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Justification of seismic triggering of large prehistoric rockslides in Zagros (Iran) and Greater Caucasus (Russia)

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Abstract. Justification of seismic triggering of large prehistoric rockslides that originated on the slopes of anticlinal ridges armoured by thick carbonate units has been performed by examples of the gigantic Seimareh rockslide in Zagros (Iran) and two structurally similar, though much smaller rockslides in Dagestan (Greater Caucasus, Russia). Such structural and geomorphic conditions allow precise reconstruction of the pre-slide topography of the studied sites that increases reliability of their back analysis significantly. Linear dimensions of landslides are much larger than thickness of the siding block that makes the simplified 2D numerical modelling of these slopes quite realistic. The pseudostatic analysis performed at the first step confirmed that the study slopes could not fail without strong earthquakes. However, further dynamic analysis performed by use of the Newmark method allowed estimating characteristics of strong motions that could result in formation of rockslides that had converted in long runout rock avalanches. Possible uncertainties and open problems are discussed as well.

1. Introduction
Finding of the actual triggering factors of large prehistoric landslides is a real challenge and its reliability is critically important for both landslide and seismic hazard assessment, as far as they are often interpreted as evidence of strong past earthquakes. However, numerous historical case studies demonstrate that very large landslides, those in the hard rock in particular, can either be triggered by strong seismic shaking, or can occur without any earthquake. Various criteria have been proposed to prove seismic origin of large prehistoric rockslides [1, 2, 3, 4], but neither size (volume) of a landslide, nor runout can be considered as indicator of their seismic origin [5, 6].

One of the most promising ways to reveal their actual trigger is the back analysis of slope stability at the sites where such landslides had occurred [7]. Such analysis, however, faces three major problems: 1) uncertainty of the mechanical properties of rocks and rock massifs used as an input data for the numerical modelling; 2) difficulties in reconstructing the pre-slide topography that predetermines mass distribution in the slope model; 3) impossibility in most of cases to determine in advance what earthquake could trigger the slope failure in question.

The first problem is typical for any geotechnical study and can be solved by rock sampling and testing. The second one seems to be even more ambiguous, except some particular cases that have been the focus of our study. We analyzed large rockslides that had originated on the ridges formed by anticlines armoured by thick relatively hard limestone units with constant thickness and constant or slightly changing dip angle, underlaid by much weaker marl or terrigenous units. If landslide had affected the upper armoring unit only, the pre-slide topography can be reconstructed with high precision, which is impossible in most of other cases. Besides, fracturing system of this rock mass can be studied with confidence using the geology structure of the headscarp back and side walls. Such conditions are typical of Zagros mountains in Iran, of the famous Seimareh rockslide (rock avalanche) about 30 km^3 in volume in particular [8, 9, 10, 11, 12, 13], and for numerous structurally similar, though much smaller rockslides (rock avalanches) in Dagestan (Russia), in the north-eastern part of the Greater Caucasus [14], two of which were modelled. These rockslides, especially the Seimareh one, have been considered as earthquake-induced features [15, 16].

This paper presents an attempt to solve the third problem – to determine strong motion that could trigger the studied rockslides. Further it could help to assess parameters of earthquakes that produced such accelerograms – at what distances from the site they could occur, their magnitudes and focal mechanisms.

2. Geology and geomorphology of the study sites

Both the Seimareh rockslide and the Western Gergebil and Kakh rockslides in Dagestan can be classified as the translational slides of thick carbonate blocks underline by much weaker terrigenous or marl layers.

The Seimareh rockslide (33.01° N, 47.6° E) displaced the carbonate unit of the Oligocene-Miocene Asmari formation armouring the northern slope of the Kabirkuh Ridge that corresponds to the northern limb of the same-name anticline (figure 1). The displaced block was about 15 km long, 5.0-5.5 km wide (in dip direction) and 300-350 m thick (figure 2). The slope has almost constant inclination of 13-14° and its structural position can be classified as a monocline (figure 3). The Asmari formation is underline by the Paleocene-Lower Oligocene Pabdeh formation – marl and marly shale with much lower strength than the Asmari limestone [17]. In the central part of the source zone, where the headscarp is deeper, the Pabdeh sediments were either eroded afterward or, probably, involved in slope failure. It should be pointed out that the armouring unit had not be undercut at the slope base by erosion prior to landslide but was sheared, most likely following some fracture system(s).
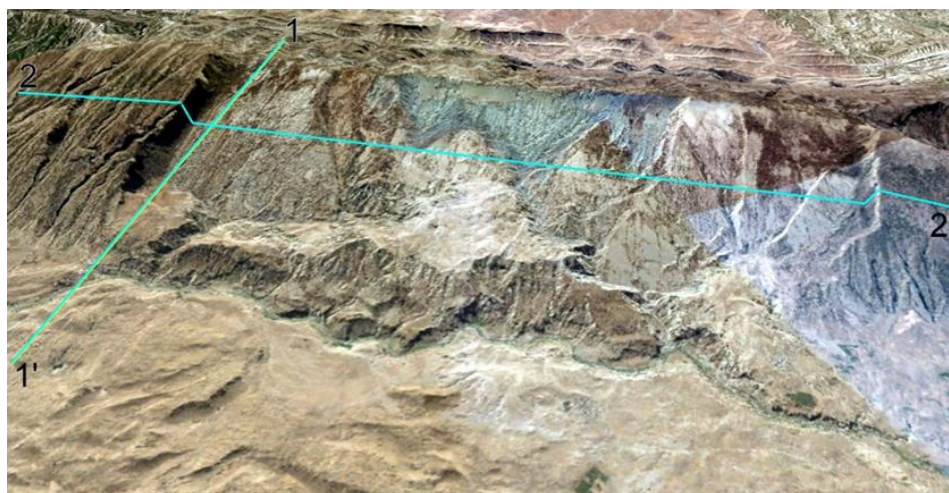

Figure 1. 3D Google Earth image of the Seimareh rockslide headscarp. Cross-section 2-2' is shown in figure 2; cross-section 1-1' – in figure 3
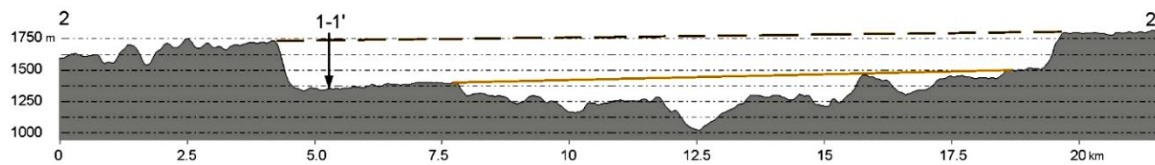
Figure 2. The profile 2-2' along the Seimareh rockslide headscarp derived from the 1" SRTM DEM. Dashed dark brown line – the reconstructed pre-slide daylight surface; solid light brown line – the assumed sliding surface at the sections where it could be eroded subsequently
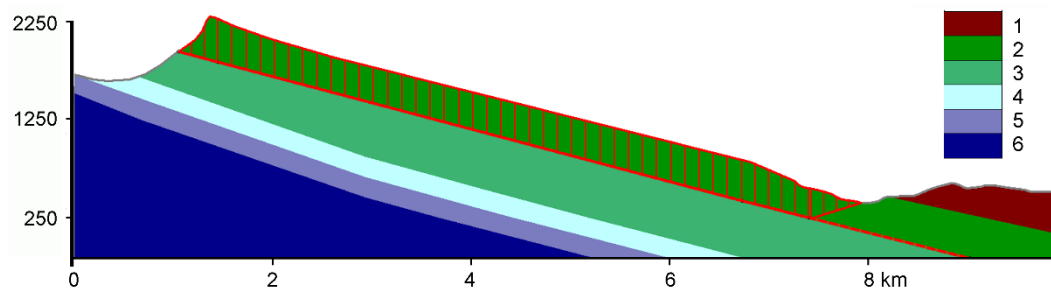

Figure 3. Cross-section of the reconstructed Seimareh slope (cross-section 1-1' in figure 1) and its computational model. Formations: 1 – Gachsaran, 2 – Asmari (limestone), 3 – Pabdeh (marl and marly shale), 4 – Gurpi, 5 – Laam, 6 - Sarvak

The studied Dagestan rockslides – the Western Gergebil at 42.542° N, 47.028° E (figure 4) and the Kakh at 42.55° N, 46.79° E (figure 5) had originated on the slopes of the anticlinal ridges armoured by the Lower Barremian thick-bedded limestone 50-90 m thick underline by the Upper Hauterivian shale and sandstone 35-60 m thick. They, in turn, are underline by the alternating carbonate and terrigenous sediments of the Lower Cretaceous and Upper Jurassic age [18]. Lower Barremian carbonate unit is represented by dense crystalline, oolitic and organic limestone, dissected by several fracture systems. Two of them are conjugated shear fractures dipping steeper and gentler than bedding, while other crosscut limestone layers almost perpendicular coinciding with rockslide headscarps back- and sidewalls. The main sliding surface is coincident with some weak layer in the terrigenous Upper Hauterivian unit and crosses the slope base, likely being associated with shear fractures in limestone dipping gentler than bedding. Position of the modelled cross-sections is shown in figure 6.

Figure 4. View of the Western Gergebil rockslide headscarp about 860 m wide (along the slope).

Figure 5. View of the Kakh rockslide. Headscarp is about 1200 m from its backwall to the slope base. Village is located on rock avalanche deposits
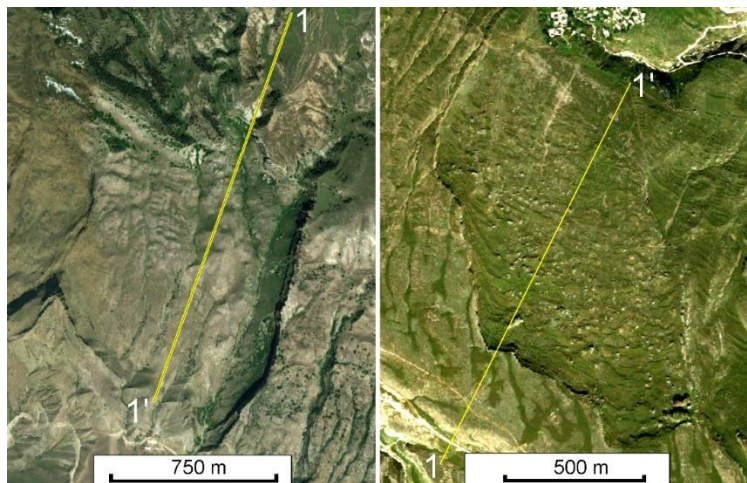
Figure 6. Position of the cross-sections used for the 2D numerical modelling of the Western Gergebil (left) and Kakh (right) rockslides

Unlike the Seimareh rockslide, both Dagestan slides had originated on the convex slopes. At the Western Gergebil site dip angle increases gradually from 12-13° at the upper part of the headscarp up to ca. 28° at the slope base (figure 7), while at Kakh site change of the dip angle is from 13-14° on top to 31-32° at the slope base is more pronounced (figure 8).
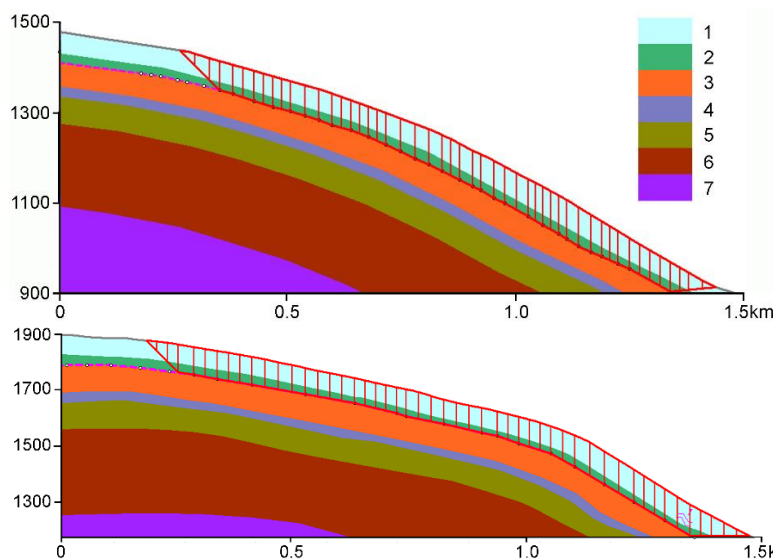

Figure 7. Cross-section of the Western Gergebil rockslide headscarp and its computational model. $1 - K_1b_1$ (limestone), $2 - K_1h_3$ (sandstone and shale), $3 - K_1h_2$ (limestone), $4 - K_1h_1$, $5 - K_1v$, $6 - J_3$, $7 - J_2$

Figure 8. Cross-section of the Kakh rockslide headscarp and its computational model. See legend in figure 7.

3. Methods

Since linear dimensions of all three landslides are much larger than thickness of their siding blocks, the 2D numerical modeling quite reliable. Calculations were performed considering the heterogeneity of the mechanical properties of the assumed sliding zones.

At the first stage the pseudostatic 2D numerical modelling of the reconstructed slopes was performed aimed to access its safety factor without seismic loading and seismic intensity required to initiate slope failure, in other words to decrease safety factor below 1.0 [14].

Hazard zoning in seismically prone regions such as Zagros and Greater Caucasus, however, requires not only knowledge of seismic intensity that is characterized in most of construction and slope stability assessment codes by acceleration values (PGA or spectral acceleration). As it was demonstrated, for example, in [19], sometimes landslides occur in the areas with medium recorded PGA, while areas with maximal PGA values have no or just few seismically induced landslides. To perform more physically based and comprehensive slope stability modeling the spectral characteristics

and duration of strong motion are as important as PGA value. Such data can be derived from the deterministic or probabilistic seismic hazard analysis that requires identification and characterization of the potential seismic sources and attenuation regularities (see, e.g., [20]). This approach is, however, out of the scope of our study.

The alternative way much more closely related to landslide studies is based on the dynamic back analysis of slope stability at the sites where landslides whose seismic origin was proved by the pseudostatic analysis had occurred. By performing numerical modeling, the critical acceleration time history required to destabilize the slope can be derived. It makes grounds to estimate, further, what earthquake could produce such effect. Could the studied slope fail due to local shallow-foci earthquake with medium magnitude, say M=5.0-6.0, that had occurred close to the rockslide side? The intensity of such earthquake could be quite high within the epicentral zone that can be exemplified by the 8-point 1966 Tashkent earthquake with M=5.1±0.2 [21] or by the 9-10 points 1960 Agadir earthquake with M=5.7-5.9 [22]. Or rock slope failure in question can be triggered by large earthquake with M>7.0 only, as it was anticipated by Macdisi and Seed [23], either close to the site or more distant? Correct solution of this problem is critical for both landslide and seismic hazard assessment in the study regions and requires the dynamic analysis when input seismic load is provided as the acceleration time history characterized not only by PGA but also by its duration and spectrum.

In this study effect of the earthquakes on slopes' stability was modeled by the Newmark method [24]. Landslide was considered as a rigid block that slides over the inclined surface with friction. The amount of its displacement was obtained by double time integration of acceleration exceeding the critical value that is necessary to overcome the static friction and to start downslope motion along the potential sliding surface (bedding plane in our cases). It requires, besides providing the acceleration time history, to determine the threshold acceleration with which force affecting the slope exceeds the friction force. No doubts that such approach simplifies real situation significantly. It does not take into account large dimensions of the sliding block comparable with seismic wave length that could result is some asynchronism in the ground motion. However, consideration of such effects requires much more complicated computational model, since the asynchronism would variate significantly depending on the direction of seismic waves propagation. Here we present more general and simplified approach.

It was assumed that the horizontal PGA that triggers landslide also results in the formation of the sliding surface that in all three cases coincides with weak layer in the sedimentary unit underlying the armouring limestone unit. Further motion takes place along this, completely developed sliding surface and, thus, calculating of the amount of displacement, one should consider not maximal (static), but the residual strength of soil within the main deformable layer (sliding surface). Following [25] we took 1.0 m as the critical displacement, which excess results in the undamped (catastrophic) slope failure.

The synthetic acceleration time history used for the Newmark analysis and its Fourier spectrum (figure 9) was sorted out to be able to trigger rockslides at the study sites and should be considered as just a model input allowing comparison of possible effects of earthquake on slopes' stability. The main criteria of its selection were the PGA and spectrum necessary to initiate slope movement.
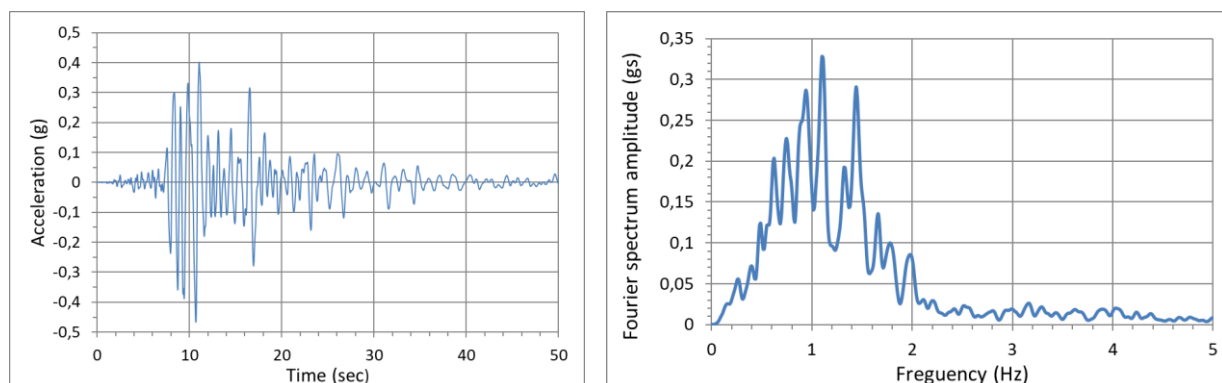

Figure 9. The input acceleration time history (left) and its Fourier spectrum (right)

4. Results

The pseudostatic analysis performed for all three case studies (Seimareh, Western Gergebil and Kakh) revealed safety factor exceeding 1.35-1.75 that means that their failure was impossible without seismic loading. Further modeling including seismic load proved that all these landslides could be triggered by earthquakes with intensity of 8-9 points of the MSK-64 scale [14]. These data were considered as a starting point for further analysis of the effect of earthquakes on the stability of the studied slopes.

Calculations performed by the Newmark method demonstrated that earthquake triggering conditions of the Western Gergebil rockslide differs significantly from those of the Kakh and of the much larger Seimareh rockslides and that these differences are caused by their different reaction on seismic loading.

The acceleration values with which the study slopes became unstable and corresponding values of safety factor (SF) were calculated using the Janbu method [26] and are provided in table 1.

Table 1. Safety factor (Sf) before and after earthquake and PGA required to produce slope failure.

Rockslide	Sf without seismic loading	PGA required to overcome rock strength at the bedding plane used as a sliding surface	Sf after strong motion pulse with PGA	Further acceleration providing safety factor value less than 1.0
West. Gergebil	1.35	0.130	0.92	0.00
Kakh	1.75	0.240	1.25	0.08
Seimareh	1.60	0.154	1.20	0.05

For the Western Gergebil rockslide just the minimal horizontal PGA value of 0.13g appeared to be critical and the slope affected by such strong motion became unstable and, according to modeling results, should slide further even without seismic loading. In such cases slope stability assessment can be performed by pseudostatic method. However, verification of the correctness of such approach should be confirmed by the Newmark analysis.

Slope stability analysis of the Kakh and the Seimareh rockslides revealed totally different results. In such cases seismic shaking is required not only to initiate sliding, but to sustain further displacement of the sliding block too.

At the Kakh site block sliding initiates with horizontal PGA$\geq$0.24 g. However, when the most intensive phase of strong motion terminates, sliding terminates too (safety factor regains up to 1.25) and to maintain further displacement horizontal acceleration of $\geq$0,08g is required. Thus, high intensity of shaking, even exceeding IX points of the MSK-64 scale, if it is provided by short high-frequency and high-amplitude shaking, most likely would not result in the complete slope failure, since the cumulative displacement would not reach the threshold value, despite in the engineering practice just the PGA is usually correlated with seismic intencity.

Same situation was found for the Seimareh rockslide, though its motion was found to start at lower PGA (0.154 g) and the subsequent acceleration providing safety factor value less than 1.0 should be slightly lower too (see table 1).

For this to happen, strong motion should be prolonged enough, rather intensive (with high amplitude) and with prevailing low-frequency vibrations (see e.g., in [27]). It corresponds with results of Makdisi and Seed [23], who performed the Newmark analysis for strong motions of earthquakes with different magnitudes. They derived that those critical displacements can be provided by earthquake with M~7.5 with maximum of the spectral power density at frequency of about 1 hertz. In such cases use of the pseudostatic back analysis would be insufficient to provide reliable assessment of slopes' stability.

We must point out that assessment of the cumulative displacement required to produce further slope failure is rather problematic and cannot be considered as being finally established. Several attempts to correlate calculated values with field data were performed after the 1994 Northridge,

California earthquake [28-31]. Similar analysis for landslides triggered by the 2014 Mw6.1 Ludian earthquake in Yunnan Province, China was performed in [32]. Here the permanent displacement range from 0 to 1.22 m, thus being comparable with 1.0 m considered in our analysis as critical. However, as mentioned in [29, 32], most of these slope failures were shallow falls and slides and, thus, their results are applicable for such types of landslides that differ significantly from the case studies discussed herein. Besides, results of calculation could not be compared with direct measurements for the events that occurred millennia ago.

5. Discussion and conclusions

The revealed results were obtained under certain assumptions. First, the 2D calculations do not consider any boundary effects. Second, the exact location of the main sliding surface is also not known, since weak sediments underlying the armouring limestone unit underwent significant post-sliding erosion. Third, we considered the sliding limestone unit as a rigid block, while in all three studies cases the initial blockslides had converted into rock avalanches. It can be assumed, based on numerous observations of recent rockslides that such transformation occurs at the early stage of rockslide formation. But how early? Considering that most intensive phase of strong motion can last from few seconds to several dozens of seconds, it might be a quite important factor.

The numerical modelling demonstrated that while the Western Gergebil rockslide could be triggered by any earthquake that could produce horizontal acceleration at this site exceeding 0.13 g, formation of the Kakh and Seimareh rockslides required the prolonged low-frequency shaking typical of large earthquakes with magnitude exceeding 7.0. Since magnitude is proportional to source rupture length [33], in Zagros, where neotectonic folds and blind faults that can be associated with anticlines in the vicinity of the Seimareh rockslide are about 100 km long, such earthquake(s) should be considered as quite reliable phenomena. However, in Dagestan such conclusion contravenes somehow with the present-day regional seismotectonic concept. It can be speculated of course that so large earthquakes are extremely rare and their causative fault(s) remains unknown. An alternative explanation is that the Kakh slope failure could be a cumulative effect of several earthquakes. Large number of structurally similar rockslides identified in Dagestan on anticlinal limbs demonstrate that sometimes their formation was rather common. We plan to model more case studies to get some statistics. Important additional information can be provided by extensive dating of such features that can be performed using the cosmogenic nuclides and OSL methods.

One more challenging problem is how to reveal the mechanical properties (strength) of the sliding properties after a strongest phase of an earthquake, when the sliding calculated by the Newmark method has terminated? Will it remain equal to the residual strength, or will recover to the initial pre-slide value (likely not), or to some intermediate state? And how it depends on the time passing after first, initial earthquake-induced displacement?

Data presented demonstrate that well-grounded justification of seismic triggering of large prehistoric rockslides based on the numerical back analysis of slopes stability is a complex and challenging problem even if their pre-slide topography can be reconstructed with high accuracy.

Acknowledgements

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