Hazard and Risk Related to Earthquake-Triggered Landslide Events

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Abstract

First, we analyse how important earthquake-induced landslide hazards are compared to other geohazards at world-wide scale. Then, we try to estimate where these hazards may have the strongest impacts—at regional and local scale. In this regard, we also consider the short- and long-term effects of geological, tectonic, climatic and morphological conditions. Hazard and risk related to these processes was also analysed based on series of case histories: e.g., the 1920 Haiyuan earthquake-landslide disaster in China, the 1970 Nevado-Huascaran rock avalanche, as well as the 1999 events in Taiwan, 2001 in El Salvador, 2005 in Pakistan, and 2008 in China. Detailed report was provided for events in Central Asia: the 1911 earthquakes in Kemin, Sarez in 1911, Khait in 1949, Gissar in 1989 and Suusamyr in 1992. Particular focus is on mega-events such as the Usoy rockslide in Tajikistan as well as giant prehistoric rockslides in other parts of Central Asia and in the world (including Europe). We will try to answer several questions such as: how likely is a seismic versus climatic origin for giant landslides; how is the general geohazards level affected by these low-frequency earthquake-triggered mega-events. One conclusion is that in semi-arid mountain regions marked by a strong seismic activity, such as those in Central Asia, seismogenic landslides and related long-term effects may represent the most important geohazards. Further, the susceptibility to seismic slope instability is highest along active fault zones and on convex slopes made of soft or fractured materials.

Keywords

Earthquakes • Large landslides • Central Asia • Impacts • Long-term effects

Introduction

During the last 10 years, after a series of disastrous earthquake events in the mountain regions of Taiwan (1999), El Salvador (2001), Pakistan (2005) and China (2008), more attention has been given to landslides triggered by earthquakes.

Previously, landslides have been considered as minor effects of earthquakes compared to the impact of the ground shaking itself. Schuster and Highland (2001) partly attributed the perception of the relatively small impact of earthquake-triggered mass movements to the fact that many related losses are often referred to as direct consequences of the earthquake.

This study of Schuster and Highland (2001) had been well completed before the M = 7.6 earthquake hit the Kashmir mountains on October 8, 2005. For this event, Petley et al. (2006) estimated that about 30 % of the total number of killed people (officially 87,350), i.e. 26,500, had been victims of co-seismic landslides. Less than 3 years later, on May 12, 2008, the Wenchuan earthquake hit the Sichuan and neighbouring provinces of China and caused 'more than 15,000 geohazards (recently, even much higher

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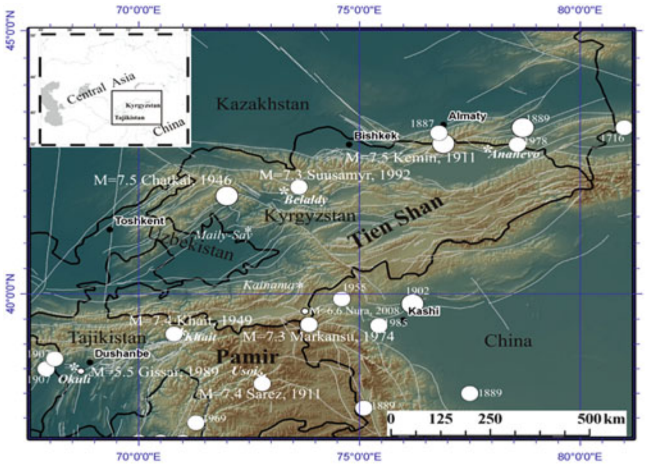

Fig. 1 Map of Tien Shan and Pamir Mountains in Central Asia with location of major faults and earthquakes (*white filled circles* show all recorded M ≥ 7 earthquakes with the year of occurrence; the magnitude is indicated for analysed events) and related major mass movements (*stars*)

numbers have been published, up to 100,000) in the form of landslides, rockfalls, and debris flows, which resulted in about 20,000 deaths' (Yin et al. 2009).

In this paper, we will evaluate the potential impact of landside hazards induced by earthquakes on the basis of a review of related geological observations. We focus on the relatively poorly known Central Asian mountain regions, the Tien Shan and Pamir, on the basis of landslide case histories related to the following earthquakes (see location in Fig. 1): M = 8.2 Kemin, 1911, M = 7.6 Sarez, 1911, M = 7.4 Khait, 1949, M = 5.5 Gissar, 1989 and M = 7.4 Suusamyr, 1992.

The documented earthquake case histories of Central Asia will be compared with some of the worldwide most disastrous events, and particularly with the M = 7.8 Haiyuan (or Gansu, 1920) and the M = 7.8 Peru (1970) earthquakes. These two events caused the greatest number of deaths in history through multiple triggered landslides and a single mass movement, respectively.

Further, our analysis will focus on those types of mass movements, that caused these disasters: rapid flows (mainly) in loess deposits and massive rock avalanches. Actually, those types also induce the highest geological risk in Central Asian regions, such as shown in the following. For a complete review of landslide types triggered by earthquakes, the reader is referred, e.g., to Keefer (1984).

Special attention is paid to long-term effects of earthquakes in mountain regions. Examples is shown for clearly delayed triggering of slope failures after earthquakes and post-seismic increase of landslide activity, such as observed after the Chi-Chi earthquake of 1999 in Taiwan (Dadson et al. 2004). In this regard, we will also analyse previously called 'secondary or tertiary effects' of earthquakes, such as natural dams and related flooding impacts. In the Tien Shan, the most recent massive natural dam was formed after the Suusamyr earthquake in 1992—it partly failed in 1993, thus causing a long-runout debris flow and widespread flooding downstream. The 2008 Wenchuan earthquake clearly marked the importance of such effects—which could have killed another few thousands of people if efficient mitigation measures had not been taken by Chinese authorities. For these cases, it will be shown that the term 'consequential hazard' proposed by Korup (2003) should be preferred over 'secondary of tertiary effects' implying a lesser degree of importance.

Factors Contributing to the Seismic Triggering of Landslides

Geology

From our field observations and an extensive literature review (summarized in Havenith and Bourdeau 2010), we conclude that there are no particular geological conditions favouring the seismic triggering of landslides (compared to the aseismic triggering). However, if cross-bedding failure occurred, a seismic triggering s more likely compared to aseismic triggering.

Morphology

Earthquake-induced landslides may be triggered from any surface morphology—even within flat areas, such as lateral spreads, or from steep cliffs, such as rock falls.

Still, several particularities can be outlined. Harp and Crone (2006) noted for effects induced by the 2005 Pakistan earthquake that '… several ridges near the top also are covered with fractures that are concentrated at the ridge crests and the summit'. They conclude that 'these fractures probably are associated with increased levels of shaking due to topographic amplification of the ground shaking'. From our own experience of earthquake-induced landslides in the Tien Shan (see below), it can be concluded that mainly the surface curvature has an influence on seismic slope stability at global scale; particularly, hillcrests and convex surface morphologies are prone to seismic slope failure. The influence of slope angle on seismic slope stability is not clear; in some cases, especially in rocks, steeper slopes are more prone to instability; in others, especially in soft sediments, gentle slopes produce most of the mass movements, indicating that the combined effect of slope and geology has to be taken into consideration. Similarly the influence of the slope aspect on slope stability is connected to environmental and tectonic conditions.

Major Seismic Landslide Events: Focus on Central Asia

Nadim et al. (2006) assessed landslide and avalanche occurrence probabilities worldwide on the basis of morphological, geological, meteorological and seismological data. They clearly showed that all landslide hotspots are located in seismically active mountain ranges. For Central Asia, they estimate that global landslide hazard can be rated as medium to very high. They further noted that some areas in Tajikistan are marked by highest mortality risk due to landslides.

The following case histories document the landslide risk triggered by earthquakes in the Tien Shan and the Pamir Mountains. A comparison will be made with the 1920 Haiyuan (China) and 1970 Peru events to outline the most important factors contributing to landslide hazard and risk in Central Asia.

Central Asian Case Histories

The Kemin Ms = 8.2 earthquake of 1911 is one of the strongest events ever recorded in the Tien Shan; it was first analysed by Bogdanovich et al. (1914). The earthquake caused extensive landsliding along the activated fault segments over a length of 200 km. The largest mass movements were two rockslides, one within the Kemin valley and the other north of the lake Issyk-Kul. The first rock avalanche (about $15 \times 10^{6}\ \mathrm{m}^{3}$) made of limestone material occurred along the activated Chon Kemin fault at about 60 km W of the epicentre, and is known to have buried a village of yourts with 38 inhabitants. The second 'Ananevo' rockslide is one of the most prominent features produced by the Kemin earthquake. Failure took place at the southern end of a mountain ridge, just above the discontinuous Chon Aksu thrust fault also activated by the 1911 Kemin earthquake. Outcrops at the foot of the southwest-oriented slope show particularly disintegrated and weathered granitic rocks within a 100–200 m thick fault zone.

During the same year, 1911, the Sarez earthquake, Ms = 7.6, struck the central Pamir Mountains, Tajikistan. Such an earthquake is likely to have triggered hundreds or thousands of mass movements, but only one is well documented: the giant Usoi rockslide, which fell from a 4,500 m high mountain down to an elevation of 2,700 m in the valley (Schuster and Alford 2004). This rockslide has formed a dam with a volume of about $2 \times 10^{9}\ \mathrm{m}^{3}$ on Murgab River. According to Schuster and Alford (2004), the location of the slide is related to 'a high degree of rock fracturing from previous tectonic activity…a major thrust fault with an unfavourable orientation …and… a series of intensively sheared zones forming geometric setting for a typical wedge failure.' Behind this 600 m high natural dam (the highest dam in the world), Lake Sarez and the smaller Lake Shadau had been impounded, the first one with a maximum depth of 550 m. Various scenarios consider the risk related to the failure of the rockslide dam due to internal erosion or overtopping as well as to a flood wave induced by the impact of mass movement into Lake Sarez. Those scenarios are discussed by Schuster and Alford (2004), among others—the worst-case scenario flood wave could affect more than 5 million people living in the Amu Darya river basin.

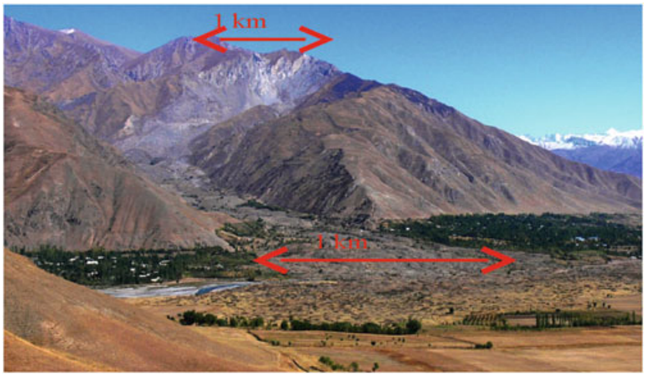

Fig. 2 Khait rock avalanche; view towards the East from Yasman valley (unpublished photograph of 2005 provided by A. Ischuk)

In 1949, the M = 7.4 Khait earthquake in Northern Tajikistan produced one of the most destructive earthquake-triggered landslide events in human history (until that time, according to Leonov 1960). The most catastrophic triggered mass movement is a rock avalanche that had buried the villages of Khait and Kusurak with thousands of inhabitants (Fig. 2); the exact number of fatalities will never be known since 'during the formidable rule of Joseph Stalin, information about accidents and natural catastrophes was suppressed unless special permission was granted' (Yablokov 2001). The volume was initially estimated to more than $200 \times 10^{6}\ \mathrm{m}^{3}$ (Leonov 1960). However, more recent investigations by Evans et al. (2007) indicated that the total volume would be much lower, of about $40 \times 10^{6}\ \mathrm{m}^{3}$. Also Evans et al. (2007) observed that a significant part of the mass movement was made of loess, which probably contributed to the mobility of the initial rockslide. They also indicate that in the Yasman valley opposite to the Khait rock avalanche, massive loess earth-flows are believed to have buried about 20 villages. In total, the Khait rock avalanche and loess earth-flows are likely to have killed more than 10,000 people during the 1949 event. In addition to the catastrophic impacts, Russian geologists described also the general conditions of the earthquake-triggered slope failures. For instance, Leonov (1960) wrote (translated from the Russian original): '…involved are also amplification effects that can explain landsliding far from the epicentre…' This observation had already been pointed out above.

In 1989, a Ms = 5.5 earthquake struck the village of Gissar in Tajikistan and triggered a series of earth-flows in loess. At least 200 people were killed and hundreds of houses were buried. According to Ishihara et al. (1990), those slides were all related to extensive liquefaction, which had developed for a horizontal acceleration of about 0.15 g. They associated the liquefaction to the 'collapsible nature' of the highly porous loess material (a silt-sized deposit with an average content of clay of 15 % and a low plasticity). The sliding surface of most landslides was located at a depth of about 15 m within the saturated part of the 30 m thick loess deposits. Ishihara et al. (1990) also noted that the scarps of many landslides were located along a water channel installed on the shoulder of the hills. They assumed that 'water in the channel had been infiltrating in the loess over years leading to final failure during earthquake due to liquefaction of water-bearing loess layer'. This is supported by their observation of muddy water oozing from the earth-flow.

The most recent large seismic event hitting Central Asian mountain regions was the Ms = 7.3 Suusamyr earthquake on August 19, 1992, triggering various types of ground failures in the Northern-Central Tien Shan.

Most of the 50 people killed in the remote areas were victims of mass movements. Korjenkov et al. (2004) described a series of ground failures: sagging of mountain slopes, rockfalls, landslides, soil avalanches and flows, mud/debris flows, and also a great variety of gravitation cracks. Extensive ground failures could be observed along the crest and southern slope of the Chet-Korumdy ridge—here, most landslides had developed from previously existing ground instabilities.

It should be noted that only one large rockslide was triggered, the Belaldy rock avalanche (Korjenkov et al. 2004). It has covered a shepherd's family and a flock of sheep. The situation before and after the earthquake of the rockslide site is shown in Fig. 3. This mass movement had formed a dam on Jalpaksu River with a thickness of about 100 m, a width of 700 m, and volume of more than 40×10^6 m^3. Behind the dam two small lakes were impounded (with an area of 200–300 m^2 in September 1992). In less than a year, the water level had increased enough to induce partial failure of the dam (Korjenkov et al. 2004). This failure resulted in a 20 km long mud- and debris-flow, which caused a lot of damage for infrastructure of Toktogul region. The aerial photograph of 1996 of the Belaldy site (Fig. 3) shows the upper part of the debris flow just below the dam.

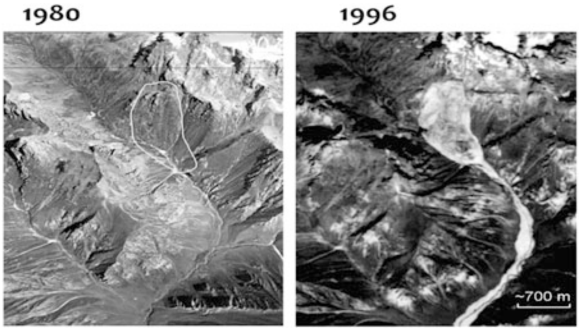

Fig. 3 The Belaldy rock avalanche. Aerial photographs before (*left*) and after (*right*) the Suusamyr earthquake

The Most Disastrous Regional and Singular Earthquake-Triggered Landslide Events

As shown previously, earth-flows in loess deposits and rock-debris avalanches proved to be the most catastrophic mass movements in Central Asian mountain regions. Therefore, the 1920 Haiyuan and 1970 Peru earthquakes were selected for comparison since they are known to have triggered, respectively, the most disastrous loess earth-flows and the most catastrophic single rock-debris avalanche.

On December 16, 1920, a M = 8.5 earthquake occurred near Ganyan Chi, Haiyuan County of the Ningxia Hui Autonomous Region in China (Zhang 1995). Several hundreds of thousands of houses collapsed and officially 234,117 people died. Zhang (1995) noticed that particularly high intensities were recorded over areas covered by thick loess deposits: '…areas with intensity of 8 … here the damage caused by the slides was more serious than the primary ones caused by the quake. Zhang and Wang (2007) report that about 100,000 people were killed by landslides in loess deposits. Dangjiacha landslide was one of the most catastrophic mass movements triggered by the 1920 earthquake. The landslide formed a dam with a volume of about 15×10^6 m^3. Behind the dam, the largest lake induced by the earthquake had been impounded. Zhang and Wang (2007) observed that loess earth-flows triggered by the Haiyuan earthquake had developed on relatively gentle slopes compared to those triggered by rainfall in the same region. These observations highlight the particular susceptibility of loess areas to ground failure, such as it was clearly shown by Derbyshire et al. (2000) analysing geological hazards affecting the loess plateau of China. The failure mechanisms of loess earth-flows and their connection with liquefaction phenomena will be analysed more in detail in the next section.

On May 31, 1970, the $M = 7.7$ Peru earthquake triggered one of the most catastrophic landslides that have ever occurred: the Nevado Huascaran rock-debris avalanche. This event is not only known for the large number of casualties it has caused, about 18,000, but also for its geologically fascinating aspects (Plafker et al. 1971). The huge mass of rock and ice with a volume of more than $50 \times 10^6\ m^3$ originated from the west face of the 6,654 m high north peak of Nevado Huascaran at some 130 km east of the earthquake epicentre. The particularity of this debris avalanche is its long travel distance of about 16 km. Before reaching the villages of Yungay and Ranrahirca, the mass slid for more than 2 km over a glacier, filled the valley floor at the foot of the slope and then was channelled through a gorge. Just before the end of the gorge, the avalanche split into two lobes one moving on towards the village of Ranrahirca, one overtopping the 230 m high southern ridge of the gorge and continuing its way to Yungay village. Peak velocities of this rock avalanche were actually estimated at more than 100 km/h (even to about 300 km/h by Plafker et al. (1971)).

Short Conclusions Based on the Case Histories

The Nevado Huascaran and the Khait mass movements show that volume, runout and speed are three important factors contributing to the impact potential of mass movements. The high speed of the Khait rock avalanche is also documented by the following notes from Solonenko (1977): '…Its rate was about 100 km/h… A powerful airwave went before the collapse. It broke constructions, uprooted trees and threw them down for hundreds of metres.' Further, the Khait rock avalanche is one of the largest (recent) runout mass movements in the Tien Shan. A debris flow developing from a dam breach may, however, have an even longer runout—about 20 km in the case of the partial Belaldy rockslide dam failure. Similarly, loess earth-flows are known to have caused rapid and long runout mass movements. For instance, in the Dzhalal-Abad region, Fergana Valley, Kyrgyz Republic, loess earth-flows had travelled over 7 km in 1994 killing several tens of people. Considering also the previous notes on geological disasters in loess deposits, we believe that earthquake and landslide hazards are particularly high in those regions of Central Asia, which are covered by several tens of meters of loess: the foothill regions of the Fergana Basin rim (Kyrgyz Republic and Tajikistan) and around the town of Dushanbe (Tajikistan) as well as mountain valleys covered by loess up to an altitude of 2,000–2,500 m.

However, a disaster such as the 1920 Haiyuan earthquake is not expected to hit any of those regions for two reasons: first, a $M > 7.5$ earthquake is very unlikely to occur in these areas; second, the loess cover is significantly thinner than on the loess plateau of China where the thickness can reach 300 m (Derbyshire et al. 2000).

Considering the enormous impact potential of massive rockslides, such as Belaldy or Khait, it is important to assess their occurrence probability. This probability is closely related to the recurrence time of the triggering earthquake (actually, only very few massive non-seismic rock avalanches are known from the Tien Shan)—but also other, climatic, aspects have to be considered as shown below. For the entire Tien Shan and Northern Pamir region, the analysis of Abdrakhmatov et al. (2003) showed that a return period of less than 20 years can be estimated for a $M \geq 7$ earthquake—able to trigger massive rockslides. Considering that the last $M \geq 7$ earthquake occurred in 1992, a rough computation of conditional probability indicates that there is a 90 % chance to exceed a 7-magnitude event within the next 10 years. The probability to have such an earthquake—and related mass movements—seems to be highest (with a chance of 90 % to exceed a $M = 7$ earthquake within the next 10 years) along the Tien Shan—Pamir boundary region, where the last $M \geq 7$ earthquake was the Markansu event in 1974 close to the Tajik-Kyrgyz-Chinese border.

Conclusions

A series of case histories of earthquake-induced landslides in Central Asia and a comparison with two worldwide known events have been presented. The volume and mobility (runout and speed) of the mass movements play an important role for related hazard and risk. In this regard, it is not surprising that the most disastrous mass movement known in Central Asia is a long runout rock avalanche with volume of about $40 \times 10^6\ m^3$, the Khait rock avalanche, which is supposed to have reached a speed of more than 100 km/h.

While these giant rockslides are almost exclusively triggered by large magnitude seismic events ($M \geq 7$) in Central Asian mountain regions, loess earth-flows may also be triggered by smaller earthquakes—or even by climatic factors alone. Here, we presented some examples of fatal loess landslides triggered directly by an $M = 5.5$ earthquake in Tajikistan and we know a series of landslides, which developed even during or after local $4 < M < 5$ earthquakes. The comparison with the Haiyuan earthquake event of 1920 showed that such loess landslides could be very disastrous.

For loess earth-flows, the high impact potential is, however, not only related to the volume and mobility of a single landslide—which are generally lower than that of massive rock avalanches. Here, the high spatial and temporal occurrence probabilities clearly contribute to related risk. The 1920 Haiyuan earthquake triggered thousands of loess earth-flows. $M > 7$ earthquakes able to trigger at least hundreds of landslides occur almost every 20 years in the Central Asian mountain regions—many of which are covered by several meters of loess, especially in the foothill areas.

The importance of mid- and long-term effects can be outlined both for rockslides and loess landslides. Several case histories showed that one important—if not the most important—long-term consequence of massive rockslides can be the formation of a dam and the impoundment of a natural reservoir. Actually, the largest still existing rockslide dam on earth had formed in 1911 in the Pamir Mountains. The worst-case scenario flood wave triggered by dam failure could affect more than 5 million people living in the Amu Darya river basin.

For many loess landslides, it can be shown that seismic ground motions must not necessarily be the final trigger, but could also be a preparatory factor of slope failure. Relatively weak seismic shaking (e.g. <0.1 g) is able to produce ground fractures, but often without inducing a mass movement. However, these ground fractures can facilitate water infiltration and related increase of groundwater pressures, which could lead to slope instability.

In this regard, it should be emphasized that similar earthquakes may not necessarily trigger the same amount of landslides, due to different climatic conditions and groundwater level at the time of the earthquake: the $M = 6.6$ Nura earthquake in 2008 triggered relatively few landslides due to the occurrence at the end of the dry summer season. Thus, predicting the total hazard of earthquake-triggered landslide events, both seismic and climatic effects have to be taken into consideration. Some local seismic effects have been highlighted, notably amplification of shaking by convex surface morphology and surficial soft materials. Recent works by Chinese colleagues had clearly proofed the morphological effects on the seismic triggering of landslides for the last 2008 Wenchuan earthquake, China.

Finally, the case histories showed that related landslides were not only instantaneous effects of earthquakes—some had already developed before the seismic shock and some continued or started moving well after the shaking. To better assess the short- to long-term effects earthquakes on slopes, landslides need to be monitored by geophysical, seismological and geotechnical systems, coupled to multi-temporal satellite imagery and numerical modeling of multi-event scenarios. In the frame of new projects on landslide problems in Central Asia, focus will be on the installation of such monitoring—modeling systems.

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