERVOIRS, 2003-2012

Using the DFLD dataset, the occurrence of landslides associated with large dams has been extracted and is presented in Table 1. In total there are exactly 500 recorded deaths in this dataset in 37 distinct events. The locations of these 37 landslides are shown on Fig. 8, alongside the full fatality DFLD dataset. The geographical distribution of the landslides is highly heterogeneous, with most of the losses occurring in South and East Asia. Analysed from a country-specific perspective (Fig. 9), losses were recorded in only nine countries, of which China and India account for 51% and 32% of the losses of life respectively. The occurrence of these

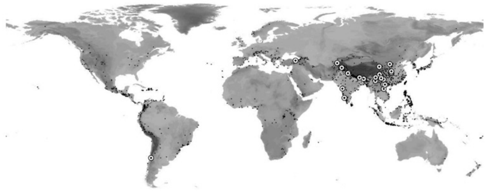

Fig. 8 - The distribution of fatality-inducing landslides associated with dams and reservoirs in the period 2003-2012. LEGEND: The small dots indicate other fatality-inducing landslides for the period 2004-2011; the large dots present the landslides associated with dams and reservoirs in the aforementioned period

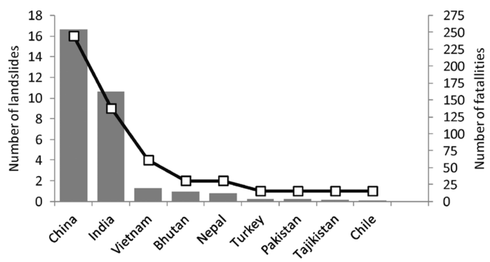

Fig. 9 - The recorded occurrence of fatality-inducing landslides, as recorded on the DFLD dataset, associated with dam and HEP projects in the period 2003-2012 inclusive, organised by country. The bar graph shows numbers of fatalities (right hand axis), whilst the line graph shows numbers of recorded events (left hand axis)

events in time possibly suggests an increasing rate (Fig. 10), although the data are too short to properly assess the trend. Note that 2007 stands out as a year with an unusually large number of landslides and resultant fatalities.

The brief description of the landslide events in Table 1 demonstrates that many (46%) of the landslides took the form of landslides or rockfalls at dam construction sites, but with 30% taking the form of landslides or rockfalls that impacted upon workers' accommodation (Fig. 11). There were also five landslides that affected workers either maintaining or travelling on highways near to the construction site, and a small number of landslides in quarries or spoil heaps. Only one Vajont-style fatality-inducing reservoir bank landslide occurred, although this event killed 24 local people and destroyed 129 houses and four factories. This was the 14th July 2003 Qianjiangping landslide (Fig. 12), which occurred during the first impoundment of the Three Gorges Reservoir (Wang *et alii*, 2004). The landslide occurred as a rapid movement on a rock bedding plane as the water level rose. This landslide had been preconditioned to failure by quarrying activities by a local brickworks from 1997-2003, and final failure occurred in the aftermath of intense precipitation.

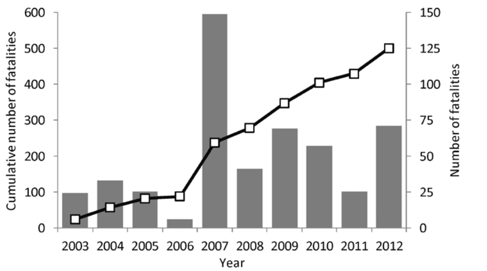

Fig. 10 The recorded occurrence of fatality-inducing landslides, as recorded on the DFLD dataset, associated with dam and HEP projects in the period 2003-2012 inclusive. Numbers of fatalities (bar graph, right hand axis) and cumulative numbers of events (line graph, left hand axis) show an increasing trend with time, although 2007 does stand out as an exceptional year

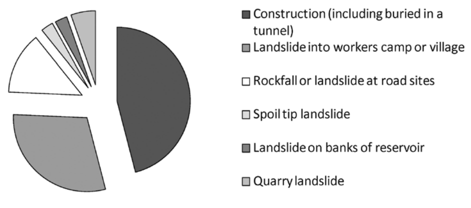

Fig. 11 - The breakdown according to types for the occurrence of fatality-inducing landslides, as recorded on the DFLD dataset, associated with dam and HEP projects in the period 2003-2012 inclusive

Many other landslides have been documented along the banks of the Three Gorges Reservoir (e.g. Fourniadis, 2007) and unanticipated efforts have been required to manage and mitigate them. In early 2012 Liu Yuan, an inspector at the Ministry of Land Resources in China reported that the number of landslides along the banks of the Three Gorges reservoir had increased substantially since the impoundment of the lake began. He is reported to have observed that that 5,386 sites were being monitored, of which 355 locations had already suffered landslides. The result is that an additional 100,000 people may need to be relocated from the banks of the reservoir.

Date	Country	Location	Deaths	Indicative dam project NB low certainty	Description
13/07/2003	China	Qiangjingping	24	Three Gorges Dam	Landslide on banks of reservoir
03/08/2004	India	Tehri Dam, Uttranchal	29	Tehri Dam	Buried in a tunnel
23/04/2004	China	Majuangou, Shaanxi	4	Small scale hydro	Landslide at dam construction site
26/04/2005	India	Mulliyar, Kerala	10	Small scale hydro	Landslide at dam construction site
28/06/2005	India	Shahpur, Ghatgar	15	Ghatghar HEP	Buried in a tunnel
07/10/2006	China	Fangxian C'ty, Hubei	6	Not known	Rockfall onto workers en route
15/12/2007	Vietnam	Tuong Duong, Nghe An	18	Ban Ve HEP	Rockfall onto quarry workers
19/07/2007	China	Sujiahekou , Yunnan	29	Sujiahekou HEP	Landslide into workers camp
20/07/2007	China	Guide County, Qinghai	8	Laxiwa HP Station	Landslide at dam construction site
10/08/2007	China	Ya'an City, Sichuan	12	Long Tou Shi Dam	Landslide at dam construction site
14/08/2007	India	Dharla, Himachal Pradesh	62	Ghanvi HEP	Landslide into workers village
07/09/2007	Bhutan	Chukha dzong	2	Chuka HEP	Landslide into workers camp
15/12/2007	Vietnam	Tuong Duong, Nghe An	18	Ban Ve HEP	Rockfall onto quarry workers
12/05/2008	China	Jinhe HEP	22	Jinhe HEP	Landslide at dam construction site
20/05/2008	Chile	San Fernando	1	Not known	Rockfall onto workers en route
07/06/2008	Bhutan	Wangkha	12	Tala HP project	Rockfall onto workers en route
31/07/2008	China	Ya'an City, Sichuan	5	Long Tou Shi Dam	Landslide onto workers en route
11/09/2008	Nepal	Khare VDC, Dolakha	1	Upper Tamakoshi HP	Rockfall onto road construction workers
07/05/2009	Tajikistan	Rogun	2	Rogun HEP	Landslide at dam construction site
03/06/2009	Vietnam	Nam Khoa, Lao Cai	4	Nam Khoa HEP	Landslide into workers camp
23/07/2009	China	Kangding C'ty, Sichuan	54	Changheba HEP	Landslide into workers camp
31/07/2009	China	Jinyang C'ty, Sichuan	9	Not known	Landslide into workers camp
23/01/2010	Vietnam	Ve village, Yen Bai	1	Nam Toc HEP	Spoil tip landslide
14/02/2010	India	Kinnaur, Himanchal Pradesh	8	Karcham-Wangtoo HEP	Landslide into workers camp
15/06/2010	China	Kangding county, Sichuan	23	Kangding Longtou HEP	Landslide into workers camp
26/07/2010	China	Gongshan Drung-Nu, Yunnan	11	Unknown	Landslide into workers camp
31/07/2010	Pakistan	Patan, Khyber Pakhtunkhwa	3	Patan Hydropower project	Landslide at dam construction site
02/08/2010	Nepal	Gaurishankar, Dolakha	11	Sipirang River HEP	Landslide at dam construction site
15/06/2011	China	Shiyan, Hubei	3	Hubei Shyan Longbeiwan	Landslide at dam construction site
18/09/2011	India	Salim Payel, Mangan	10	Teesta HEP	Landslide at dam construction site
18/09/2011	India	Teesta HEP, Sikkim	1	Teesta HEP	Landslide into workers camp
18/09/2011	India	Teesta HEP, Sikkim	7	Teesta HEP	Landslide at dam construction site
28/02/2011	India	Asiganga, Uttarakashi.	4	Asiganga Phase I	Landslide at dam construction site
28/06/2012	China	Ningnan C'ty, Sichuan	40	Baihetan HEP	Landslide at dam construction site
13/07/2012	China	Shuicheng C'ty, Guizhou	3	Maojiahe HEP	Landslide into workers camp
30/08/2012	China	Liangshan Yi Sichuan	24	Baihetan HEP	Landslide at dam construction site
15/05/2012	Turkey	Kızıltaş, Dereli, Giresun	4	The Kanat Regulator	Landslide at dam construction site

Tab. 1 - Reported landslides associated with major dam and HEP projects, as recorded in the DFLD dataset. In some cases the indicated dam project is speculative as clear information is not available

Fig. 12 - The Qianjiangping landslide on the banks of the Three Gorges Reservoir in China. This landslide, which was responsible for the loss of 24 lives, was associated with the first impoundment event of the Three Gorges Dam

FUTURE PROSPECTS FOR LANDSLIDES ASSOCIATED WITH DAMS AND RESERVOIRS

The analyses presented here portray an interesting view of landslides associated with dams and reservoirs. The data suggest that since the 1963 Vajont disaster, the dam and reservoir industry has in general been successful in preventing recurrence of this type of accident. However, two very clear patterns emerge:

a. In the planning phase of many dam and reservoir projects there is a failure to recognise either the existence of ancient landslide bodies (as indeed was the case at Vajont) or to identify landslide potential on reservoir banks. The upshot has been in many cases project costs that have been substantially higher than expected, and completion dates that are later than planned;

b. In the construction phase of many projects, landslide accidents continue to occur regularly. In many cases these events are situated in or around construction sites; landslides onto temporary camps are also common. These events have been responsible for an unacceptable level of loss of life in the last decade.

It is notable that the distribution of fatality-inducing landslides associated with reservoirs and dams in the last decade does not correlate well with the list of dams completed in the same period (as indicated by the GRanD dataset), even though nearly all landslides occurred during the construction phase of the projects (Fig. 13). The occurrence of these landslides in South and East Asia appears to have been disproportionately high in comparison with other areas. The cause of this is not clear, but is likely to be associated with the level of natural landslide activity associated with this geographic region. East and South Asia are both tectonically active (which is responsible for both generating a landscape that is landslide-prone and for triggering landslides through large earthquake); subject to high rates of weathering under tropical or semi-tropical conditions; and affected by intense rainfall, especially in the summer monsoon period. The importance of these meteorological conditions is illustrated by the month of occurrence of the landslides associated with reservoirs or dams (Fig. 14). It is clear that the majority of these landslides occurred during the northern hemisphere summer when monsoon rainfall is dominating the weather conditions of South and East Asia. This pattern reflects that observed for this region for other fatality-inducing landslides (e.g. Petley 2010, 2012a, 2012b; Petley *et alii* 2005).

A logical conclusion may well be that landslide hazards associated with large dams in East and South Asia are not being managed as well as might be optimal. The reasons for this are likely to be complex and varied, and may well include factors that are socio-economic and/or political, and are thus beyond the scope of this paper. From a technical perspective three aspects may be important:

a. Occasional seismic activity can profoundly alter the rates of activity of the landscape, such that conditions that apply during a site investigation phase may no longer be current during the construction of the dam and associated infrastrucucture;

b. In a tropical or sub-tropical landscape, there is frequently a combination of thick layers of weathered material and dense vegetation. This can render the identification of potential or pre-existing landslides very challenging. Thus, it is likely that many potential instabilities are being missed during the site investigation and planning phases;

c. The climate and geological environment of these areas are different to those in other areas in which

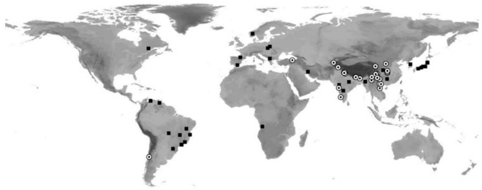

Fig. 13 - A comparison of the distribution of fatality-inducing landslides associated with dams and reservoirs (point symbols) with the distribution of large dams completed in the period 2003-2012 (square symbols) as indicated by the GRanD database

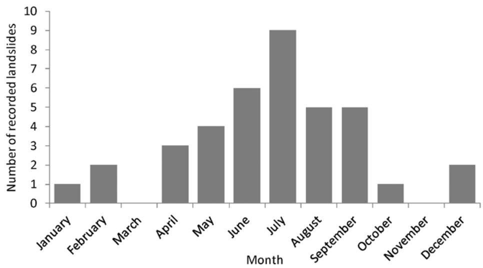

Fig. 14 - The number of recorded fatality-inducing landslides associated with dams and reservoirs by month of occurrence in the period 2003-2012. Note the higher incidence in the Northern Hemisphere summer, which suggests a strong meteorological influence on their occurrence

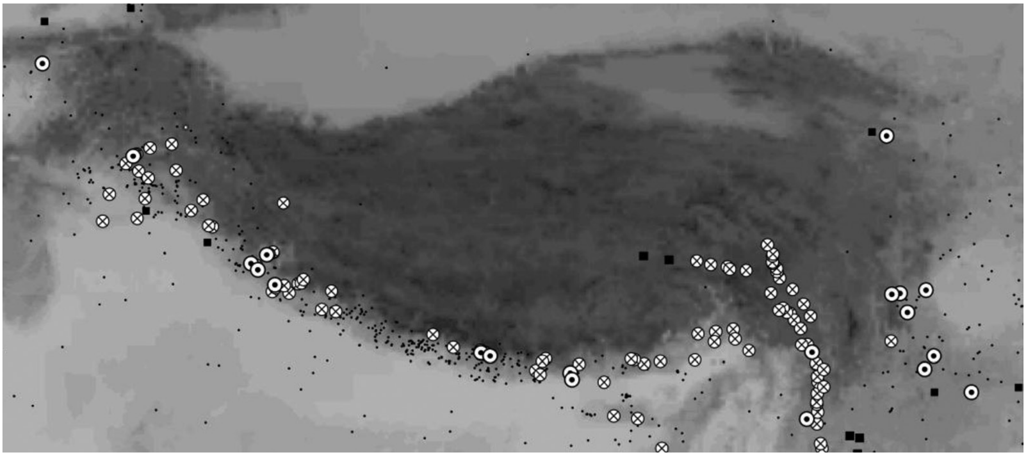

Fig. 15 A comparison of the distribution of fatality-inducing landslides associated with dams and reservoirs (point symbols) with the distribution of large dams completed in the period 2003-2012 (square symbols) as indicated by the GRanD database, the distribution of planned dams (crossed circles) and fatality-inducing landslides (small dots)

large dams have been constructed. In particular, the dynamic nature of the landslide can be easy to under-estimate.

In the coming years a very large amount of dam construction is planned around the world as the need for hydroelectric power increases for both social and environmental reasons. Major hydroelectric power projects are planned or proposed in high mountain areas on all of the inhabited continents. However, the global centre for large-scale dam and reservoir projects in the next two decades will inevitably be South and East Asia, with the steep valleys of the Himalayas being responsible for a substantial proportion of that planned activity. Fig. 15 presents the distribution of fatality-inducing landslides associated with dams and reservoirs, fatality-inducing landslides for the period 2003-2011, existing large scale dams from the GraND dataset and the distribution of planned large-scale dams (data from International Rivers 2013 and other sources). It is clear that a very large number of new projects are planned in this region in the coming years. In most cases these projects will be constructed in areas that have been subject to high levels of landslide activity in the past, such that palaeo-landslide deposits are likely to be extensive. Landslide activity under contemporary climatic conditions is likely to be high, and most of this area is also subject to occasional large or very large earthquakes, which are likely to be associated with extensive landslide activity. Finally, the effects of climate change in this area may be increased precipitation intensity (e.g. Petley, 2010), which may increase landslide activity in coming years. Thus, without careful management there is a strong potential for continued landslide impacts on large dam and reservoir projects.

DISCUSSION AND CONCLUSIONS

The 1963 Vajont dam disaster undoubtedly represents a watershed moment in the management of landslides associated with large dams and reservoirs. Fortunately, since the disaster there has been no repeat event on a similar scale. However, landslides continue to be a substantial issue in the planning and implementation of large dam projects. Schuster (2006) demonstrated that in a large number of cases, landslides have caused significant disruption to dam sites themselves, often requiring expensive mitigation programmes to foundations and abutments. Landslides on reservoir banks inflict substantial levels of loss, as the 2003 Qianjiangping landslide on the Three Gorges reservoir demonstrates. It is likely that the impact of landslides will continue for many years in the Three Gorges reservoir. Fortunately, to date only one of these landslides has been responsible for loss of life, although great care will be needed in exceptional rainfall events over the next few years.

However, it is clear that in recent years a substantial problem with landslides associated with dams and reservoirs has developed. This is associated with landslides that occur during the construction and impoundment phase of dam projects. Large numbers of fatality-inducing landslides have been occurring, with substantial levels of loss of life. The majority of these landslides have occurred in South Asia and East Asia, and in particular on dam projects in India and China. In most cases the victims have been people employed by the dam project, with most of the landslides having occurred either on construction sites associated with the project or on workers' accommodation sites. Clearly, there is a need for improved management of these sites to reduce the impact of landslides. At this stage it is not clear as to whether these events might indicate that there is an increased chance of landslides during the impoundment phase of these large dam projects.

As Fig. 14 demonstrates, in coming years there are many further large-scale dam and reservoir projects planned for landslide-prone areas. There is a notably high number of these projects planned for the Himalayan region, which is both highly landslide-prone and has a track record of large landslide events associated with reservoirs and dams. Landslides associated with these projects have the potential to continue to generate substantial human and economic losses unless improvements are put in place to reduce to reduce the occurrence of landslides at and around the dam construction sites. In the areas in question, it is also likely that changes to weather patterns associated with climate change, and in particular increases in peak rainfall intensity, will change patterns of landslide activity. At least some of these sites are also likely to be affected by earthquakes, which generate large numbers of landslides, during their design life.

Since the Vajont disaster, the dam and reservoir industry has very successfully identified and mitigated landslides, albeit at times at very high cost. A similar level of action is now required to address landslides occurring at and around dam construction sites and in the camps housing the workers, especially in East and South Asia. To do so will require concerted effort from planners, funding agencies, regulators and construction companies.

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