The Role of Simultaneous Impact of Exogenous and Endogenous Forces in Landslide Process Activation

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Abstract

This paper reviews recent case studies completed on mass movements with probable co-seismic origin in the Uzbekistan part of Tien—Shan, Central Asia. Landslides, as any geological phenomena, formed due to simultaneous action of exogenous and endogenous forces. We consider simultaneous formation in the different areas of large landslides caused by the influence of these forces as a trigger effect. The nature of this connection, it is not only change of tectonic stress field, but at the same time the impact of climatic factors, the movement of groundwater, as well as the value of the natural frequency of oscillations in landslide-prone slopes. In this paper we consider the natural frequency of landslide-prone slopes in comparison with maximum spectral frequency of long-acting low-frequency oscillations of Hindu Kush earthquakes which caused major landslides in 2015 and spring 2016.

Keywords

Landslides • Earthquakes • Triggering mechanism • Case study • Resonance

Introduction

The influence of site effects on landslide triggering by earthquake impact has been presented in several studies, but its evaluation is difficult due to complexity of factors controlling dynamic response of potentially unstable slopes and also due to lack of local ground motion instrumental observations. While many seismic slope stability analysis methods exists with varying degree of complexity, details of interactions between seismic waves and incipient landslides are not well understood and rarely incorporated. For the last two decades, studies of resonance phenomena in the formation of landslides, has attracted interest of many researchers in different countries (Italy, Japan, Canada, France, Germany, Belgium, etc.). A variety of field studies have shown that Nakamura's (Nakamura 1989) empirical technique for estimating shear wave site resonance frequencies is a robust method that can present useful information about near-surface structure of the landslide site that may be used for landslide hazard assessment.

The interaction between seismic waves and hill slopes is complex (Geli et al. 1988; Sepulveda et al. 2010). Sparse field data and observations (e.g. ground motion records on or close to seismically deforming slopes), however, provide only limited insights into wave-slope interaction phenomena. Sepulveda et al. (2010) highlight the importance of topographic amplification in controlling landslide patterns, while Ashford et al. (1997) and Geli et al. (1988) emphasize that eigenfrequency excitation and topographic amplification are difficult to distinguish. Del Gaudio and Wasowski (2011) attribute high importance to site amplification arising from velocity contrasts between the landslide body and underlying bedrock. They further note that the preferred orientation of amplification may be controlled by a combination of topographic, lithological and structural factors that together redistribute wave energy. Bourdeau and Havenith (2008);

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M. Mikoš et al. (eds.), *Advancing Culture of Living with Landslides*,
DOI 10.1007/978-3-319-53485-5_2

Table 1 Landslide sites in various countries

Landslide	Date	M	Resonant frequency
Vittorio Veneto	1936	5.8	3.0–5.0
Ak-Bura, Kyrgyzstan	1994		2.5
Kainama, Kyrgyzstan	2004		3.0
Passo della Morte	2011		3.0–4.0
Machu Picchu			2.0–4.0
Alps, France			0.6–3.6
Apulia, Italy	2009	6.3	4.0
Kamikamato, Japan	2011	7.0	2.5

Havenith and Bourdeau (2010) found that amplification relevant for landslide triggering mostly arises from geological site effects (i.e., seismic velocity contrasts between material layers), while topographic amplification plays a secondary role. Torgoev et al. (2015) found predominant frequency of the Ak-kul landslide dam measured in most places about 3 Hz indicating an average thickness of 30–35 m. Locally this frequency could be lower (down to 1.3 Hz) where the thickness is close to 70 m. Based on the comparison results of the response spectra, Hata et al. (2015) determined that the effect of frequency components of the seismic waveforms on the earthquake induced landslide is less than 2.5 Hz. Multiple types of amplification can play a role in co-seismic landslide triggering. However, in-depth understanding of the details of wave—slope interactions, amplification phenomena, and landslide triggering does not currently exist. Slope analysis of the natural frequencies H/V of the data measured in the clay rock in various landslide sites in various countries showed that most resonance frequency range from 2.5 to 3.3 Hz at depths up to 30 m (Table 1).

Hindu Kush Earthquakes Triggered Landslides in the Spring of 2015 in 2016

Here we present observed factors of landslide triggering cases under the influence of long-term low-frequency vibrations of Hindu Kush earthquakes.

The work is aimed at a better understanding of the physics of landslides in dispersed soils triggered by distant earthquakes. It is associated with the place of moistening of contact zone between the moving mass of the landslide and the underlying clayey rocks, and the direction of the slope, which redistributes the wave energy.

Ground motions of these earthquakes with similar magnitude and depth, recorded at similar distance, may have significantly different waveforms and frequency content. Interesting events have occurred in the spring of 2015 and 2016. All secondary landslides formed in the circuses of old landslides in sandy-clay rocks under the influence of Hindu Kush earthquakes with hypocenters at depths of 95–227 km which are located at a distance from the epicenter from 408 to 520 km (Table 2).

Case Studies

Landslides formed in some places, at shallow depths (up to 30 m), and are local in nature, characterized by a closed system, where is located maximum vibration center. It is considered that most of present-day landslides are inherited process of the slopes. The ancient landslide cirques alter the shape of the slopes, expanding catchment area and concentrated surface runoff, where lithologic rocks varieties are favorable for movement of groundwater in the local areas and formation of the sliding surface. There are different tectonic faults in conjunction with the ancient erosion gullies have formed a closed system with localized sites of recharge, movement and discharge of groundwater. They are different in scale (0.7–5.0 million m^3), shallow (22–30 m),

Table 2 Landslides caused by earthquakes in the Hindu Kush in 2015–2016

Landslide	Date of earth-quake	M	Resonant frequency	Dis-tance, km
Chaigul	15.03.15	4.4	3.0	460
Nondek	24.03.15	4.3	2.8	408
Tegirmonkul	27.03.15	4.5	1.7	471
Khandiza	06.04.15	4.2	3.0	391
Duab	13.04.15	4.8	2.4	452
Karaily	18.01.16	5.0	3.0	521
Kaltatoy	26.03.16	4.3	2.5	465

Fig. 1 General view of Chaigul landslide

with simultaneous destruction of the structure and the loss of rocks strength and moving at different velocity and direction across the landslide area. They are characterized by maximum velocity of the vertical and horizontal displacements in the first days.

Chaigul landslide occurred March 16, 2015 in sand-clay rocks with volume of 2.7 million m^3 (Fig. 1).

Shape of the landslide in plan is triangular, with wide side in the upper zone equal to 350–380 m and very narrow at the bottom 20–30 m. The length of the formation zone is 280–300 m, the width is 350–380 m, i.e. width is greater than the length, the depth of displacement is 28–40 m. The zone of spreading is 250 m with thickness in lower zone 40–50 m. The date of formation of the landslide on March 16, 2015 coincides with the date of the Hindu Kush earthquake on March 15 M = 4.4, h = 173.8 km, duration 110 s, dominant frequency 3 Hz (Fig. 2).

Simultaneous displacement of rocks in different parts of the landslide was confirmed by high separation wall (30 m) and side ledges (20–28 m), and is characterized by a smooth surface. Moreover, the form of rocks fracturing throughout the area of the landslide has the same type of lateral direction and relatively uniform, which is typical for thixotropic liquefaction landslides. Horizontal displacement of the landslide within 3–4 days was 200 m. The landslide stopped at the zone of the limestone outcrops.

Landslide Nondek was formed March 24, 2015, with volume of 5.0 million m^3, and is located in the upper reaches of the Aksu River.

In the displacement has been involved all old landslide massif (1992) with total length of 1.8 km with a height difference of 436 m. The width of the landslide in the upper zone is 180 m, length 800 m, in the middle and lower zones width increased up to 390, and length is 1 km, the average depth is 10–12 m (Fig. 3).

Crack with length of 140 m, crossing the highway, within 3 h moved in 4.0 m. Repeated observations in the next day (25.03) showed that on the road area right side of landslide moved to 32 m, on the left—47 m, above the central part of the road was displaced to 10–12 m.

Reactivation of the landslide occurred within the boundaries of the old landslide under the influence of Hindu Kush earthquake, March 24 at 00 h 10 min (GMT), M = 4.3, H = 141 km, duration of 135 s (Fig. 4).

Landslide occurred in the area Khandiza in April 6, 2015, between 9 and 10 a.m., volume of 1.5 million m^3. The reason for its formation supposed the snow melting (up to 8.0 cm/day), and watering of the garden for 4 days (from April 2 to 5).

But as the trigger of the start of landslide movement, perhaps served Hindu Kush earthquake, which occurred April 6 at 5 h 21 min (GMT), M = 4.2, H = 128 km, duration 80 s. Entire contour of separation wall was delineated by cracks up to 3.0 m where a series of transverse cracks formed length of 50–60 m, width of opening 10–30 cm, all cracks were filled by water.

The length of the landslide in the formation zone on the right side and the upper reaches of up to 100 m in the middle

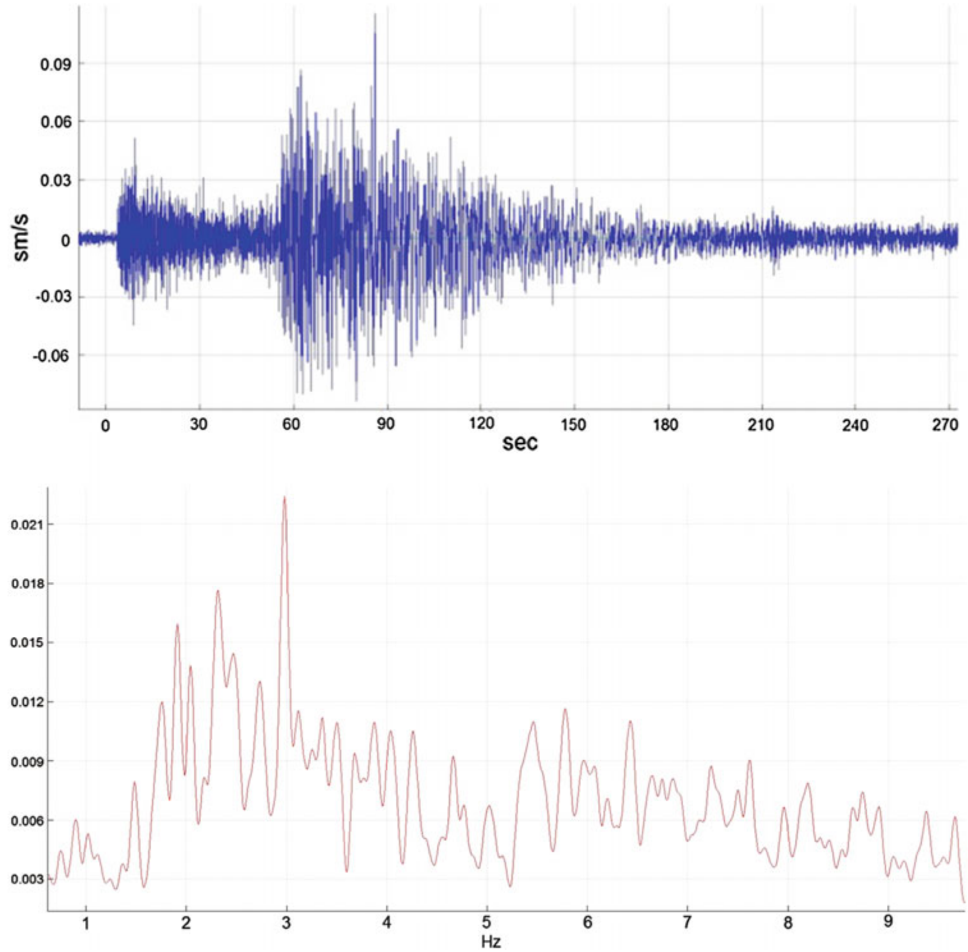

Fig. 2 Record and spectra of Hindu Kush earthquake 15.03.2015 (seismic station Samarkand)

Fig. 3 The upper and middle zones of the mud flow Nondek

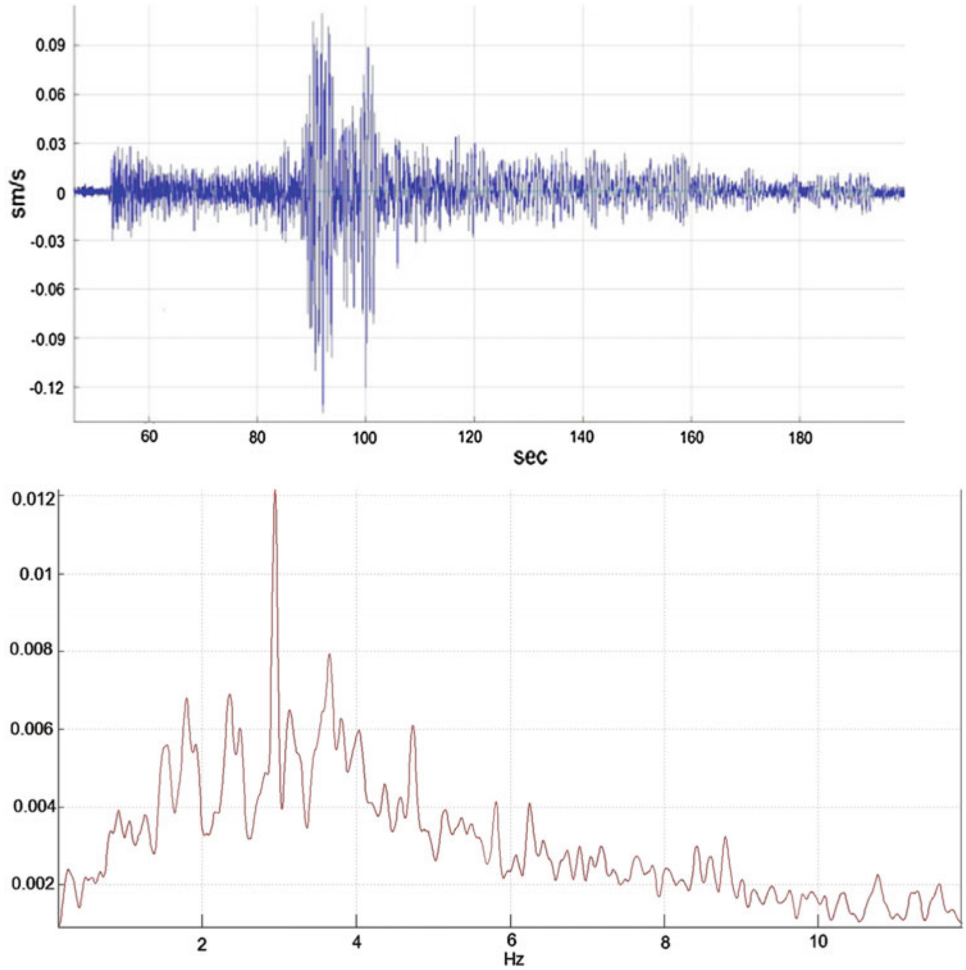

Fig. 4 Record and spectra of Hindu Kush earthquake 05.04.2015 (seismic station Ferghana)

and lower zones and the width of 640 m, i.e. width was 6 times greater than the length. The thickness of displaced ground in the upper zone is 30–35 m, 25–30 m in the middle and at the bottom to 25 m. As a result it was formed thixotropic liquefaction landslide in dispersed soils (loam, clay, sandstone), which transformed into mud flow (Fig. 5).

Landslide Tegirmonkul was formed in the circus of the old landslide in March 27, 2015, with volume of 1.0 million m^3. It's formation is associated with the Hindu Kush earthquake 27.03.2015 at 02 h 00 min (UTC), M = 4.5, H = 227 km, duration 80 s. It is combined by loess and sand-clay rocks with a large number (20%) of clastic rocks (Fig. 6). Basically, the new displacement of landslide occurred on the left side of the separation wall with length of 140–160 m and height of 30 m. The final run-off distance is 70 m in horizontal direction, and 20–25 m in vertical direction. The most active displacement occurred at the boundary zones. Above the separation wall and its lateral boundaries were formed many large cracks. In general, the upper zone has been settled, the lower has been raised to 2.0 m and blocked the channel of gully, above which formed small lake. The active landslide movement continued for 3–4 days. All this characterizes the simultaneous fragmentation of ground throughout the area of the landslide on the deeper sliding surface caused by resonant vibrations during Hindu Kush earthquake.

Landslide Duab (77 thous. m^3) was formed 04.13.2015 in the borders of the old landslide circus. Landslide formation place is confined to the place where the bed of Degomoron sai strongly undercut the slope at distance of 120–130 m up to the height of 10–14 m (Fig. 7) and became vulnerable to seismic vibrations. In the displacement are involved loess and sand-clay rocks, lying on the Cretaceous siltstones and sandstones.

Landslide is triangular in shape with an extension in the lower zone up to 110–120 m. Landslide has several blocks with different directions of movement and orientation of cracks. Particularly intense they occurred in the right side of the landslide. Total value of horizontal displacement was 5–7 m. The soils at a depth up to 5 m are in dry state. Therefore, the only source of landslide formation could be the earthquake that occurred in the Hindu Kush on April 13, M = 4.8 at a depth 94 km, duration of the vibrations of 130 s and a frequency of vibrations is 2.4–3.4 Hz (Fig. 8).

Fig. 5 Transverse cracks in the area of formation of the landslide Khandiza

Fig. 6 A general view of landslide Tegirmonkul

Landslide occurred within the boundaries of the old landslide circuses, in the Cretaceous waterlogged sandy-clay sediments and silt loams, which during long (90–150 s) low-frequency vibrations (2.5–4 Hz) instantly liquefied. It can be assumed that the basis of their mechanism is the phenomenon of resonance, when the maximum weakening of dispersed soils occurs due to sharp increase of amplitude of the vibrations in long low-frequency seismic vibrations.

Landslide Karaily located on the bank of river Kichik Uradarya and occurred January 19, 2016 with volume 1.8 million m^3. It was formed on a gentle slope with steepness in the central part 4°–6° and 12°–14° in the lower zone (Fig. 9). The form of cracks in the surface is characterized by the simultaneous formation of three separation walls, separated by longitudinal gullies. In addition, each separation wall is characterized by its graben shaped cracks

Fig. 7 General view of Duab landslide

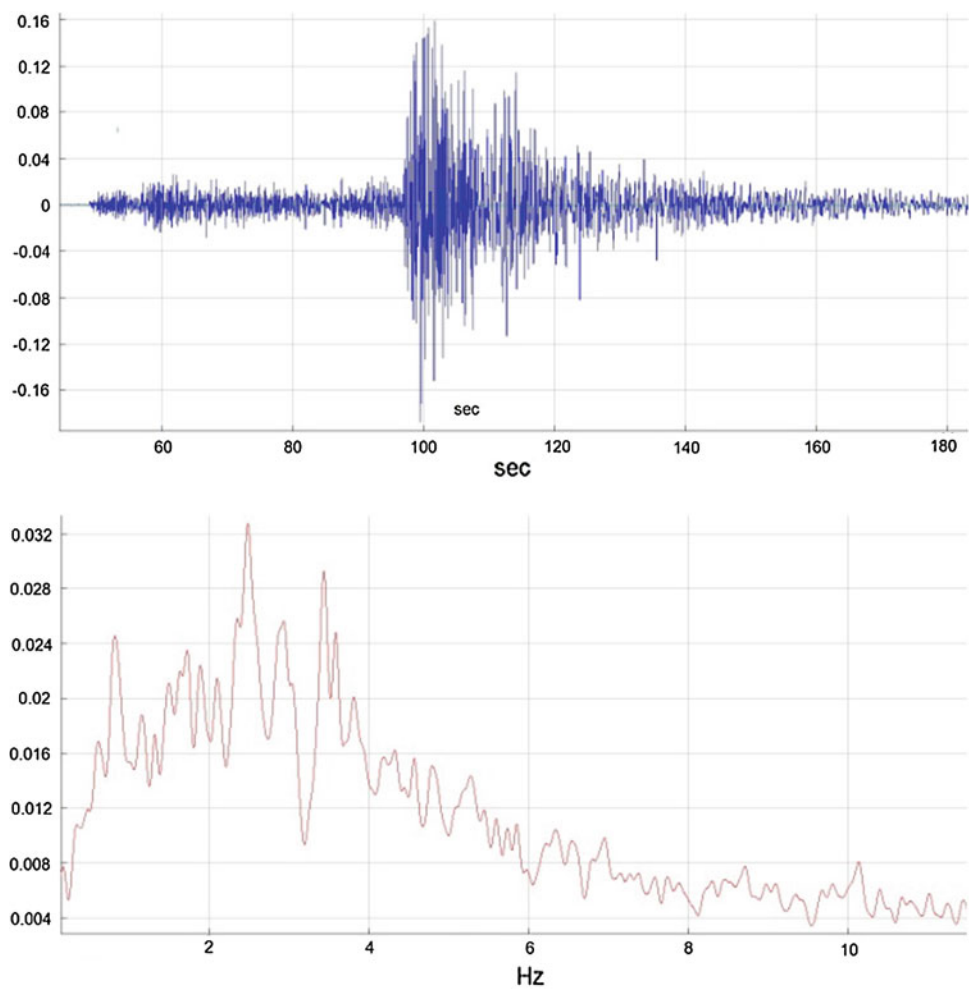

Fig. 8 Record and spectra of Hindu Kush earthquake 13.04.2015 (seismic station Pachkamar)

in width from 20 to 50 m and an amplitude of 2–6 m. Landslide has spherical form, the maximum width in the central zone—360, 280 m the upper and lower—160 m. Separation wall height is maximal in the landslide center 18–22 m, in the lateral zones of 8–10 m. Formation time of the landslide is connected with Hindu Kush earthquake of

Fig. 9 Photo of Karayli landslide

17 January 2016, M = 5.0, H = 180 km, duration of vibrations 130, dominant frequency 2.95 Hz (Fig. 10).

The surface of the landslide was damaged by longitudinal and transverse cracks with stepped shape, with length of 40–80 m and amplitudes up to 1.5 m. The transverse compression fractures are located below the central zone, the area is characterized by compression between the fixed and movable area, characterized by uplift of rocks over 60–80 m, with amplitude of 2–3 m. All this characterized vertical lowering of landslide mass of 10–20 m, with horizontal run-off of ground at a similar distance. Riverbed of gully was not blocked, but groundwater, formed small lake (7 × 5 m). After 7 days, the lake area increased up to 22 × 10 m. The landslide is in the active state.

Strong Hindu Kush Earthquakes Which not Caused Landslides

October 26, 2015 in the Hindu Kush occurred strong earthquake, M = 7.5, depth 212.5 km. It is characterized by a long duration (4–5 min) and very low dominant frequency of oscillations 0.16–0.31 Hz (Fig. 11). Then, in the next few days from 26 to 28 October there were another 15 aftershocks with M = 4.1–4.8, at depths ranging from 195 to 216 km. After the earthquake State Survey for Monitoring of dangerous geological processes conducted survey in the foothill areas, but new manifestations of landslides were not found. We suppose that it was due to the fact that the loess and clay rocks on the slopes were dry due to the lack of precipitation in the summer.

April 10, 2016 occurred Hindu Kush earthquake M = 6.6, H = 212 km, duration 180 s, dominant frequency on different seismic stations Fergana 0.3–0.5 Hz, Charvak—0.7 Hz, Kitab—1.2, Pachkamar 1,1 Hz. Precipitation for April 10 at the foothill zone is equal to 20–40 mm, which is a very small amount. As a result, new large landslides were not occurred.

Comparison of the Predominant Oscillation Frequency

We analyzed changes of maximum frequency spectra of vibrations depending on the distance from seismic stations of Institute of Seismology, in comparison with location of potential landslides area. Most close station between 12 and 48 km—Pachkamar station, 32 and 90 km—Kitab station. Far stations are Samarkand at 72–132 km, and Tashkent at 300–370 km. However, it is not observed large variation of spectra of dominant frequency of Hindu Kush earthquakes, triggered landslides in 2015 and 2016. Dominant frequencies measured at different stations range between 1.2–1.5 and 2.5–3.0 Hz. Comparison of earthquakes frequency spectra, triggered landslides with dominant frequency of strong earthquakes with M = 7.5 and M = 6.6 (0.2–0.5 Hz) showed that vibrations has much lower frequency. Perhaps this is the reason that it does not cause deformation of the

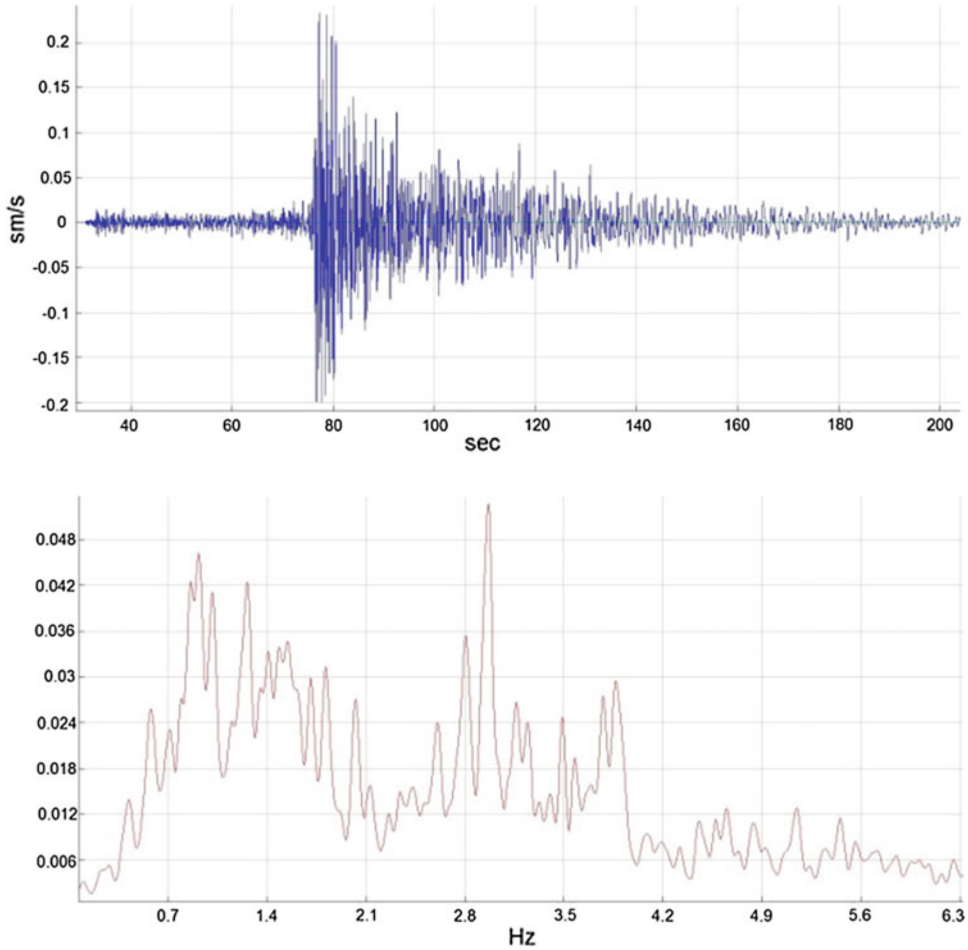

Fig. 10 Record of Hindukush earthquake 17.01.2016 (seismic station Kitab)

rocks due to the mismatch of the dominant frequency of strong earthquakes and natural frequencies of landslides.

The effect of resonance amplification of seismic waves by near-surface unconsolidated soils leads to the fact that, depending on the soil type and thickness, amplitudes in some frequency ranges may be selectively amplified, and the other is almost completely absorbed. For example, as a result of seismic observations in the landslide areas in Kyrgyzstan and Tajikistan were identified own landslide frequency in the range of 1.3–3 Hz depending on soil and layer thickness (Torgoev et al. 2015).

Peculiarities of Landslides Occurrence

Characteristic property of landslides caused by resonance fluctuations is formation of the separation wall from the surface up to the depth of sliding surface with slope 85°–90° and smooth surface. At the same time it delineates the entire area of the landslide and cracks of compression and tension. Landslides mainly occurred on the gentle slopes of 10°–15°, where the underlying clay rocks are watered. In the displacement usually involved sand-clay rocks of Cretaceous age with average thickness 20–30 m. The width of the landslide in the formation zone is greater than length.

Conclusion

Landslides in 2015 and 2016 are formed in the sand-clay rocks in tectonically disrupted areas in the old landslide circuses under the influence of deep Hindu Kush earthquakes located at a distance of 400–540 km. Analysis of the data of natural frequencies of the slopes measured on landslides in various countries showed that the resonance frequency is generally ranges from 2.5 to 3.5 Hz at depths up to 30.0 m. All investigated in this paper landslides are characterized by a one-time simultaneous displacement, occurred at dominant frequency of earthquakes vibrations 2.5–3.5 Hz and duration nearly 180 s. We suppose that they have been caused by resonant vibrations in these sites, because at dominant frequency of oscillations 0.16–0.35 Hz with higher amplitudes of vibrations of Hindu Kush earthquakes the landslides were not occurred.

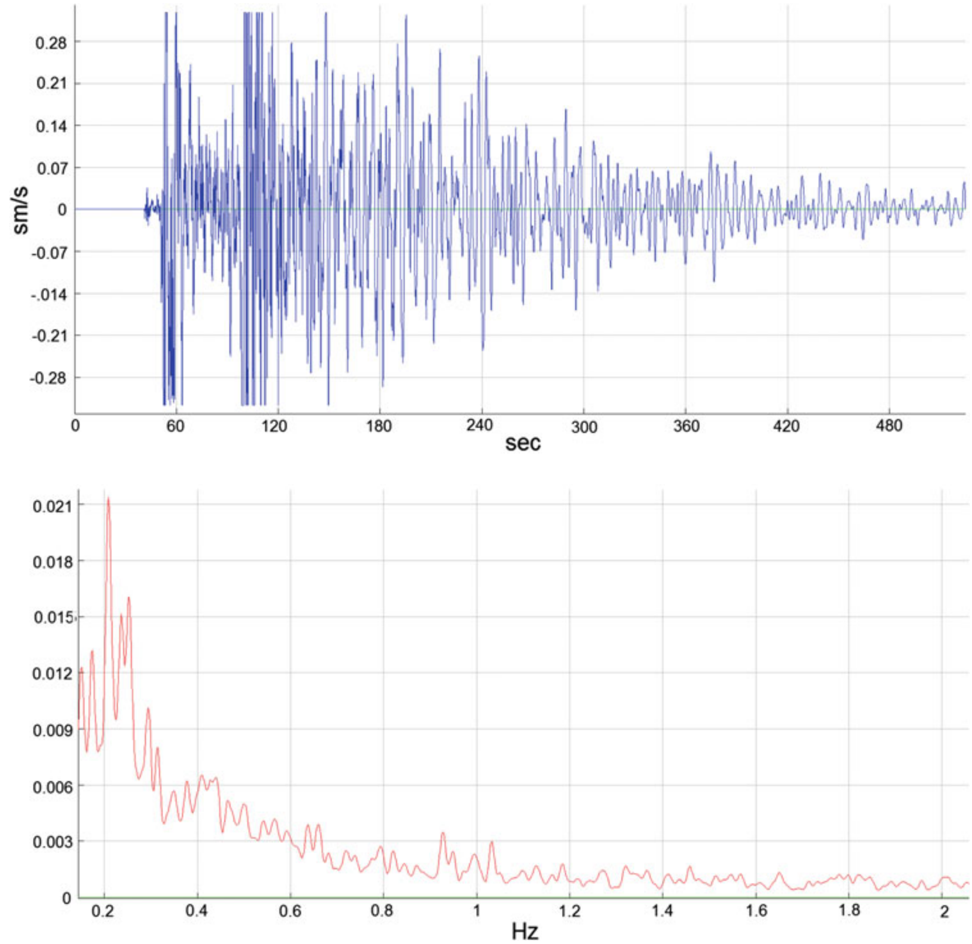

Fig. 11 Record of Hindu Kush earthquake 26.10.2015 (seismic station Fergana)

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http://www.springer.com/978-3-319-53484-8

Advancing Culture of Living with Landslides
Volume 4 Diversity of Landslide Forms
Mikoš, M.; Casagli, N.; Yin, Y.; Sassa, K. (Eds.)
2017, XXII, 707 p. 554 illus., 500 illus. in color.,
Hardcover
ISBN: 978-3-319-53484-8