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Analysis of landslide and mudflow scenarios in loess and clay soils that caused tragic incidents in Uzbekistan

[1]Niyazov Rustam, [2]Uralov Ibragim, [2] Anorboev Fazliddin,

[1]"Institute of hydrogeology and engineering geology", Laboratory of Engineering Geodynamics, Tashkent, 100064, Uzbekistan.
[2]"State Geological Monitoring Service", Department of hazardous geological processes, Tashkent, 100064, Uzbekistan.
Correspondence to: Anorboev Fazliddin Zaynitdin o'g'li (fazliddinanorboyev2018@gmail.com).

Abstract. The article describes real landslides occurred in Uzbekistan, divided into two groups. The first group is about landslides that caused accidents, where the separation zone, the form of movement, blockages and the nature of the destruction of residential buildings are considered. These are landslides of a one-time separation, rectilinearly directed and covering residential buildings; liquefaction landslides that demolish or overwhelm buildings located in the lower part of the slope; mud streams moving along the channel of the brook, transferring to the opposite side and flooding the buildings located in the floodplain of the brook. The second group is about landslides that block the riverbeds and form blockages of transverse and longitudinal shape. Scenarios for the formation and erosion of blockages, the height of blockages in loess and clayey rocks, the parameters of dammed lakes, and the places of debris erosion are considered.

Introduction

In Uzbekistan, systematic studies of landslide processes began in 1958 with the establishment of the Bostanlyk Landslide Station (Niyazov, 1974). Over the years, in response to tragic incidents, it evolved into the Special Engineering-Geological Expedition in 1991, and later in 1994, it transformed into the State Service for Monitoring of Hazardous Geological Processes under the State Committee of Geology(Niyazov et al, 2013).

During the 30-year period from 1991 to 2020, the Monitoring Service, through its seven territorial stations, recorded 1417 cases of various types of hazardous geological processes (with a volume exceeding 1000 m^3). Among them, there were 217 cases with a volume exceeding 100000 m^3, 42 cases with a volume exceeding 1 million m^3, 117 cases of mudflows and 27 cases of temporary riverbed blockages. Unfortunately, during this period, there were 13 tragic incidents (Niyazov et al, 2021). In the global ranking of the prevalence of hazardous processes Uzbekistan ranks 45th.

There is no overall trend of increasing or decreasing the total number of hazardous geological processes over the years in the long-term period. Mass formation of such processes (ranging from 135 to 190 cases per year) still occurs during years with abundant rainfall, associated with 11-12-year solar activity cycles. Active years occur in cycles of 7 years, during which 50-70 cases can be observed in a single season, while in moderately humid years, the number ranges from 25 to 35, and in dry years, there are only 5-7 cases (Niyazov et al, 2021).

The territorial distribution of the largest number of hazardous geological processes has shifted from the eastern regions to the southwest, which is attributed to the strengthening of air mass movement from latitudinal to meridional direction.

Around 40% of the total number of hazardous geological processes are caused by human activities. Excavations and embankments in the slopes of roads and railways are the main causes, with the most significant impact observed during the construction time and initial years of operation (Niyazov et al, 2021).

The number of residential buildings destroyed by hazardous geological processes has decreased, but the number of local threats to new residential structures from the formation of various landslide-prone cracks has increased.

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

Natural Hazards and Earth System Sciences
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EGU
Discussions

In Uzbekistan, mountainous settlements are typically small, with around 50-60 households, locally situated at elevations ranging from 900 to 2000 meters, occasionally reaching 2500 meters, and with a limited infrastructure. The choice of settlement locations is associated with the presence of water sources and fertile land. Unfortunately, these areas are favorable for the occurrence of landslide processes and buildings and structures constructed in mountainous zones are highly vulnerable (Niyazov et al, 2021). The vulnerability of the structure is determined by people's ability to take safety measures, such as choosing the safe position of structures or buildings in relation to the direction and extent of landslide movement, as well as using the proper building material and structural type. The location of settlements in relation to the direction of potential landslide movement and the extent of propagation largely determines the nature of building damage, where the descending mass covers residential structures or floods them with mudflows, making it impossible to take safety measures. In other cases, gradual cracking of buildings occurs due to rock deformation (subsidence), allowing for safety measures to be implemented.

Here, we study different landslides occurred in Uzbekistan and classify them into two groups and 5 sub-groups. The development of various types of landslide scenarios aims to improve understanding of different episodes of manifested landslides and to provide a comprehensive assessment of various indicators to enhance methodological approaches to area-wide monitoring for early warning purposes (Frodella, 2022; Unified, 2021).

Identification of landslide scenarios

The two different groups of landslides and the associated sub-groups are described hereby together with the considered indicators (Niyazov et al, 1991).

I-group. When developing scenarios, more attention is given to landslides that have caused accidents (the rupture zone, the nature of movement and the form of debris accumulation, as well as the nature of residential building destruction).

The analysis of the rupture zone is based on determining the effective area of influence, morphometric indicators and the geometry of the surface and subsurface destruction. The aim is to identify whether it was a one-time or repetitive displacement and to determine the areas of compression, extension, or shearing within the landslide mass, thereby linking everything to the mechanism of landslide development.

Debris accumulations formed beneath slopes with a very limited transit zone are studied. The shape, volume and degree of fragmentation of the rock material, as well as its water saturation, are examined, along with the conditions contributing to its formation through collapse or horizontal displacement. Furthermore, the reasons why people were unable to take safety measures are investigated. These debris accumulations are formed as a result of the movement of mudflows along the side channels of ravines, leading to the obstruction of the main river channel. Their shapes, volumes, the state of fragmentation and water saturation of the rock material, as well as the forms of the debris mound, are considered. Special attention is given to the location of erosion, whether it occurs on the debris mound itself or in the adjacent slope areas, as well as to indicators of water permeability, erosiveness, and other related factors. Additionally, the temporary indicators of water accumulation and erosion on the debris mound are taken into account.

The transit and accumulation zones of mudflows, their kinematics along the ravine channel, height, discharge, flow density, and so on are studied. Analysis of emergency situations has revealed that in many cases, the extent of mudflow propagation (up to 3-5 km), the location and height of the deposition of fragmented rock masses on the opposite bank of the ravine, changes in the direction of mudflow movement, and the suddenness of its formation due to seismic and dynamic fluctuations are unpredictable. Mudflow-debris flows in loess deposits occur during abnormally high-water years and are characterized by a short formation period. The slopes prone to landslides become waterlogged through closely located areas of water supply and discharge from underground sources, leading to an almost synchronous correlation with temperature rise, snowmelt and intense precipitation since the onset of landslide formation. A common feature in

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

the formation of landslide-debris flows is that regardless of the type of rock disintegration (subterranean erosion, liquefaction, fragmentation), the rock material moves along the sliding surface with a very gentle inclination (4-60 degrees), independent of the lithology of the underlying rocks. No significant phenomena of shearing in the overlying rocks are observed or they play a subordinate role. Multiple displacements occur over a short period of time during the development of landslide-debris flows. The increase in the volume of displaced rock material does not affect the acceleration of movement but increases the extent of mass displacement. The thickness of the flow and the properties of the rocks along its length remain nearly unchanged. The mudflow discharge in loess deposits ranges from 1.5 to 3.0 m, while in clayey deposits, it varies from 8 to 12 m.

Type I-1. Landslides are characterized by sudden, instantaneous formation and simultaneous displacement from steep slopes. They directly impact and cover residential structures located on gentle terraces below the slope or on the opposite side of the ravine. In these cases, individuals are unable to take safety measures due to the rapid onset of the landslide.

Landslides exhibit immediate movement and occur as a one-time detachment on high, steep (30-400 m) convex-shaped slopes, where the sliding surface is located above the base of the slope and has a steep inclination parallel to the slope itself.

The significant spread of landslide masses and the concentration of maximum thickness in the terminal part can be explained by the convex shape of the slope and the presence of a step or bench in the lower portion of the slope, which acts as a launching pad. Surfaces with decreasing downward curvature offer less resistance to the deformation of the landslide mass, as tension develops within the sliding mass along these surfaces. The resistance of the rock materials to tension is significantly lower than to compression. However, if the landslide occurs in a narrow valley, the sliding mass of rock material is thrown onto the opposite side due to the shape of the sliding surface. The height of this throw is approximately one-third of the difference in elevation between the headwall and the valley floor.

The Cheborgata landslide occurred on April 9, 1960, on the left bank of the Chaulisay River, in the vicinity of the Cheborgata village school. It had a volume of 20,000 cubic meters and resulted in severe consequences. The displaced clayey material, moving through the underlying porphyritic rocks, formed a strip with a length of 80 meters and a width of 120 meters. It crossed the Chaulisay River and reached the opposite right bank, causing destruction to residential and industrial buildings. The height of the headwall was 5-6 meters, and in the lower zone, there was a spring with a flow rate of 1 liter per second.

The displacement occurred rapidly during daylight hours (10-15 seconds) along one of the cracks within the outline of an old landslide, which had occurred in 1959 (recurring movement). According to eyewitness accounts, the lower part of the slope collapsed first, followed almost immediately by the upper part, accompanied by underground rumbling. The displacement occurred on a convex-shaped slope with a steepness of 30-400 m, composed of loess deposits with a thickness of 6-8 meters. A spring with a discharge of 0.1-0.2 liters per second was located in the lower part, increasing to 2.0 liters per second during the spring period. The headwall elevation above the riverbed was 100-110 meters(Niyazov et al, 2021).

During the displacement, the landslide mass was completely transferred to the opposite bank, without filling the river channel, covering an area of 150x100 meters. The area of the displaced mass was 3,600 m^2, with a volume of rock material amounting to 250,000 m^3. The tongue of the landslide mass rose up to 30 m above the Chaulisay River channel.

The Gurdara landslide is located in the Buldzhuan area on the right bank of the Palkhaksay River, 1.2 km from its confluence with the Kyzylsu River. The landslide slope, with a height of 100-120 m and a convex shape, has a steepness ranging from 40 to 450 degrees. It consists of a layer of loess deposits with a thickness of 10-15 m, resting on weakly cemented Neogene sandstones. In the upper part of the slope, near the watershed, there was an old landslide

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Natural Hazards and Earth System Sciences
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Discussions

crack measuring 70-80 m in length and up to 20 cm in width. A few days before the disaster, it subsided as a block by 1.0-1.5 m (Fig. 1).

On May 8, 1969, at 4:00 local time, a sliding landslide occurred with a depth of engagement of 10-12 m and a volume of 0.12-0.14 million m^3. The landslide moved down from a height of 120 m, burying the settlement of Gurdara, which had a population of 300 people (Niyazov et al, 1991).

The detachment zone had distinct characteristics. The width of the landslide cirque in the lower zone was 1.3-1.4 times greater than in the upper zone, measuring 130-140 m. The interior of the landslide cirque was completely cleared of displaced rock masses. The upper boundary of the detachment wall was smooth without any undulations, while the lateral boundaries of the detachment wall were slightly lower in height than the main detachment wall. All these features indicate a unified and simultaneous displacement of the rock masses. The Gurdara landslide is located in the Buldzhuan area on the right bank of the Palkhaksay River, 1.2 km from its confluence with the Kyzylsu River. The landslide slope, with a height of 100-120 m and a convex shape, has a steepness ranging from 40 to 450 m. It consists of a layer of loess deposits with a thickness of 10-15 m, resting on weakly cemented Neogene sandstones. In the upper part of the slope, near the watershed, there was an old landslide crack measuring 70-80 m in length and up to 20 cm in width. A few days before the disaster, it subsided as a block by 1.0-1.5 m (Fig. 1).

Fig. 1. Gurdara Landslide (1969)

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Debris Avalanche: The displaced mass of loess deposits from the right bank of the slope cascaded onto the left bank along a gentle terrace. The displaced mass was in a moist and highly fragmented state, but the soils were not in a fluid state. The avalanche engulfed the settlement in a uniform strip, extending approximately 150-170 m in length and 100-120 m in width, with a consistent thickness of 3-4 m. The formation of the avalanche likely occurred through the overlapping and simultaneous horizontal spreading of the landslide masses upon each other within the floodplain. The displacement and spreading of the collapsed rocks occurred instantaneously, resulting in the loss of all human lives in the affected area.

The Djigiristan landslide occurred on May 4, 1991, at 7:15 a.m. local time on the left flank of the Djigiristan headwaters. In 1990, new circular cracks with a length of 100-120 m, a width of 0.01-0.2 m, and an amplitude of 0.5-0.7 m formed on the left flank of the landslide. In 1991, in addition to the tension cracks, lateral shear cracks with a length of 80-90 m developed, and the shape of the landslide changed from circular to horseshoe-shaped with distinct lateral cracks (Fig. 2).

Due to the threat posed by the landslide to residential buildings in the settlement, a decision was made to unload it from top to bottom. As a result, over a period of 5-7 days, a portion of loess soils above the detachment plane was removed, and the unloading of the landslide continued.

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

Natural Hazards and Earth System Sciences
Discussions

However, on May 4, a landslide occurred with a volume of 170000 m^3. The triggering mechanism of the landslide displacement may have been two bulldozers that were ascending the slope to unload material at its upper part. At 7:15 a.m., while traversing the lower and central parts of the landslide, approximately 3-5 m apart, they possibly created resonant vibrations, leading to the instantaneous displacement of the entire mass of the landslide. As a result, the bulldozers were displaced and covered by the landslide. The displacement occurred within a short period of 20-30 s, as a woman who was located at a distance of 100-120 m, upon witnessing the onset of rock destruction, was unable to warn her children in time.

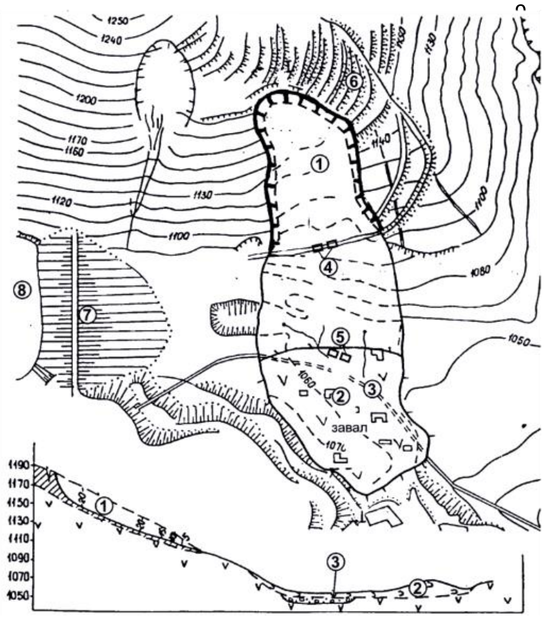

Fig. 2. Plan and profile of the Jigiristan landslide (1991)

Detachment Zone: The rock displacement occurred simultaneously across the entire area of the landslide, which is evidenced by the smooth contour of its cirque and the polished surface of the detachment plane. No water manifestations were observed on the detachment plane, although the moisture content of the rocks in the lower part of the detachment plane was 23-24%.

Deposition Area: The displaced landslide mass spread over an area of 240 m with a thickness of 5-8 m, covering eight farms and resulting in the loss of 56 lives. The loess materials in the deposition area were heavily fragmented and in a poorly moistened state. The maximum thickness of the deposition, reaching 8 m, was located at the center, with a length of approximately 120 m and a width of 90-100 m. The volume of the deposition was estimated to be around 60-70 thousand m^3.

Tokberdy-1 landslide (April 18, 1994). On a straight slope with a height of 170 m and a gradient of 35-400 along the watershed line, a large crack measuring up to 400 m in length and 0.3-0.5 m in amplitude was observed. In March 1994, the crack began to lengthen, and lateral shear cracks appeared, dividing the landslide mass into two parts (Fig. 3).

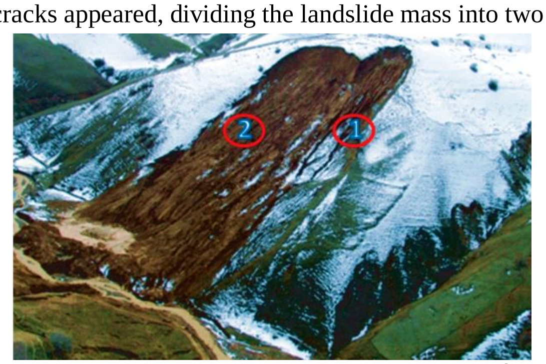

Fig. 3. Tokberdy landslide (1994)

Three hours before the landslide occurred, the daily rate of crack widening reached up to 2-18 mm per day. The landslide, with a volume of 0.16 million m^3, covered the riverbed and partially buried houses. People were warned, and two individuals who were dismantling their house lost their lives. Ten years later, on April 25, 2004, the right side of the Tokberdy landslide, with a volume of 0.2 million m^3, moved at a speed of 5 m/s, shifted 140 m, blocking the riverbed and the area where residential structures had previously been located. Two individuals who were herding cows and sheep in the morning perished.

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

Thus, the detachment zone was located in the upper, gentle part of the watershed at an elevation of 160-170 m above the riverbed. The average depth of displacement was approximately 10 m. The length of the detachment zone and its width ranged from 80 to 110 m, and the gradient of the detachment zone was very steep, ranging from 35 to 400. The rock displacement occurred in a single cycle.

Deposition area: As a result of the landslide displacement, the Gushsay riverbed was temporarily blocked by a deposition spanning approximately 40-50 m in length, over 200 meters in width, and with a thickness of 2.0-2.5 m, forming a small lake. Within 3-4 hours, the deposition was washed away. The loess materials in the deposition were heavily fragmented and moistened. A second deposition occurred after the second landslide in 2004, which spread to the opposite slope over a distance of 160-170 m with a thickness of 2-4 m. The loess materials in this deposition were in a fragmented and loosened state. Tokberdy-1 landslide (April 18, 1994). Here, on a straight slope with a height of 170 m and a gradient of 35-400 along the watershed line, a large crack measuring up to 400 m in length and 0.3-0.5 m in amplitude was observed. In March 1994, the crack began to lengthen, and lateral shear cracks appeared, dividing the landslide mass into two parts (Fig. 2).

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Deposition area: As a result of the landslide displacement, the Gushsay riverbed was temporarily blocked by a deposition spanning approximately 40-50 m in length, over 200 m in width, and with a thickness of 2.0-2.5 m, forming a small lake. Within 3-4 hours, the deposition was washed away. The loess materials in the deposition were heavily fragmented and moistened. A second deposition occurred after the second landslide in 2004, which spread to the opposite slope over a distance of 160-170 m with a thickness of 2-4 m. The loess materials in this deposition were in a fragmented and loosened state (Niyazov et al, 2012).

Type I-2. Landslides of sudden simultaneous displacement from adjacent slopes and spreading in a liquefied state along the flat surface of adjacent terraces. Residential structures located within a distance of up to 100 m between the landslide and roads (both highways and railways) may be demolished or buried.

The Khodjikent landslide occurred on March 14, 1961, in the western part of the village of Khodjikent. The displaced mass had a volume of over 250,000 m^3 and 12 people lost their lives.

Zone of detachment: The landslide originated on an adjacent slope, dissected by small gullies. The head of this landslide was associated with the beginning of one of these gullies. The height of the detachment wall reached 10-15 m, with a length of 300 m and a width of 250 m, resulting in a volume of 250,000 m^3. The slope consists of loess-like clay with fine gravel, up to 2.5 cm in size, and has a thickness of 20 m.

Another Khodjikent landslide occurred on May 25, 1969, with a volume of 400,000 m^3. The landslide slope consists of a terrace surface and a convex-shaped escarpment. The lower part has a steepness of 30-350, while the upper part has a steepness of 20-220. The surface is composed of loess deposits, 20 m thick, overlying Paleozoic rocks and porphyrites. The clays in the lower part are waterlogged. The length of the landslide in the formation zone is 200 m, with a width of

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

100 m along the edge of the scarp and a displacement depth of 20 m. The volume is estimated at 0.4 million m^3 (Fig. 4).

The detachment zone of the landslide has a curved shape in plan, widening in the lower part to 120-130 m. The height of the detachment wall ranges from 25 to 30 m, with a steepness of 80-850. A spring with a discharge of 0.2 liters per second emerges between the middle and lower parts. The upper lateral boundary of the landslide is close to the height of the detachment wall, measuring 18-20 m and decreases in the lower part following the slope inclination. The upper edge of the detachment wall has a smooth and straight form, indicating a single detachment event. The detachment wall was formed due to extension rather than shear displacement.

Fig. 4. Photo of Khojikent landslides (1961 and 1969)

Spread zone: The displaced mass of loess deposits moved as a muddy flow along the flat surface of the terrace, covering a distance of up to 400 m and descending into the Chirchik River, forming a mudflow with a thickness of 2.5-3 m and a width of up to 200 m. The area of displacement was 19,000 m^2, while the spreading area covered 42,000 m^2.

The Aktash landslide is located in the Urgut district and formed on the right adjacent high (200-240 m) and steep (400) slope.

The landslides occurred three times. The first landslide occurred in 1992 with a volume of 30,000 m^3 as a result of slope base erosion. The riverbed of Saya was partially blocked, posing a threat to residential houses located near the river. The second displacement took place on March 11, 1993, with a volume of 30-40 thousand m^3, originating from the right side in the lower zone, partially blocking the riverbed of Saya. The main third displacement occurred 1.5 hours later, with a volume of 80,000 m^3 meters, originating from the upper part of the slope. The landslide mass was transferred to the opposite slope of Saya Aktash, at a distance of 160 m and a height of 20-22 m above the riverbed of Saya.

Zone of detachment: The main detachment wall formed on the watershed surface. The height of the detachment wall ranged from 6 to 8 meters, and the boundaries of the detachment zone were straight, without meandering, indicating a simultaneous displacement in three cycles. The width of the landslide cirque was 150-160 meters, taking on a conical shape.

Deposition: The displaced mass of loess deposits spread on a gentle terrace in a fragmented and liquefied state, covering a distance of 180 m and a width of 70-80 m, with a thickness of 2-3 m. At the end of the flow, one house where people were located was buried, resulting in the loss of five lives.

Type I-3. Two types of mudflow landslides are considered.

The first type is landslide that form in the upper parts of the slope and move linearly along its surface, targeting residential structures located in the lower part of the slope.

The second type is mudflow streams that form in the upper parts of river valleys, characterized by sudden or repeated detachment and sequential rapid displacement of liquefied dispersed materials, transferring them across the riverbed to the opposite bank. These landslides, in addition to the detachment zone and accumulation zone (debris deposition), have a transit zone for the moving mudflow. In the case of the first two types, the debris deposition led to the destruction of residential structures, whereas for the third type, the debris deposition is only temporary, and the danger lies in the movement itself. During the movement, buildings located in the floodplain of the rivers are destroyed. In this case, the damage is more economic than social since people have time to evacuate from hazardous areas.

Mudflows form in the upper part of the slope and move along its surface, burying residential structures located in the lower part of the slope. Another case involves local residents cultivating gardens higher up on the slope, and when watering them, small masses can be set in motion and directly affect residential buildings. A characteristic example is the Kashkasay landslide-flow that occurred in Gushsay on March 21, 1994, with a volume of 0.6 million m^3.

The detachment zone of the landslide is located along the line of the unusually steep watershed surface, with a length and width of 200 m and a depth of 15 m. The surface of the detachment zone's boundaries is flat, indicating a simultaneous and unified detachment. The simultaneous displacement of the entire mass of the 0.6 million m^3 landslide resulted in movement in two directions (Fig. 5).

The main portion, with a volume of 0.4 million m^3, advanced along a lateral tributary for over 800 m and covered the floodplain of the river for a distance of 350 m. The second part of the landslide, with a volume of 0.2 million m^3, moved towards the left side of the slope, with a flow width of 18-25 m, and also descended towards the Kashkasay riverbed for a distance of 350-400 m, causing damage to one residential building and auxiliary structures.

Fig. 5. Kashkasai mudflow (1994)

Thus, there was no collapse or landslide dam formation. The entire mass of the landslide dispersed and remained on the slope with a thickness ranging from 1.0 to 2.5 m. The loess materials were in a loosened state but not in a liquid condition.

Another example involves two mudflows occurring in the same valley above the village of Karakishlok but moving in different directions with varying extents of propagation. The first mudflow, with a volume of 400,000 m^3, occurred on March 29, 1994, at 5 a.m., originating from a slope with a steepness of 300. The landslide mass, originating from a height of 300 meters and with a slope inclination of 170, rapidly moved along a winding channel, covering a distance of 1.2 km while changing its direction four times. Upon entering the Gushsay Valley, the mass of debris struck the right bank, causing it to rotate by 800 and follow a curved path for a distance of 200 m. It then ascended the right bank to a height of 30 m, resulting in the destruction of a property on the opposite bank (Fig.6).

Fig. 6. Karakishlak mudflow (1994)

The second landslide occurred on the right bank of the lateral stream on April 16 at 3 a.m. The landslide mass, with a volume of 800,000 m^3, moved from the same height along this stream and also changed direction four times. Upon reaching the Gushsay Valley, the mass of debris struck the left bank at an angle of 35-40 degrees and continued to move upstream, ascending to a height of 60 m on the opposite bank. As a result, a road was blocked for a distance of 140 m, and nine properties were destroyed. However, people were alerted and evacuated in time (Fig. 7).

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

Fig. 7. Mudflows in Gushsay-Guldarama (1994)

Fig. 8. Djauz mudflow (1993)

Due to the unpredictability of the direction and extent of the landslide masses, a catastrophe occurred in the village of Djauz on July 11, 1993. At 10:40 p.m., a landslide-flow with a volume of 700,000 m^3 occurred, advancing over a distance of more than 500 m. It developed in two stages (Fig. 8).

During the first stage (May 9, 1993), which occurred two months earlier, there was a displacement of rocks in the lower zone with a volume of 150-160 thousand m^3. The displaced mass, in the form of a flow, moved along the channel and then reached the main channel of the slope after 400 m. It crossed over to the opposite side at a height of 20-25 m. A portion of the soil, in the form of a cover with a thickness of 2-4 m and a width of 40-50 m, remained in the channel, blocking the outlets of springs.

During the second stage (July 11, 1993), there was a displacement of heavily saturated soil in the channel, resulting in the upper part of the slope losing support. The almost dry loess rocks were displaced. The shifted mass of soil crossed over to the opposite slope at a height of 60-70 m, rebounded off it, changed direction by 25-300 degrees, and caused the collapse of a residential structure (Niyazov et al, 2013).

II-group. The formation and erosion of transverse and longitudinal landslide deposits. The forms of the deposits, their thickness, volume, degree of fragmentation and water saturation of the rocks are considered. Special attention is given not only to the deposits themselves but also to the parameters of the resulting landslide dammed lakes, the location of erosion (on the deposit or in the adjacent slope areas), indicators of permeability and erodibility, and so on. Significant attention is also given to the temporal indicators of water accumulation and erosion of the deposit.

Landslide deposits formed by mudflows in loess and clayey rocks, unlike highland avalanches, occur more frequently and are located in the foothills near mountain settlements. Their erosion by surface water occurs within several hours or days. It depends on the shape, volume, height and density of the rocks in the deposit, as well as the rate of surface water inflow. Based on the manner in which the channels of the slopes are blocked, landslide deposits can be divided into two groups: transverse and longitudinal.

Type II-1. The formation of transverse forms of landslide deposits and their erosion.

Transverse forms of channel blocking typically occur on the slopes of river valleys and terraced cliffs, where the mass of rocks displaces onto a gentle floodplain, obstructing the river channels. This process is characterized by a one-time or rapid sequential displacement and high initial velocity. The transition zone has a steep slope, a considerable length of 0.8-1.2 km, and a narrow width of 40-60 m. Therefore, the displaced rock masses cannot accumulate directly in this

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

zone but continue to move downstream along the channel. Upon encountering the gentle surface of the floodplain, the mudflow enters the river channel, with the lower layers coming to a halt and the upper layers sliding over them, thus forming a landslide dam. Let's consider several examples of transverse forms of landslide deposits formed by landslide processes.

The Karankul mudflow occurred on April 20, 1969, with a volume of 5.4 million m^3. It originated on the convex slope with a gradient of up to 30 degrees in the right tributary of the Karankul River, along a tectonic fault, in an ancient erosion basin composed of highly weathered water-saturated metamorphosed andesite-basalt porphyry with a thickness of 3-6 meters, overlain by loess deposits with a thickness of 18-35 meters.

The displacement of rocks began in the early morning between 4:00-6:00 a.m., with numerous small volumes and continued for almost two days. The horizontal movement of the mudflow started along the basin located across the slope and blocked the channel of the Karankul River, creating a dam with a width of 100 m and a height of 6-8 m, above which a lake began to form. Within the first 20-35 minutes of displacement, a cirque with a length of 560-600 m, a width of up to 300 m and a thickness of 20-22 m was formed, affecting a volume of approximately 5 million m^3. Another portion of the rock mass, turning 90 degrees, continued to move down the main channel of the Karankul River at a speed of 150-200 meters per hour, with an average flow thickness of 2.5-3 m. After covering a distance of 2.5 km within a day, the mudflow blocked the roads and railways with a width of 250 m and reached the Chirchik River. After 20-22 hours, the volume in the lake reached 125000 m^3 and on April 21 at 12 o'clock, the water in the lake began to overflow at a rate of 0.5 m^3/s, eroding the dam. Part of the landslide volume transformed into a mudflow, which greatly widened to 300 m in the lower part, inundating 15-18 households in the village of Karankul. The total length of the mudflow reached 3.3 km(Niyazov et al, 1991).

“Crystal” landslides were recorded with the following volumes: 120000 m3 in 1961, 30000 and 70000 m^3 in 1969, 160000 m^3 in 1979, and 600000 m^3 in 1994. In May 1979, for the first time, a cone-shaped flow with a width of up to 200 m and a thickness of 2.5-3.2 m obstructed the channel of Ugam River. The elevation difference between the detachment wall and the water level in the river was 250 m. The detachment zone had a length of 195 m, and the transit zone extended for 500 m, resulting in a total length of 1100 m. The river channel had several bends, where the landslide mass collided with the banks, fragmented, mixed and became more homogeneous (Fig. 9).

Fig. 9. Crystal landslide (1994). Mudflow and washout section of 200 m long, 40-45 m wide and 3 m thick.

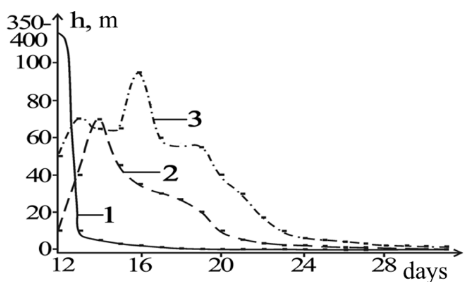
During its movement along the channel, the landslide left traces on the outer side of the bend, approximately 4-6 m higher than on the inner side, indicating a high velocity of movement. A secondary landslide-flow event occurred in this zone on May 9, 1994, with a volume of 600000 m^3. It traveled along the channel for a distance of 1100 meters and completely obstructed the Ugam River, which was 40-45 m wide, 200 m long and had a thickness of up to 3 m. After 20 minutes, instead of the dam, the erosion began on the left bank of the river channel. With a discharge of 97 m^3/s and strong current, the river eroded a narrow passage with a width of 4 m within one hour.

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

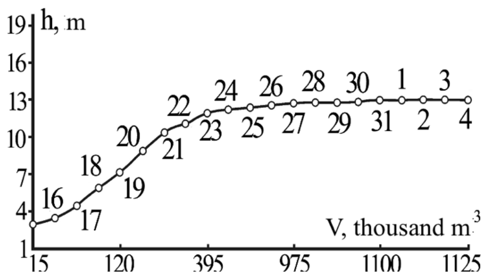
Subsequently, the water started widening the channel, eroding the left bank bypassing the cone-shaped obstruction, thus forming a new floodplain. As a result, no mud or debris flow was formed.

The Langar landslide, located on the left bank of the Langar River, occurred on May 12, 1998, with a volume of 10.5 million m^3. The detachment zone is associated with the watershed. On a slope with a height of 420 m, a detachment scarp was formed, measuring 600 m in width and 800 m in length, with a depth of 20-25 m of clayey rock displacement. The development of the landslide occurred through consecutive and rapid displacements, ranging from 50 to 80 meters per day, additionally involving the underlying sandy-clay deposits with a thickness of 8-10 m (Fig. 10 and Graph 1, 2).

Fig. 10. The upper zone of the Liangar landslide failure and the lower zone, where the overlap of the river bed and the formation of the dam occurs (1998).



Graph 1. Changes in the magnitude of displacement of different zones (1-top, 2-middle, 3-bottom) of the landslide



Graph 2. Changing the height and volume of the slab over time: the volume increased, but the height did not change

During this event, the lower zone exhibited the most active displacement, with speeds of up to 90 meters per day, while the upper zone had a minimum movement rate of 5-10 meters per day. After three days, on May 16, the displaced mass began to fill the Langar River.

Within a span of four days, the river was completely obstructed by a transverse dam measuring 160 m in length, 80 m in width and reaching a height of up to 4 m. By May 21-22, ten days after the start of the landslide, the dam's height had increased to 12-13 m, with a volume of 0.4-0.45 million m^3. The movement of the landslide continued, leading to an increase in the dam's volume. By June 1, after 18 days, the volume of the dam had grown to 1 million m^3. Although the dam's height remained at 12 m, the landslide movement persisted. As a result, a lake with a length of 400 m, width of 80 m and a depth of 4-5 m, with a volume of 150,000 m^3 meters, formed. However, there was no erosion or breaching of the dam. To ensure the safe passage of water from the lake, a trench was excavated on the right bank of the river, allowing the water to create a new channel through erosion.

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

The "Kattakishlok" landslide, which occurred on March 10, 1969, is located on the right bank of the Uradari River. It consists of clayey layers with a thickness of 3-4 m, underlain by sandstones and aleurolites with interlayers of clay from the Cretaceous period. The sandstone and aleurolite layers, with a thickness of 15-20 m, shifted along the clayey layers of the Cretaceous formation, resulting in a displacement of 0.7 million m^3 of material. The landslide mass extended over a length of 600 m, with a width of 150 m at the upper part and 200 m at the lower part. The circular-shaped scarp had a height of 35 m.

Fig. 11. A landslide rockfall and a lake in the village of Kattakishlok in the Uradarya river basin, March 10, 1969.

During the displacement, the landslide mass moved downward along the slope by 80-100 m and obstructed the channel of the Karankulsay River, creating an obstruction with a height of 6-8 m at the upper part and 20-25 m at the lower part. As a result, a dammed lake formed, extending up to 200 m in length and 80 m in width. The lake has persisted for 44 years, from 1969 to the present day. There has been no abrupt breakthrough, and water flows through an erosion channel with a depth of 3-4 m (Fig. 11).

On April 17, 2002, a mudflow occurred along the Sharqilamasay in the Bostanlyk zone, extending for a distance of 800 m after overflowing through a debris dam with a height of 8-10 m. We attributed the formation of this landslide to earthquakes that occurred either on March 3, 2002, with a magnitude of M=7.4, or on April 14 with a magnitude of M=5.5 (Niyazov et al, 2013).

The events unfolded in several stages:

I. The rock material liquefied at depth and vertically settled, creating a circular-shaped subsidence and providing support for the release of underground water.

II. The accumulation of a water pocket with a discharge rate of 2 liters per second led to intensified underground erosion, resulting in a landslide volume of 480,000 m^3 in the form of a karst sinkhole with a diameter of 120-140 m. The scarp of the sinkhole had a uniform height of 18-20 m along its entire perimeter and exhibited a consistent steepness of 87-90 degrees, with a narrow neck formation that can only be produced through prolonged (1.5-2 minutes) vibrational effects.

As a result of the landslide displacement, with a length of 100 meters in the detachment zone, a width of 120 m and a depth of 20 m, the landslide mass overturned onto the opposite slope to a height of 50 m and a distance of 200 m, moving in a zigzag pattern with a splash onto the slope crest at a height of 10 m (Fig. 12).

At the base of the slope, a debris accumulation formed, measuring 40 m in width, 50 m in length and 8-10 m in height. A debris lake was formed, and it underwent erosion, resulting in a mudflow. The volume of water in the lake, which formed over a few hours, amounted to 840 m^3 (60x20x7), as the water discharge in Sharkilamassai was approximately 100 m^3/hour.

Thus, the analysis of the scenarios of transverse debris accumulations in loess and clay soils indicates that transverse accumulations in loess deposits generally constitute 0.5-0.6 parts of the landslide volume (30000-40000 m^3) in loess deposits and up to 1-2 million m^3 in clay soils. The height of the debris accumulation varies from 2.5-3.5 m in loess deposits to 8-12 m in clay soils.

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

Natural Hazards and Earth System Sciences
Discussions

Fig. 12. Breakaway wall and mud flow along the Sharkilamasai (2002).

The erosion process of the debris accumulation in loess deposits depends on the water discharge in the channel and occurs after 20-30 minutes, lasting for 5-7 hours with a flow rate of 0.5-1 m^3/s. Erosion occurs in the form of a channel with a width of 2-4 m, which forms on the opposite side of the channel crest. The erosion process starts not with the erosion of the debris accumulation but with the saturation of dry loess materials on the slope crest due to the rising water level in the channel. As a result, a depression forms at the junction of the accumulation and the slope crest, initially bypassing the debris accumulation and then eroding it, not through overflow but through lateral erosion, thus preventing debris flows from occurring. Transverse debris accumulations in clay soils reach heights of 8-12 m or more and have a larger volume. The erosion process also occurs on the opposite side of the channel, not in width but in depth, reaching the channel bed. The erosion duration of debris accumulations in clay soils is 3-5 years or more and does not transition into debris flows.

Type II-2. Formation and erosion of the longitudinal shape of landslide debris. The longitudinal shape of channel blockages is formed by landslides and flows in lateral major channels, where displacement occurs in multiple detachments and the landslide develops from bottom to top. After the main displacement, the rocks may collapse in small volumes over significant time intervals. For example, Sulisai and Kairagach landslides moved over a period of 3 days, while Karankul moved in 2 days. Each subsequent portion, catching up with the previous one, provided an additional impulse, increasing its volume and power, which facilitated the further movement of the flow. The volume of the mudflow constitutes 60-80% of the landslide volume. Its length exceeds the width by 30-50 times, and the flow depth is 2.5-3 m, becoming relatively uniform after stabilization. In areas where the mud mass blocks the lateral tributaries, debris lakes with a volume of 30-40 thousand m^3 are formed. The water in the lake gradually filters through the debris accumulation and seeps downstream at a distance of 50-120 m within 10-20 hours or several days along its old channel. The erosion of the debris accumulation occurs without transitioning into a debris flow. Let us consider several examples in this regard.

The Sulisay landslide occurred on November 27, 1994, on a slope with a height of 150 m and a gradient of 25-300, within the old landslide cracks of 1969. The abundant precipitation was the cause of its formation. From November 22 to 25, 1994, over a period of 4 days prior to the displacement, there was a rainfall of 92.2 mm. In the last 24 hours, 71.3 mm of rainfall was recorded, which exceeded the long-term average by four times. The displacement of the landslide occurred in multiple stages and lasted for 11 days. The initial volume amounted to 1.6 million m^3. A mudflow formed at the upper part of the left bank of the channel, crossed over to the opposite bank, and flowed uniformly downstream with a depth of 24 m and a width of 5-7 m, covering a distance of up to 2 km. In the subsequent days, additional displacements of 200000 and 300000 m^3 occurred, extending the reach of the mudflow to 3 km, with a consistent depth of 1.5-2.5 m and a width of 5-6 m in the lower part. The flow passed beneath a highway bridge without damaging

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

its supports. In the following spring, water erosion in the channel eroded the mud deposits, resulting in the formation of a floodplain terrace.

The Baybaksay landslide formed on April 7, 2005, in an area where cirques and landslide cracks from 1969 were present. The displacement occurred on a slope with a height of 250 m and a gradient of 30°, consisting of loess deposits. The mudflow, with a volume of 1.4 million m^3, formed in a zone with a length of 350 m and a width of 200 m. In the first day, it advanced 700 m with a depth of 6-8 m and a width of up to 60 m. Four springs with a total discharge of 4-5 liters per second emerged from the wall of the detachment area. Three days later, during the night of April 10th to 11th, the mudflow progressed an additional 200 m and began to cover an overland road bridge. By this time, the road authorities had removed the upper part of the bridge, and the mudflow passed through the section of the bridge, following the channel of the river (Fig. 13).

Fig. 13. Baibaksai landslide

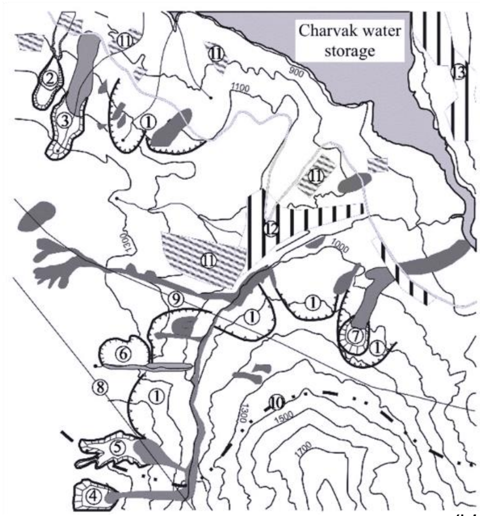


Fig. 14. Overview of Mazarsay mudflows

On June 10, 1969, two simultaneous mudflows occurred in parallel located valleys - Mazar-Say with a volume of 0.7 million m^3 and Gulkam with a volume of 2 million m^3. The landslides were triggered by the Pamir-Hindukush earthquake that occurred on March 10 at 22:52 (M=5.5), which caused liquefaction of the loess deposits and subsequent multiple detachments. The detachment zones of both landslides have an oval shape, with the greatest expansion in the central part. The upper part is characterized by numerous individual cirques with winding walls, while the lower part resembles a bottleneck, narrowing down to 5 m, through which the entire volume of landslide masses passed. The height of the detachment wall reaches up to 15 m and is composed of loess deposits. The maximum width of the detachment zone is 250 m and its length is 580 m. The loess deposits lie on water-saturated reddish clay, aleurites, and sandstones. The saturation of the soil with groundwater has a linear pattern. The entire mass was highly liquefied, allowing it to flow out of the formation zone through a narrow bottleneck of the valley and advance as a mudflow for a distance of 3.2 km. The length of the landslide in the displacement zone is 580 m and its width is 60 m. After traveling 350 m along a 3-4 m wide channel, the displaced mass turned 900 to the north and merged with Mazar-Say, reaching the Chatkal River within 10 hours, forming a mudflow with a length of 3.1 km and a depth of 0.5-1.5 m (Fig. 14).

The Navodiya mudflow formed in the basin of the Djinnidarya River, in the left tributary of Navodiya Say, with a volume of 0.3 million m^3. The movement of the mudflow was recorded on March 11, 2015, at 9:30 a.m. The displacement of the rocks occurred through two mudflows formed along the edge slopes of the landslide. A small flow occurred on the left slope, with a

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

Natural Hazards and Earth System Sciences
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EGU
Discussions

length of 400 m and a volume of 8000 m^3. The total volume of the landslide in the formation zone was 0.3 million m^3 (120x120x22).

The detachment zone of the landslide is characterized by two stages. The upper stage is straight with a height of 10-22 m, while the lower stage has a height of 22-25 m in the center. The wall of the detachment has a cirque-like shape, with a total width of up to 160 m. The displaced loess deposits are in a liquefied state with a natural moisture content of 22-24%. The flow depth in the displacement zone varies from 5-8 m in the upper part to 2-3 m in the lower part. The width of the flow changes from 20 m in the upper zone to 35-40 m in the middle zone and 17 m in the lower zone. The mudflow, with a length of 620 m and a height of 24-25 m, came to a stop 40 m away from the highway after 6 hours.

On April 29, 1992, at 23:40, a rock avalanche known as the Ikari-Guldara landslide occurred, with a volume of 1.1 million m^3. According to accounts from local residents living 4 km away from the landslide, a powerful explosion was heard, accompanied by seismic tremors of magnitude 4-5. The movement involved a 60 m thickness of rock, consisting of 30 m of Jurassic sandstones and 30 m of Middle Jurassic clays with interlayers of coal and sandstones, which provided the conditions for the accumulation of methane gas. The explosion, acting as a trigger mechanism, induced the landslide and simultaneous earthquake.

The detachment zone, characterized by a distinct vertical cliff and lateral boundaries at a 90-degree angle, forming a smooth circular shape, indicates a simultaneous instantaneous displacement resulting from stretching. The rocks within the landslide's cirque were predominantly uniformly fragmented. Almost the entire volume of rock, 1.1 million m^3 (24x800x60), exited the detachment zone, burying the gorge over a length of 250 m and a width of 100-120 m, with a depth ranging 10-15 m. Subsequently, over a period of 6 days, these fragmented rocks, which were mostly dry, advanced along the channel of the stream for a distance of 1.5 km, with a height difference of 2.5-3 m.

Results and conclusion

In this work, we analyze different landslides occurred in Uzbekistan and identify scenarios based on a number of factors, described hereby.

1. Analysis of the detachment zone, based on morphometric features and the geometry of the surface and subsurface of the failure, allows determining whether it was a single or multiple displacement event and reveals the mechanism of landslide development, including compression, extension, or shear within the landslide mass. Various types of indicators and their values that can be used for modeling and predicting landslide processes have been identified. Three types of landslide scenarios leading to tragic incidents have been distinguished:

- Simultaneous displacement in a straight direction, causing the burying of residential structures or crossing to the opposite side of the slope at a height of one-third of the slope.
- Single displacement landslide-flows spreading in a loosened state along the slope surface, demolishing structures through horizontal movement.
- Mudflows with simultaneous detachment, rapid sequential displacement of loose cohesive sediments, flowing along the stream channel and crossing to the opposite side of the slope.
- The scenarios suggest focusing more attention on the detachment zone as it determines the mechanism of landslide development. The shape of the detachment zone (circular, linear, or curvilinear) and its lateral boundaries (straight, smooth, or sinuous) are important factors. The height of the detachment wall determines the maximum depth of the landslide and the location of springs. It is necessary to determine whether the detachment wall formed due to compression, extension or shear, and whether it resulted from a single sequential displacement or multiple movements of the rock mass.
- Scenarios for the formation of the spreading zone were based on the analysis of its connection with the formation zone and collapses from a safety perspective. The most dangerous

https://doi.org/10.5194/nhess-2023-110
Preprint. Discussion started: 1 August 2023

Natural Hazards and Earth System Sciences
Discussions

sections are those where there is no transit zone, and collapses occur directly at the locations of settlements. In such cases, the form of collapse is characterized by the absence of a covered stream channel and involves the destruction or removal of structures, indicating the direct movement of the landslide from the slope onto the terrace.

2. For surface landslide-flows and mudflows moving along the slope surface and the stream channel, the spreading zone differs in terms of length, width, thickness, rock composition, density and other factors. The main concern is the direction of movement, how it changes, and which direction the flow will be discharged when it reaches the main stream channel. It is important to assess the possibility of forming a collapse and how far it can spread to the opposite side of the slope.

3. Transverse collapses in loess deposits typically account for 0.5-0.6 parts of the landslide volume (30000-40000 m^3) and up to 1-2 million m^3 in clayey deposits. The height of a collapse varies from 2.5-3.5 m in loess deposits to 8-12 m in clayey deposits. The erosion process of a collapse in loess deposits depends on the water discharge in the channel and occurs after 20-30 minutes, lasting for 5-7 hours with a discharge rate of 0.5-1 m^3/sec. Erosion occurs in the form of a channel (rill) with a width of 2-4 m, which forms at the junction of the collapse and the opposite side of the channel. The erosion process starts not with the collapse itself but with the wetting of dry loess deposits on the opposite side due to the rise of the water level in the channel. As a result, a channel is formed in the junction zone, initially encircling the collapse and then eroding it, but not through overflow, rather through lateral erosion, preventing the occurrence of debris flows. Transverse collapses in clayey deposits have heights ranging from 8-12 m or more. The erosion process also occurs on the opposite side, not just in width but in depth, reaching the level of the stream channel. The erosion of a collapse in clayey deposits lasts for 3-5 years or more and does not transition into debris flows.

4. Longitudinal collapses of stream channels occur more frequently than transverse collapses and are considered more dangerous due to their complex and diverse scenarios. In all cases, the displacement is not a one-time event but multiple detachments in the upper zone, lasting several hours or days or recurring every 2-3 years. They are characterized by long distances of mudflow propagation (3-5 km) and a prolonged period of horizontal movement within the stream channel, ranging from several hours (6-7 hours) to 3-5 days. Additional rock volume from the channel is usually not captured during the movement. The length of a mudflow is typically determined by the volume of displaced rocks, rather than the initial velocity of movement. The formation of temporary dams - longitudinal collapses - is the most challenging to identify, as they can occur at the beginning of the mudflow due to a decrease in velocity in the lower layers or at the end of the mudflow due to a decrease in velocity, volume, and horizontal pressure above the moving rocks. The process of dampening horizontal movement of a mudflow is usually characterized by a uniform distribution of a 2-3 m thickness along the length of the flow. Analysis of mudflows has shown that longitudinal collapses can form in the middle section and reach heights of up to 30 m. This indicates that the soils are in a fragmented but not saturated state. Other collapses located in the middle section of the flow can undergo repeated movement and form new transverse collapses in the lower, more gentle part of the slope rather than within the stream channel.

Therefore, longitudinal blockages of stream channels by mudflows are diverse, occur more frequently, and pose greater risks to settlements located relatively far from the high-level stream channels

Data Availability

Data and pictures of the landslides were collected during the project *World Bank project "Unified Regional Risk Assessment for Earthquakes, Floods, and Analysis of Individual Landslide Scenarios to Strengthen Financial Resilience and Accelerate Disaster Risk Reduction in Central Asia"* and are not publicly available

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Authors contribution

RAN IFU and FZA collected the data and developed the analysis. RAN prepared the manuscript with contributions of all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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