Evaluation of Landslides in Uzbekistan Caused by the Joint Impact of Precipitation and Deep-Focus Pamir-Hindu Kush Earthquakes

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Abstract

This paper presents the results obtained during implementation of the IPL-146 project "Spatial monitoring of joint influence of an atmospheric precipitation and seismic motions on formation of landslides in Uzbekistan (Central Asia)". In studying the effect of seismic events on the time, place and mechanism of development of landslides and mud flows in Uzbekistan, special attention is given to deep Pamir-Hindu Kush earthquakes. According to the catalogue of earthquakes for the period from 1960 to 2010, 655 earthquakes with $M > 4.5$, with long durations (1.5–3.0 min) and low-frequency vibrations, occurred in the spring months (February–June). Comparing the dates of landslides formation and earthquakes revealed 56 possible earthquake-triggered landslide sites. The mechanism of landslides and their subsequent development after the earthquake are discussed. Post-earthquake inspection and monitoring are also valuable because earthquakes can trigger new or renewed slope instabilities.

Keywords

Large-scale landslides · Earthquakes · Triggering mechanism · Case study

17.1 Introduction

Many authors attribute the triggering factor for many landslides to short, intense rainfall (Wieczorek and Glade, 2005), often associated with certain amounts of rainfall before the event. Most authors agree that rainfall-based techniques for determining landslide hazard are valid in a specific geological-geomorphological-climate context but cannot be applied directly to other situations. The formation of local large landslides is usually influenced by processes both in the atmosphere (climatic) and within the earth's crust (antecedent groundwater conditions, seismicity). In the vast majority of cases, the beginning of landslide displacement is not an evolutionary but a revolutionary process. Revolutionary changes take place when the accumulation of quantitative changes in the characteristics of the conditions reaches a critical value and there is a qualitative transition of the rocks from a solid to a liquefied state.

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In Central Asia, large landslides and mudslides that formed during the Faizabad (1943), Khait (1949), Sarez (1911) and other large earthquakes have been studied thoroughly. However the role of deep Pamir-Hindu Kush earthquakes in the formation of landslides, liquefaction, extrusion and other types was never considered, because the earthquakes occurred at a distance of over 500 km and were of low intensity (3–4 MSK intensity units).

In Uzbekistan, the influence of local earthquakes in the formation of landslides has gained little attention, mostly because the studies focused on the role of rainfall and groundwater in the formation of new landslides. In the period from the 1990s, from the experts of the State Service of Monitoring for Dangerous Geological Processes, information began to appear that during the formation of landslides (Niyazov and Nurtaev, 2004) the local people could feel vibrations of the earth's crust. Unfortunately, this factor has been neglected, since the vibration intensity was only 3–4 MSK intensity units. Yet, there have been some doubts – it is very difficult to explain why a mass of rock with volume of 2–20 million m^3, in few minutes, was able to split so evenly, or how such a quantity of water could simultaneously appear on the surface of the landslide, or what energy is required to form large graben-like depressions in the upper stretching zone, and bulging ridges below in compression zones in gullies.

The aim of this paper is to present the results obtained in implementing IPL-146 project "Spatial monitoring of joint influence of an atmospheric precipitation and seismic motions on formation of landslides in Uzbekistan (Central Asia)". We evaluated the role of the joint influence of rainfall and long, low-frequency deep Pamir-Hindu Kush earthquakes in the time, place, scale and mechanism of development of modern landslide processes to identify factors determining the starting time of landslide movement.

The Pamir-Hindu Kush zone of deep earthquakes is a permanent seismic source. Here in the central part of the continent, within a fairly small area (about $60-70\,km^2$), there is an extremely high level of seismicity at depths ranging from 70–300 km. Every year in this region, more than 200 earthquakes occur at depths of 200–250 km. Some of them reach magnitude 7 or more; the intensity of motions in Afghanistan is up to 9 MSK intensity units. In Central Asia, the intensity of the motions from these earthquakes is not more than 4–5 units, but they are characterized by a long duration and low-frequency spectrum of vibrations. The focal zone of these deep earthquakes is a band 100–150 km in width and 600 km in length, extending along the boundary of the Eurasian and Indian plates from southwest to northeast, from near the city of Faizabad in Afghanistan to Khorog in Tajikistan (Lukk, Nersesov, 1976). Such zones in the continental lithosphere, which are relics of oceanic subduction zones, are known in Spain, Romania, Burma, Colombia and Afghanistan. For the Hindu Kush, the most active depths are 80, 100, and 180–240 km. There, for the Hindu Kush and the entire zone, the level of seismic energy released at a depth of 180–240 km, is around 3–4 times higher than in the upper seismic horizon (Fadina, 1986). For the Hindu Kush, the number of events is 5–6 times higher than for the Pamir. The spatial distribution of earthquake foci is very complex, due to the collision of two plates – Eurasian and Indian.

Due to attenuation with distance from the earthquake source, high-frequency vibrations pass into the low-frequency, lasting from 1.5 to 4.0 min. According to the Hindu Kush earthquake catalog of Berkeley (USA), during the past 50 years (1960–2000) 2208 events with $M > 4.5$ were recorded, of which 655 occurred in the spring. Values of precipitation and number of Hindu Kush earthquakes ($M > 4.5$, depth > 180 km), for one year and in the spring season are presented in Fig. 17.1.

17.2 Evaluation of the Joint Influence of Two Spatial Factors in the Formation of Landslides

Landscape sensitivity, the degree to which a landscape can cope with rates of change, should be considered as a consequence of combined changes in the preparatory factors (e.g. precipitation events, antecedent groundwater conditions) and triggers (e.g. seismic vibrations at this time). Relationships between rainfall patterns and slope instability are reported in the literature for a range of slope failure mechanisms and climates. These studies demonstrate the importance of considering the likely impact of future climate change on slope

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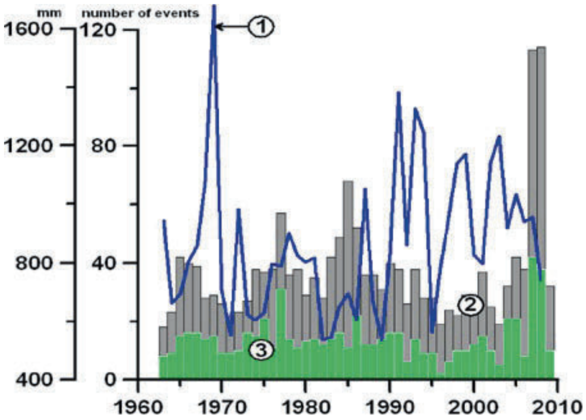

Fig. 17.1 Diagram showing (1) precipitation in mm, (2) number of Hindu Kush earthquakes with $M > 4.5$ in one year, depth > 180 km and (3) the number of Hindu Kush earthquakes in spring season

instability. However, triggers and antecedent rainfall thresholds are highly specific for particular sites, regions and materials, and therefore studies reported in the literature cannot be used as a guide to future behaviour of landslides in regions with different climates and triggers.

The mechanism by which climate change may cause the increased number of landslides at the turn of the twenty-first century is related to the increased frequency of turnover of wet and dry years, including the number of years when the amount of precipitation in a preceding period between November and February was more than 550–600 mm. In March–April heavy rainfalls of 30–40 mm fall more often, with an intensity of 8–15 mm/hour. There are more cases where rainfall over two to three days is 90–110 mm. This large volume of precipitation is enough to saturate the soil or weathered rock and raise the water table, thus contributing to many soil (debris) flows and making steep slopes more likely to fail during earthquake shaking (Niyazov, 2009).

The seismic impact was determined from the parameters of amplitude, dominant frequency and duration of vibrations. The latter factor could be decisive for the stability of slopes in the wet spring season, but short-duration shaking, even with very high acceleration, may not be dangerous. Therefore, large amount of precipitation or severe earthquakes in this region may not cause landslides, or alternatively may form several landslides, or even several hundred (Emelyanova, 1972). Much depends on whether the slope has reached a critical state of stability.

Seismically generated landslides usually do not differ in their morphology and internal processes from those generated under non-seismic conditions. However, they tend to be more widespread and sudden. Almost every type of landslide is possible, including highly disaggregated and fast-moving falls; more coherent and slower-moving slumps, block slides, and earth slides; and lateral spreads and flows that involve partly to completely liquefied material. The effect of two separate spatial factors, rainfall and earthquakes, on the time and place of formation of the landslide, produces a very complex relationship. Changing seasonal conditions of moisture saturation of slopes can increase their susceptibility to seismic vibrations (Keefer, 1984).

The earthquakes in the mountainous areas of Uzbekistan initiate long-duration (1.5–3.5 min) low-frequency (1–5 Hz) oscillations in the spring on wetted slopes, beginning the initial process of subsidence, liquefaction of rocks and disturbed conditions of groundwater discharge. Landslides, mudflows, and sinks caused by Hindu Kush earthquakes are hazardous due to their suddenness of formation, and many can form in different places at the same time. It is thus impossible to predict their place and time. The recent landslides usually form within the boundaries of ancient landslide hollows. The volumes of landslides triggered by seismic vibrations vary from 70,000 m^3 to 800 million m^3, more frequently being from 200,000 to 300,000 m^3.

The earthquakes occur at a distance of 500 km and more from Uzbekistan and are characterized up to 10 events of $M > 4.5$ in the spring, recorded by many seismic stations of the Institute of Seismology AS RUz. For example, typical records of earthquakes of various magnitudes are given for seismic station Samarkand (Fig. 17.2). The mountainous territories of Uzbekistan are located at distances from 250 up to 570 km from the epicenter of earthquakes. Landslides mainly occurred in the Surkhandarya and Kashkadarya regions (southeastern parts of the republic) at distances of 250–350 km, and in Tashkent region, at 530–570 km, from the epicenters.

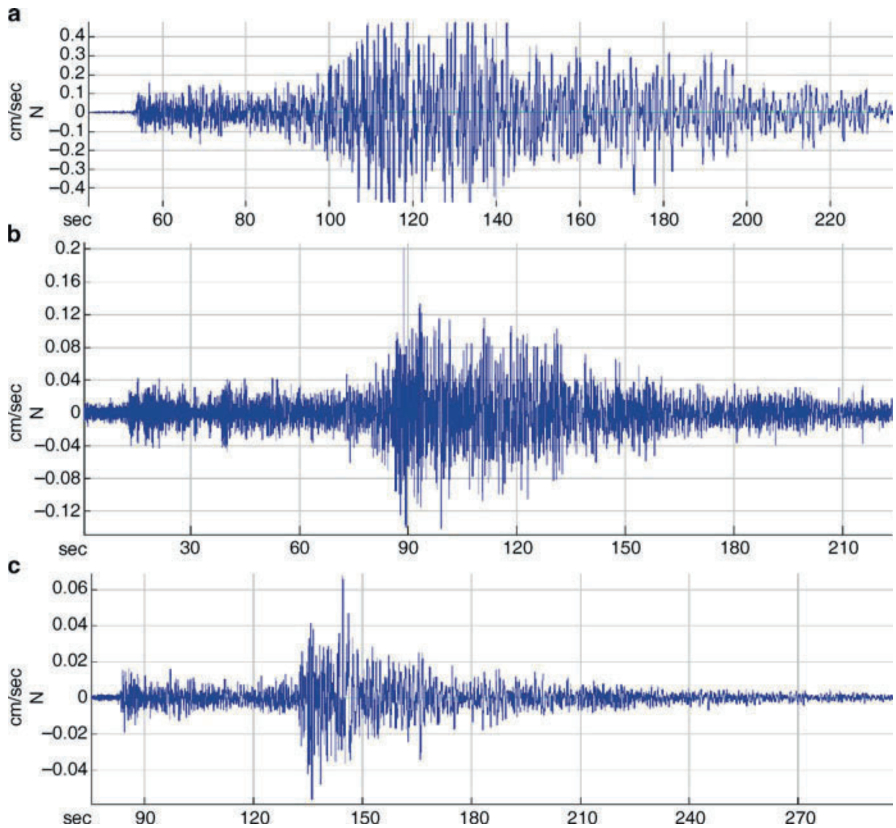

Fig. 17.2 Sample records of Hindu Kush earthquakes, seismic station Samarkand: **a** 3.04.2007, $M = 6.2$; **b** 28.04.2007, $M = 5.0$; **c** 9.04.2009, $M = 4.6$

17.3 Evaluation of the Mechanism of Landslides Influenced by Low-Frequency, Long-Duration Seismic Vibrations

The mechanism of displacement of landslides during earthquakes is characterized by almost simultaneous deformation of rocks throughout the landslide area. Liquefaction of soils occurs in thin layers inside the massif or the entire mass, with the simultaneous appearance of a large amount of water on the area of the landslide. At some sites, the first signs are temporary springs, cracks, and settling of the ground surface above cavities, i.e. there is first a vertical deformation, which disrupts the movement of groundwater. Then, there is subsurface erosion, the water issuing from springs becomes turbid, and within 5–10 days flows occur. Under the influence of low-frequency, long-term seismic vibrations, landslides such as block slides, liquefaction and mud flows are generated.

For extrusion types of landslides, the beginning of their formation is always associated with a seismic shock. These are deep, long, large-scale landslides with bulging ridges in the floodplains of gullies and a graben-like wall of separation at the top of the slope. They are formed in old and ancient landslide hollows.

Angren is one of the characteristic areas of deep landslides in Uzbekistan. Angren coal mine is spread over 10 km. Coal mine dumps, from 200 to 2500 m in length and with heights from 20 to 65 m, are located downstream, and extend directly onto the riverbed of Akhangaran. In the central part of the slope is an operating coal mine and underground coal gasification plant. There, eight major landslides, with volumes of 20–25 million m^3 (Niyazov, 2009), were formed in the period from 1950–1969.

In 1972, on the left bank slope of the river Akhangaran, the largest landslide-extrusion Atchi (Fig. 17.3), began to develop. The formation of Atchi landslide is related to the expansion of displacement that was formed over the past 17 years. Degasification of a 5–15 m thick coal layer at a depth of 100–130 m in the middle of the slope, within an area of about 1.5 km^2, created a cavity, with a subsequent lower-

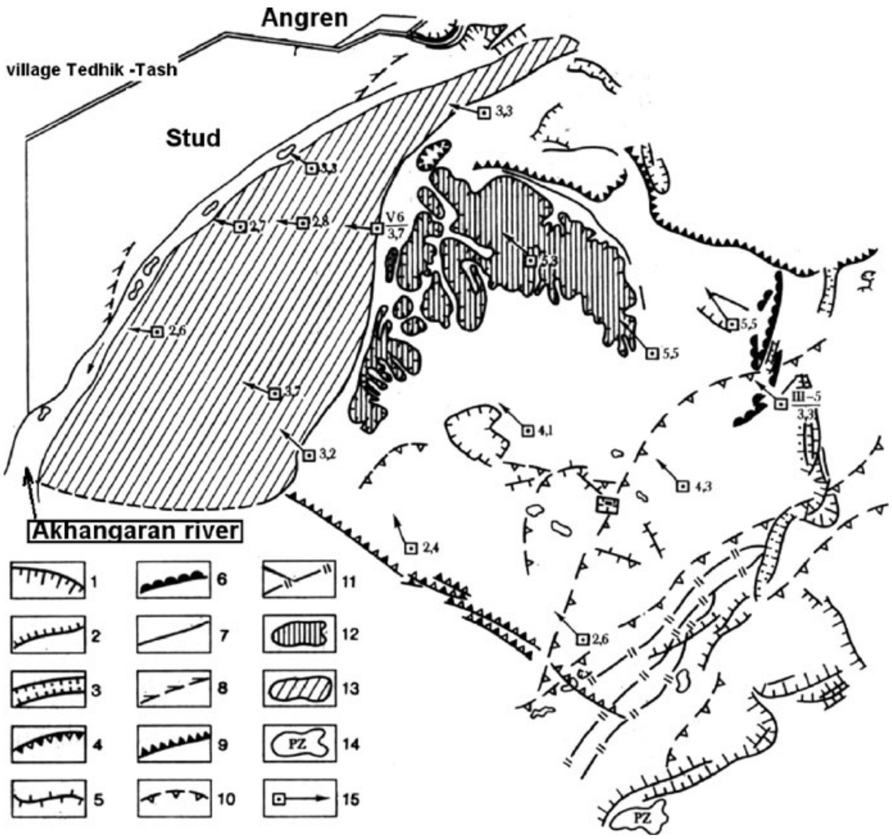

Fig. 17.3 Scheme of Atchi landslide 1) slip band; 2) slip boundary; 3) downdip blocks; 4) shear and subsidence cracks; 5) sliding cracks; 6) compression-shear cracks; 7) yielding cracks; 8) flow ground bank; 9) ancient landslides; 10) thrust fracture; 11) faults by geophysical data; 12) zone of underground gasification; 13) waste dump; 14) Paleozoic outcrops;15) benchmarks, arrows showing direction of movement

ing of the ground surface by 5 m. This resulted in the loss of lateral support of thick Cretaceous and Paleogene rocks located above the slope and to a change in the groundwater regime, resulting in the formation of Atchi landslide, with an area of 8 km^2, an average depth of 100 m and a volume of 800 million m^3.

On the right bank, in the village of Teshik-Tash, within a terrace, a bulging ridge appeared, destroying residential buildings, and deforming the road, river, channel and bridge.

The first cracks and deformations of high-voltage transmission towers were found in the upper part of the slope (1450 m a.s.l.) in the spring of 1972. Large cracks and graben-like sinks appeared in loess.

In April 1973, the landslide moved into an active phase of development on the right bank of the river, forming bulging ridges and starting to deform houses in Teshik-Tash village, and breaking the railway and road, channels, and a coal slurry pipeline. The development of the landslide could cause it to overlap the Akhangaran riverbed, with destruction and flooding of the village (13,000 inhabitants), the destruction of railways and deformation of the pit shaft.

From 1974 to 1986 extensive studies have been made of the mechanism and movement dynamics of the landslide area, and on the development and implementation of complex measures for managing and stabilizing the biggest landslide without stopping the existing energy producing businesses within its range (Niyazov, 2009). Control geodetic observations have been carried out for 36 years and are currently continuing (Fig. 17.4).

However, nobody paid attention to the role of the dynamic factor that triggered the early deformation of rocks. Loss of lateral support to a depth of 130 m, loss of support in the middle of the trough created by subsidence caused by underground coal gasification, within an area of 1.5 km^2, high hydrostatic pressure of groundwater in the Cretaceous-Paleogene deposits of high mine dumps created critical conditions for the stability of the slope. But, some dynamic impact for the simultaneous formation of various cracks over an area of 8 km^2 was necessary. In our opinion, that factor

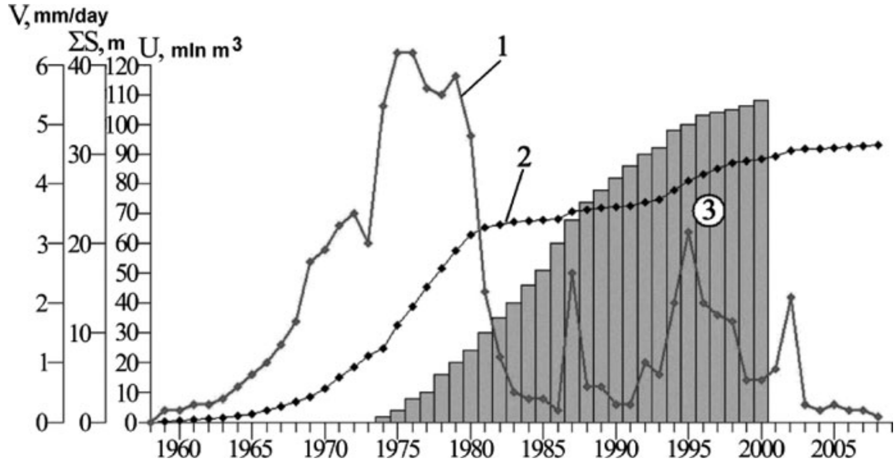

Fig. 17.4 Diagram of rates of displacement of Atchi landslide 1) landslide displacement rate; 2) general value of displacement; 3) volume of buttress dumping

may have been deep earthquakes in the Pamir-Hindu Kush zone. In 1972, at the time of formation of Atchi landslide, a series of earthquakes occurred on January 20 (at a depth of 213 km and $M = 6.0$) and February 22 ($M = 5.4$).

The first activation of Atchi landslide in April 1973 may also be related to the series of earthquakes that occurred on 8th, 10th, 12th, and 25th April at a depth of 136–230 km with $M = 4.7-5.2$. The second activation of the landslide occurred at the end of September–October 1973, perhaps and can also be related to earthquakes, because on 22nd, 25th, 26th September and 26th October there have been four events with $M = 5.0-5.5$. In 1973, there were 11 earthquakes with $M > 5.0$ in Hindu Kush.

Another large landslide, extrusion Kamar, with a volume of 60 million m^3, was formed as a result of the earthquake of May 7, 1993 (Fig. 17.5). The landslide formed on the left side of Tanhozdarya River on a steep (22–24°) slope up to 300 m high. The zone affected by the displacement has a width of 930 m along the channel, with a length of the slope of 1100 m. Neogene clays and sandstones of the Shurhan thrust were involved in the movement. In the lower zone, there was soil liquefaction and as a result, an ancient landslide remobilized. In the upper part, a graben-like depression was formed, with an extent of 500 m, a depth of 15–28 m and a width of 30–40 m, which indicates a deep slip zone. A bulging ridge with a width of 30–40 m and height of 0.6–0.8 m, was formed on the flood plain of the gully.

The Kashkadarya foothill zone had a wet spring in 2009 – in March, 116.8 mm fell and in April, 172.0 mm. A landslide caused by a Hindu Kush earthquake was recorded at one site on the Hisorak-Sarychashma road. In April, two earthquakes occurred: on April 9, 2009 ($M = 4.6$) and on April 17, 2009, ($M = 4.5$). Landslide cracks were first found on 18 to 19 April. The most active landslide movement occurred between 19–22 April. This resulted in the landslide-extrusion formation, located on the right bank of Tamshush river. It formed within an ancient landslide scar, on a slope with a height of 110–130 m, with a step-like form with flat surfaces in the middle and lower slope. The landslide was up to 300 m long, 160–150 m wide and had an area of 400 m^2, the

Fig. 17.5 Photo of the Kamar landslide

thickness of the rock that shifted on average was 10 m, and the landslide volume was 4 million m^3. Neogene loess soils with siltstone, sandstone and shale were involved in the movement. In the riverbed of Tamshush, a bulging ridge arose, with a length of 40–45 m and a height of 30–50 cm. The height of the headscarp of the landslide in the central part is 6–8 m, and on the left side up to 10–12 m. The surface of the steps is covered by a series of block cracks with an amplitude from 0.3–1 m and a length of 20–40 m. The landslide destroyed the roadbed for 200–250 m.

Landslide-extrusion Karakishlok is located on the right side of Kichik Uradarya River. The landslide occurred at the boundaries of an ancient landslide on a gentle (4−12°), low (50 m) semicircular slope. Loess soils with high content of clastic rocks (30 %) with interbedded sand and clay up to 8 m thick, have been involved in the movement. The displacement of rocks occured in Paleogene clays. The landslide has a length of 340 m, a width of 200 m, an area of 68,000 m^2, an average depth of displacement of 5 m, and a volume of 350,000 m^3. On April 11, 2010, between 7:00 and 21:00 hours, 32.9 mm of precipitation fell, which was heaviest between 20:00 and 21:00 hours. As a result, in the Kichik Uradarya river valley, the water level in the channel rose by 1–1.5 m, which led to the washing out of the toe of the slope in the area of landslide overnight for up to 300 m with height of 2–3 m. On April 12, a Hindu Kush earthquake ($M = 4.5$) occurred. As a result of the joint influence of precipitation, the undermining of the base of the slope and the earthquake, renewed displacement of landslide extrusion Karakishlok occurred.

Local residents in the early morning saw the beginning of the deformation of rocks on the slope and watched the formation of transverse cracks on the slope. Horizontal displacement of rock in the upper zone was 2–3 m, and in the middle and lower zone was 1.2–1.5 m. A bulging ridge more than 120 m long and with a height of up to 0.5–0.8 m was formed in the river bed. The landslide covered 2 homes, a pumping station, 300 m of roadbed and 12 supports of a local power line.

Block landslides often occur on slopes where its toe is washed out or cut. As a result of seismic motions, liquefaction occurs at 30–60 cm depth in the zone of sliding where impermeable flat-lying (5−10°) sand-clay rocks on the plastic clay, are found. Block landslides are characterized by the simultaneous displacement of the rocks throughout the area and uniform fragmentation of the landslide. The nature of the motion is not uniform and shows seasonal peaks during the period of maximum groundwater level.

In 1995, on May 16, a Hindu Kush earthquake with $M = 5.9$ at a depth of 189 km occurred. It has been recorded by many seismic stations in Uzbekistan (Tashkent, Samarkand, Gazli, etc.). Its intensity in the Angren area was 3–4 units and the duration of felt motions was around 2 min. Seismic effects of long low-frequency vibrations resulted in liquefaction of a 1.5–2 m thick Paleogene layer of water-saturated sand-clay rocks and squeezing at the working face of the Naugarzan coal mine. Thus was formed extrusion landslide of 25 million m^3, with a length of 580 m. The landslide can be divided into three sections based on its geological structure. The first – top, where the slip involved loess up to 20 m thick in contact with a zone of Paleozoic weathering. Second – middle section, above the quarry, where the displacement occurs on weak sandy-clayey water-saturated rocks of the Paleogene, and the third – the western section, where the zone of sliding is deeper into the kaolin clay crust, with a thick sequence of gravel at the base of the slip zone. In the first 3–4 days, the rate of displacement in the upper section was 370–840 mm/d, and in central part of the western section 880–960 mm/d. The rate of displacement of the Western (left) flank consistently increased from 56 to 408 mm/d over 20 days. After 65–70 days, it decreased to 31–40 mm/d in the central and up to 22 mm/d at the bottom of the western section. Overall, the slip in the period of active development (May, 1995–1996) in the central part of the landslide was 26–27 m (Niyazov, 1999). In spring 1999 it began re-activating, when its speed rose from 12.8 to 50–70 mm/d. The displacement from October 1998 to April 2001 in the top was 6–7.7 m, in the middle was 4.3–4.8 m and at the bottom was 5.6 m. In general, the rate of displacement of the upper block was 1.3–1.5 times higher than the rate of displacement of the lower, developed on it and squeezing out the western flank. Overall, the slip exceeded 40 m. At present, the landslide is in a state of active movement.

In 2004, March 12, a Hindu Kush earthquake occurred at a depth of 218 km, $M = 5.8$. At the same time, on the left bank of Uradarya river, in the hollow of an old landslide, a block landslide with a volume of

Fig. 17.6 Khandiza block landslide site

$576{,}000\,m^3$, was activated in the western margin of the village of Kushkul. The main type of deformation was numerous cracks in loess with lengths of 10–25 metres and widths of 0.2–0.3 m. The deformed zone was over 200 m long, with a width of 180 m, and with a slip zone depth of 10–16 m.

The trigger that caused the displacement of the Khandiza block landslide on April 25, 2008, perhaps was an earthquake in the Pamir-Hindu Kush region (April 25, $M = 4.9$). The block slide occurred in loess with a thickness of 12–15 m, in contact with loamy shale of Jurassic clay on a 70 m high slope of 30°. The landslide is triangular in shape, widest (70 m) at the bottom. Its length is 70 m and width, 50 m on average. The volume is $525{,}000\,m^3$ (Fig. 17.6). The surface of the landslide was within a few minutes covered with a series of vertical, tension and shear fractures. The top and right side of the landslide have the highest scarps (4–7 m) and a wide graben-like depression with longitudinal cracks up to 10 m deep and 12–20 m long.

The landslide occurred in an industrial construction site. At the base of central part of the slope, over a width up to 30 metres, a high (10–12 m) cut was made into the slope, which disrupted its stability. The trigger that caused the slide was perhaps a deep Pamir-Hindu Kush earthquake (April 25, $M = 4.9$). According to the incident review, an excavator had unloaded the landslide toe. At 17 h, after the end of the day, the driver left the excavator at the foot of the excavated slope. After 20–30 min he was called to move the excavator to a safe place, since rocks had started to fall from the slope. Some witnesses gave information about the mechanism of the landslide – at first a crack appeared, delineating the boundaries of the landslide, and at the same time there was a vertical displacement that formed a head scarp with a height of 5–7 m. A variety of tension cracks appeared in the landslide, but the boundary of the hollow has not changed.

In February 28, 2010, in Kashkadarya submontane zone, the block type Modmon landslide (Fig. 17.7) occurred. Its timing followed an earthquake in the Hindu Kush region on February 27, 2010. The earthquake, with $M = 5.7$ in Uzbekistan, had an intensity of 3–4 units for up to 3 min. Displacement of loess with a thickness of 5–7 m occurred on the slope, which was ca. 25–30°, and had a height 70–80 m. The landslide is 150 m long, 35–40 m in width at the top of the zone and 90 m at the bottom, with an area of $10{,}000\,m^2$, thickness of displacing rocks 5–7 m, and a volume of $60-70{,}000\,m^3$.

The landslide has a cirque-like form, the height of the head scarp is up to 3.0 m and the lateral boundaries 0.2–1.0 m. The whole area of the landslide developed a series of transverse cracks over 20–25 m, with amplitudes of 0.2–0.5 m. The landslide was a first-time failure occurring all at once. The deformation was mostly vertical, while the horizontal movement was small and mostly in the lower zone. The cause of landslide was a combination of moisture in the rocks during the snow melt, increase of water flow in springs, washout of the slope base by runoff and earthquake motions.

Landslides of liquefaction are formed by long-term seismic vibrations, when loess and sandy-clay soils are already moist at the time of the earthquake and there is a water-bearing horizon with low permeability. Liquefaction occurs throughout the rock mass, with the simultaneous appearance of water on the surface of the entire area of the landslide. After 10–20 days the water is absorbed and soil compaction occurs with the stabilization of the landslide. This is one of the main characteristics of these landslides (Niyazov and Nurtaev, 2010).

A landslide in the village of Tally (Kashkadarya) is associated with an earthquake on March 5, 1969 ($M = 6.6$). According to eyewitnesses, the flow from springs sharply increased at first, forming a sinkhole with a diameter of 2 m in the middle part that later reached 60 m. The movement began in Cretaceous clay

Fig. 17.7 Photo of Modmon landslide

rocks higher and lower on the slope. The sinkhole was then completely filled. The amount of mass displaced was up to 0.4 million m^3, with a length of 550 m, and width from 70 to 150 m. The landslide moved slowly, with fragmentation of the surface. In the final stage, ground flowed across the stream's alluvial fan (which is connected with soil liquefaction).

This earthquake also triggered the Suffa landslide, with a volume of 0.4 million m^3, formed on the right side of river Igrisu (Kashkadarya). According to available data, on March 6, 1969, springs with flow rates up to 0.1–0.2 l/s appeared in the middle of the slope in an area of houses in the upper village. Initial soil displacement began on March 7, with the appearance of hillocks swelling up along the slope. A few hours later cracks appeared, and the whole mass began to move, without inversion of layers, and at the bottom began to form small mounds. Landslide movement was slow and continued for four days. The landslide had a length of 500 m, a width at the top of 300 m, and below of 80–120 m, and a depth 5–6 m. A mass of mud moved 50 m and the thickness of debris at the bottom reached 10–12 m. Eleven farms were destroyed.

As a result of a Hindu Kush earthquake on May 30, 1998 ($M = 7$), Tashbulak landslide, with a volume of 360,000 m^3, occurred in the basin of the Tanhozdarya river, in the Kashkadarya area. According to the locals, the time of the earthquake and landslide liquefaction coincided. In the village, the earthquake was felt with an intensity of 3–4 units, and there were long horizontal motions. The mud flow was within the old landslide scar in the sandy-clay rocks. The landslide had a length of 330 m, an average width of 100 m, and a depth up to 10 m. The movement of landslide was accompanied by intensive fracturing and abundant groundwater outflow. The maximum speed for 3 h was 1–1.2 m/h, and then within days 10–15 m/d and the next two days 3–5 cm/d. The displaced mass temporally blocked the Tanhozdarya riverbed.

On February 25, 2005, there was an earthquake with $M = 6.1$ at a depth of 114 km. The active edge of the ancient landslide Beshbulak (after the 1907 Karatag earthquake), which has a volume of 280 million m^3, extends 4 km and has average width of 3.5 km (Fig. 17.8) is one of 13 major slides along the front of the Beshbulak thrust. In March 2005, two major landslides occurred. The first landslide, block-shaped, was on the eastern margin, with a width of 740 m and length of 550 m. The entire area is divided into many blocks with heights from 0.5 to 2 m, and is covered with small lakes and karst-like sink holes. Second, a liquefaction landslide occurred in the southwestern part of the ancient landslide, with an area of 2 km^2 and a volume of 33 million m^3; it moved up to 60 m until March 21 (26 days after the earthquake). The total length reached 2.4 km, with a width of 1 km, and the movement involved sandy rocks with an average thickness of 15 m.

Fig. 17.8 Photo of landslide liquefaction Beshbulak

On May 5, 2009, on the right bank of the Sangardak river, a liquefaction landslide, Chaknak 2, with a volume of 1.5 million m^3, was formed during an earthquake of $M = 4.7$. Loess rocks with a thickness of 15 m were cut by numerous cracks filled with water over a distance of 500 m. During the period from 6 to 11 May, the landslide displaced to 10–11 m. There were two springs flowing at a rate of 0.1–0.2 l/s from the toe. Within 10–12 days, the landslide movement stopped.

Mudslides are widespread in the loess, and present the greatest damage and threat to human life. They are extremely dangerous due to their sudden motion in few minutes at high speed and large distance of displacement (up to 4.5 km). When the landslide mass collides with the bottom of the valley or canyon, it loses its structure, and gains powerful dynamic momentum. In plan they have a glacier shape, and the rock mass is fragmented and liquefied and moves like a viscous fluid. The movement of the landslide mass is in pulses – the initial rate is much higher than the final, and the average velocity varies sharply along the length of the flow. The nature of their development is very diverse, and they are characterized by both landslide and mudflow processes. The headscarp is characterized by a steep slope, with a clean smooth surface contour and smooth edges, which is characteristic of a first-time simultaneous displacement of the entire mass following seismic shaking.

Formation of the Chimgan landslide-flow, with a volume of 0.24 million m^3, was related to an earthquake on May 21, 1969 ($M = 5.8$). One day before the landslide, there were no indications of probable movement. Loess rocks, with a thickness of 15 m failed at the contact with clays and silts of the Paleogene-Neogene deposits, and flowed catastrophically quickly in the form of a stream for a distance of 250 m, destroying buildings in a recreation area.

Two $M = 5.5$ earthquakes 38 min apart occurred on June 10, 1969. As a result, in the basin of river Gulkam (Tashkent region) and in a number of parallel small canyons at the same time, there were two mud flows – Mazarsay, with volume of 0.7 million m^3 and Gulkam, 2 million m^3. The entire mass was highly liquefied, which allowed it to escape from the source area through the narrow neck of a gully and move in the form of a mud flow for a distance of 3.1 km.

The typical area for the mass occurrence of loess-flow landslides is the Gushsay-Guldarama area (Tashkent), where over a ten-year period from 1994 to 2005, more than 20 individual landslide flows, were formed (Fig. 17.9). The main feature of these slides was that they were confined to the upper reaches of gullies around the boundaries of the watershed. In each gully, 3–4 fan-shaped landslide basins were formed, which is not observed in other landslide areas. In practically all sites on the slopes there were large landslide cracks at the beginning, which then after a few years or months developed into landslides. Pamir-Hindu Kush earthquakes in this area played a major role in the formation of the large cracks and predetermined the development of the landslides.

On April 23, 1994, in the uppermost part of the Tokberdy region (Tashkent area), a landslide flow with a volume of 70,000 m^3 occurred from a 170 m high, steep slope (35°), with a loess thickness up to 10–12 m (Fig. 17.10). The headscarp of the landslide occurred along a crack formed in 1991, with a width of 80–90 m, and a length of 100 m. The landslide mass, which has spread to the opposite side of the gully, has a height of 30 m and a total length of 350 m, and it covered res-

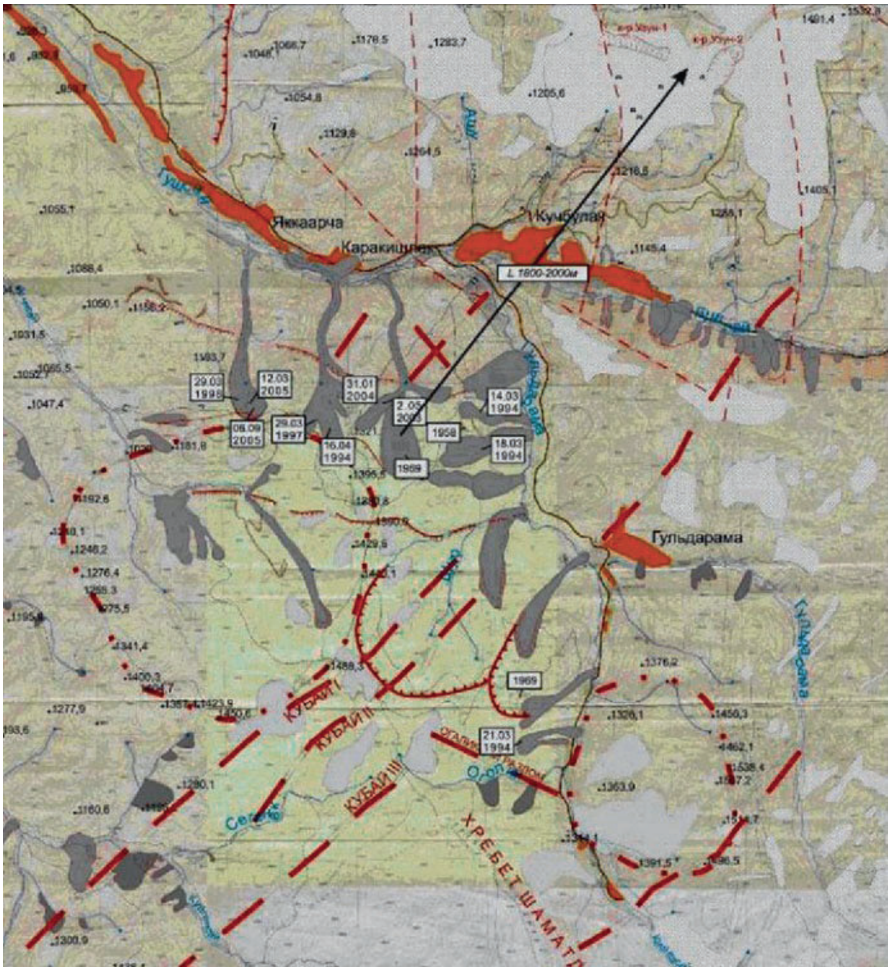

Fig. 17.9 Map of landslide locations in the basin of Gushsay River

idential buildings, from which the residents had been evacuated in advance.

The time of the initial landslide initiation, in our opinion, was the Pamir-Hindu Kush earthquakes that occurred on April 22, 1994 ($M = 4.4$). On April 23, staff of Angren monitoring station observed extension of the crack and informed the residents. The landslide occurred 8 h after the earthquake.

The second landslide-flow occurred on April 23, 2004; it had a volume of 200,000 m^3. Displacement of loess occurred from the existing crack to a distance of 560 m, with a width of 150–240 m, and spread to the opposite side up to a height of 25 m. The flow blocked the riverbed of Gushsay to a height of 5–7 m. The resulting blockage had been washed away within an hour; the water flow in river was 3 m^3/s. The trigger of the landslide was probably an earthquake, which occurred on the April 23, 2004 ($M = 4.7$). Two men who were passing below the slope at the time remain buried under the rubble.

We link landslide Shohkutan (Surkhandarya), with a volume of 2 million m^3 with a Hindu Kush earthquake on March 21, 1998 ($M = 6$). Strata of sand and clay soils, overlain by loess with a thickness of 10–14 m, was involved in the movement. As a result of liquefaction, a mud flow was formed, with a length of 750 m, temporarily blocking the riverbed. The landslide was 250 m long, and 300 m wide, the steepness of the slope was 25−30°, and the height was 250 m. In the area of the headscarp there were 5 springs with a total discharge of 3 l/s. The landslide headscarp is steep (80−85°), clean, and smooth, features that characterize first-time displacement.

An earthquake in the Hindu Kush on April 5, 2004, at a depth of 187 km ($M = 6.6$), is connected with the formation of the Sangenek landslide. A landslide-

Fig. 17.10 Photo of the two landslide – flows at Tokberdy. One from 1991, the second in 2004

flow with a volume of 300,000 m^3 appeared on the left bank of a gully, on a slope with a height of 210–220 m and a dip of 40–45°. The separation wall, with a height of 12–15 m, occurred in the upper part and had a width of 150 m and a length of 180 m. In the head-scarp area there are no springs; the entire mass of soil moved almost simultaneously, spreading 30 m thick to the opposite side at distance of 350 m. The loess was moist and highly fragmented, but not in a flow state. In the gully riverbed a temporary dam was formed, up to 3–5 m high and 40–50 m wide, that in the morning of April 6 had already been washed out, as the water discharge reached 200 l/s.

17.4 Damage and Safety Measures

According to incomplete data from the mountainous regions of Central Asia in the period from 1960 to 2000, more than 40 landslides occurred resulting in the tragic deaths of about 1,500 people. In Uzbekistan, for the period from 1960 to 1994, 12 events were recorded causing the deaths of 124 people.

The most common type of loss was the destruction or damage of residential and industrial buildings, recreation areas, blockage of roads, destruction of transmission towers, and damage to water pipes.

The main measure applied to ensure safety was the resettlement of the inhabitants of mountain villages to safer places. Over the years, the state built new settlements in every region, where residents from landslide-prone areas gradually resettled.

Our work suggests that relevant agencies could devote more attention and resources to early detection, warning, and loss prevention of landslide hazards associated with Pamir-Hindu Kush earthquakes.

17.5 Conclusion

This study shows for the first time the relationship between the timing of large landslides and formation of mud flows in the mountainous areas of Central Asia to the timing of long-duration, low-frequency distant Pamir-Hindu Kush earthquakes. Fifty-six cases of landslide liquefaction, extrusion, and mud flows at the time of earthquakes were found in which there were with complex relationships between precipitation and earthquakes, in the time, place and mechanisms of the landslide development.

The main risk of landslides and mud flows caused by the Pamir-Hindu Kush earthquakes is in the suddenness of their formation, and it is very difficult to predict their place and time. As a result, it is suggested that agencies devote more attention and resources to early detection, warning, and loss prevention of landslide hazards associated with Pamir-Hindu Kush earthquakes.

Results of this works have allowed specialists of the State Survey for Monitoring for Dangerous Geological Processes, during supervision in a mode of increased readiness, to determine sites of probable active cracks and landslide formation, to estimate probable socio-economic consequences and to distribute precautionary information to the population.

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