Seismically Induced Delayed-Landslide in Synej-Bagoje (Albania), March 2009

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Abstract

Seismic, geomorphologic and meteorological patterns of March 21, 2009 landslide in Kavaja region, (western Albania) have been thoroughly analyzed in this paper. Our comprehensive analysis aims to highlight the role of the possible factors influencing the activation of Bagoje's landslide, focusing especially on seismological ones. The landslide affected the Bagoje village, W-SW of Kavaja, causing severe damages. This mass movement was preceded and followed by an intense micro-seismic activity. It occurred 72 hours after the earthquake of March 18, 2009 (M4.3), located 6 km offshore to the west, one of the largest events among a series of 51 earthquakes that continued from January to September 2009. Several fault segments, part of the Periadriatic Foredeep tectonics, have been instantaneously and dynamically activated as it is indicated by the migration of epicenters from Rreth-Grethi to Durresi, concentrated mainly around the landslide area. From the geological point of view, this region is largely constituted by Pliocene formations, represented by the deposits of Helms and Rrogozhina suits, of the lower to middle Pliocene correspondingly. With regards to meteorological patterns, as indicated by measurements of Vrapi meteorological station (about 25 km to the east), the period from January to March 2009 has been characterized by moderate seasonal precipitations. As for the role of seismic triggers it is clearly shown using focal mechanism solutions and principal stress orientation. Our findings support the near-field effect of the local strike-slip tectonics to the affected area, which cuts through the longitudinal tectonic lineaments along Ballaj-Kryevidhi-Karpen. Results reveal the characteristics of the Bagoje's landslide as a seismically induced delayed one.

KEYWORDS: seismic induced, delayed landslide, seismic action

1. Introduction

On March 21, 2009, an enormous mass movement occurred on the eastern slope of the hilly terrainsin Bagoje village, 6 km W-SW of Kavaja, along the western Albanian coastline. Field observations evidenced the completely destruction of nine dwellings and relief effects, classifying this landslide asemergent risk to this location, (Daja, Sh., et al., 2011). It occurred 72 hours in delay to the March 18 (M4.3) earthquake, the major seismic event of the sequencestarted on February and lasting till August2009, numerating 51 earthquakes. In spite of the fact that co-seismic landslides,the most historically well known and frequentmass movements worldwide, are typically instantaneous to moderate and large earthquakes (Keefer, D.K., 2002),another wayof theiroccurrence is significantly after the end of earthquake shaking, i.e. delayed failures. Mostly,co-seismic landslides have been observed so far in Albania, singling outthe earth slides caused by 1905 (M6.6) earthquake, on both banks of Buna River; two earth slides on Stogos mountain slope caused by1930 (M6.4) earthquake, respectively 15-70 m long and 15-50 m wide; five earth slides in Gjergjevica, Polena, Lavdar and Vithkuqi villages, caused by1960 (M6.4) earthquake; several earth slides caused by1967 (M6.3) earthquake, sized 20-30 m to 50-70 m along of the Drini river; 5 earth slide on the Taraboshi Mountain slopes, 13 earth slide on Buna River banks and 9 earth slide in Lezha's Drini River bank, caused by1979 (M6.9) earthquake, sized from 10-20 m to 50 m in length. Up to now there is no documented evidence on delayed seismic landslide. Worldwide cases show thatlater have been mainly observed in cohesive soils, predominantly silt and/or clay slopes (Wartman, J., 2010). It has been hypothesized to be a result of one or more circumstances, but the most likely triggering mechanism is supposed to be a transient state of effective stress associated with excess pore water pressure generation/dissipation, known as void redistribution mechanism, (Malvick, E.J., et al., 2006). Therefore, this paper is based on a comprehensive analysis of all possible factors triggering the Bagoje's landslide, aiming to highlight the main role of seismic activity as the primary dynamic factor.

2. Method

A comprehensive analysis of possible passive and active factors, and/or a possible interrelation between them is the basis of the applied method. Triggered landslides, especially on the areas affected by earthquakes, are primarily controlled by the earthquakes magnitude and their focal depth. Although other factors, difficult to be quantified, such as rock mass stability and ground water regime, are considered important in determining susceptibility to failure of slopes during earthquakes. On the other hand, asymmetry, directivity, the type of acting mechanism (focal mechanism) as well as activated fault to landslide distance is very important factors to judge upon the landslide-earthquake interaction, being either co-seismic or delayed seismic triggered ones. In the following sections, the geology, geomorphology, hydro-geology andseismicity patterns along with meteorological conditions are analyzed.

2.1 Geological patterns

The case study region,extending along Ballaj-Kryevidhi-Karpeni,is situated northwestof the Pliocene-Quaternary structures of the Periadriatic Depression (Aliaj, Sh., 2012). This binder like structures,composed by Pliocene deposits, spreadalong the western lowland of the Periadriatic Foredeep, from Vlora to Ishmi. Pliocene formations are represented here by Helmesi and Rrogozhina suites, corresponding namely to the Lower and Middle Pliocene. Both these formations differ in being composed by a rhythmic combination of clayey, silt-sandy, and of sandy with substantially thick gravelite-gravelly layers, respectively. Relationship between Miocene-Pliocene structures,to the surrounding geological environment in the Periadriatic Foredeep, is mainly tectonic and partially in a stratigraphical discordance. Tectonic contactshave been observed primarily from the regional morphology, where positive structures rise up in the middle of the plain terrain, with steep slopes dipping towards the lowland. Tectonics is young and very active,dating since the Holocene, which is constituted of thrust and back-thrust faults with southeast to northwest extension. Longitudinal tectonics, on both sides of Ballaj-Kryevidhi-Karpeni structure, is dissected by a transversal dextral strike-slip fault, on the northern side. All the faults along the Periadriatic Foreland, of the Middle Pleistocene-Holoceneage, appear active nowadays. Their seismic activity is particularly high on the northern side near Durresi, and on the south, near Fieri. Region under studyis characterized moderate seismic activity.

2.2 Geomorphological patterns

Slided slope is built up ofsandy-alevroliticdeposits of Pliocene, striking 230^0 – 235^0 and dipping 50^0 – 55^0, to the northeast. These layers are inclined 12^0 - 18°, ending at a watershed to the west-southwestern side. This watershed is located 50-80 m from the crest of the slide slope. From this point to the west, the terrain dips 15^0-25^0, in the opposite direction to the scarp, over a sector 50-60 m in width, (Daja, Sh., et al., 2011). The landslideshows a block slide pattern, (Figure 1). Depth to the sliding bed is determined 12 m, through the resistivity tomography method. The totalrock matrix thickness is determined 20 m. Block displacement is observed showing the presence of old sliding. Thick material penetrating through these block cracks as wedge inserts, probably has allowed the percolation of the surface water. While, underground waterpercolated through the sandy layers, towards the clayey layers of Rrogozhina’s suite by decreasing the frictional resistance between layers, leading to the excessive shear stress domination. Based on above, the contact between sandy and clayey layers,arriving at 11-13 m of depth, served as the sliding bed. Two distinct sectors, the upper onefrom the crest to the center and the lower one arriving to the landslide’s toe, are clearly evidenced. Transversal and longitudinalcracks to the sliding direction, due to compression and tensional stresses, are observed.

Figure 1. *The landslide field observation view, evidencing its geomorphological characteristics.*

2.3 Hydrogeological patterns

Quaternary hydrogeological formations, found in the area under study, show peculiar aquifer characteristics regarding their rag composition, unconsolidated and loamy state with a thickness of 3-4 m. They are typically characterized by large disposal capability,during prolonged precipitation periods, and lower ones during drought season. Quaternary aquifers, serve like channels, allowing the surface water to percolate into the Pliocene hydrogeological formations. Rrogozhina suite’s formationsare considered as the most important aquifer in the region under study, which due to thick grain composition and porosity allow the percolation of the underground water. Silty-alevrolitic layers serve as “mirrors”, forcing water to outsource in the form of springs, where these layers are eroded.

2.4 Meteorological data

Based on records of Vrapi meteorological station (25 km east of study area) precipitation values, during January-March 2009 indicate a decreaselevel, probably excluding the direct influence of rainfall factor on the Bagoje’s landslide. As such, during January,there is recorded 249.5 mm rain as compared to the climatic reference norm of 137.7 mm; during February, 50 mm as compared to 140.1 mm andduring March, 194 mm as compared to 140.9 mm. Slight increases of precipitations during March, doesn’t influence the mean variation value for the whole trimester, stating no unusual occurrence. Moreover it is evidenced, based on results of previous studies, no influence of rainfall on the seismic activity in the outer regions, near to the coastline, (Muço, B., 1995).

2.5 Seismic sequencecharacteristics

Region under study is located within one of the most active seismic areas in Albania, noted as Adriatic–Ionian longitudinal fault zone, where moderate to strong earthquakes have hit time to time. The studied seismic sequence started on February 20, 2009 and continued intensively until the end of August, (Table. 1). The most energetic events are located at the complicated tectonic node, where longitudinal segments of thrust-backthrust type and the dextral transversal strike-slip fault, are in contact, (Figure 2). A number of 51 earthquakes have been located (Table. 1; Figure. 2), based on Albanian Seismological Network (ASN) recordings. Statistical investigation using ZMAP software, FPS analysis and stress inversion, are used to further characterize seismic role in triggering Bagoje’s landslide.

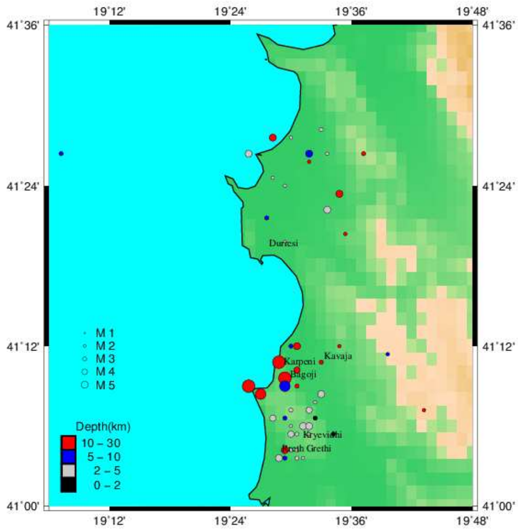


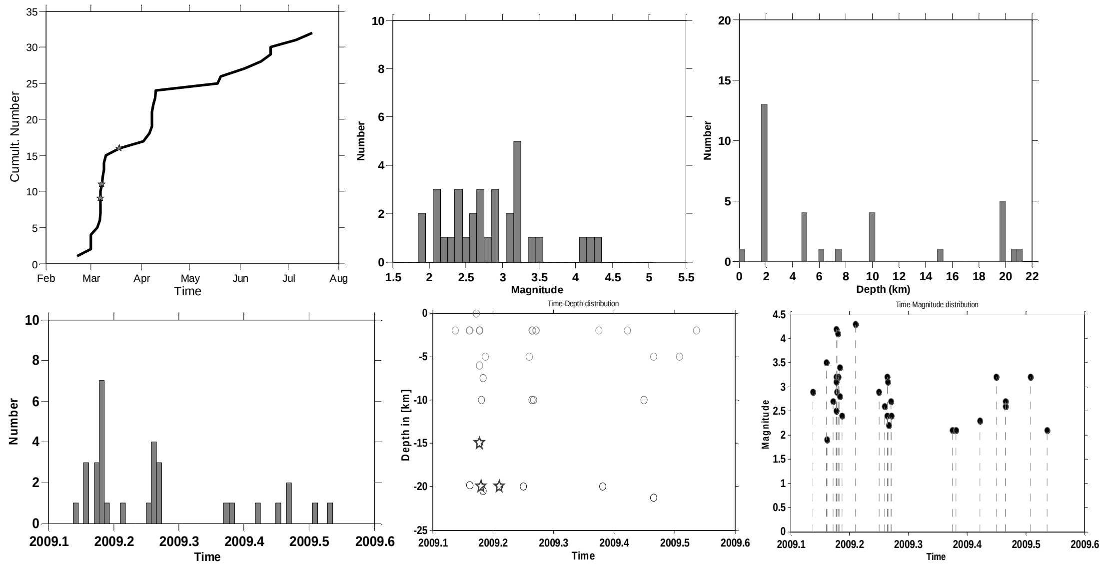
Figure 2. *Areal distribution and magnitude-depth characteristics of the Bagoje’s seismic sequence of 2009*

No.	Date	Time	Lat.	Lon	Dep.	Mag.
	dd/mm/yyyy	*hh:mm:ss*	*(NS)*	*(EW)*	*(km)*	*(ML)*
1	20/02/2009	09:41:32	41.47	19.55	2.0	2.9
2	28/02/2009	17:36:29	41.44	19.43	2.0	3.5
3	28/02/2009	20:49:43	41.41	19.47	2.0	1.9
4	28/02/2009	20:56:42	41.34	19.59	19.8	1.9
5	04/03/2009	17:39:13	41.09	19.57	0.0	2.7
6	06/03/2009	15:45:15	41.14	19.55	2.0	3.2
7	06/03/2009	18:12:36	41.20	19.50	6.0	2.5
8	06/03/2009	22:59:25	41.06	19.48	2.0	3.1
9	06/03/2009	23:06:44	41.16	19.49	15.0	4.2
10	07/03/2009	00:11:01	41.07	19.50	2.0	2.9
11	07/03/2009	18:51:21	41.18	19.48	20.0	4.1
12	08/03/2009	04:56:40	41.20	19.51	10.0	3.2
13	08/03/2009	22:43:17	41.07	19.49	20.5	3.4
14	08/03/2009	23:07:45	41.06	19.49	7.5	2.8
15	10/03/2009	07:29:45	41.19	19.66	5.0	2.4
16	18/03/2009	16:20:36	41.15	19.43	20.0	4.3
17	02/04/2009	05:45:24	41.18	19.55	20.0	2.9
18	06/04/2009	00:31:28	41.44	19.12	5.0	2.6
19	07/04/2009	13:49:52	41.46	19.47	10.0	3.2
20	07/04/2009	16:00:31	41.44	19.56	2.0	2.4
21	07/04/2009	16:43:49	41.37	19.56	2.0	3.1
22	08/04/2009	09:44:32	41.12	19.72	10.0	2.2
23	09/04/2009	16:59:30	41.12	19.53	2.0	2.7
24	10/04/2009	04:05:28	41.10	19.50	2.0	2.4
25	18/05/2009	01:25:10	41.40	19.49	2.0	2.1
26	20/05/2009	03:14:09	41.43	19.53	20.0	2.1
27	04/06/2009	04:06:35	41.46	19.50	2.0	2.3
28	14/06/2009	05:12:51	41.39	19.58	10.0	3.2
29	20/06/2009	02:16:48	41.44	19.62	21.3	2.7
30	20/06/2009	02:31:45	41.36	19.46	5.0	2.6
31	05/07/2009	12:40:20	41.44	19.53	5.0	3.2
32	15/07/2009	21:17:00	41.33	19.49	2.0	2.1
33	05/08/2009	06:32:32	41.14	19.45	10.0	3.8
34	05/08/2009	08:39:08	41.10	19.52	2.0	3.1
35	06/08/2009	01:09:16	41.13	19.54	2.0	2.4
36	06/08/2009	07:42:13	41.07	19.51	2.0	2.7
37	08/08/2009	18:50:16	41.15	19.51	20.0	2.8
38	08/08/2009	20:50:05	41.06	19.51	2.0	2.6
39	08/08/2009	20:50:25	41.12	19.50	2.0	2.5
40	08/08/2009	21:51:51	41.11	19.54	0.0	2.8
41	09/08/2009	00:20:19	41.20	19.58	19.8	2.2
42	13/08/2009	14:06:43	41.09	19.50	2.0	3.0
43	13/08/2009	15:49:38	41.15	19.49	5.0	3.6
44	13/08/2009	18:04:45	41.11	19.47	2.0	3.0
45	14/08/2009	03:30:39	41.17	19.51	15.0	3.0
46	17/08/2009	16:21:25	41.09	19.51	2.0	2.8
47	17/08/2009	18:12:53	41.12	19.53	2.0	3.0
48	20/08/2009	19:01:23	41.10	19.53	2.0	3.2
48	26/08/2009	15:49:38	41.09	19.53	2.0	1.9
50	26/08/2009	23:49:10	41.11	19.49	8.0	2.8
51	28/08/2009	13:32:29	41.06	19.52	2.0	2.3

Table 1. *Data of the Bagoje's seismic series of 2009.*

3. Results

The most explicitly observed property, of this seismic sequence, is the migration of hypocenter along the segments of active faults. ZMAP software is used to analyze parametric data, (Wiemer, S., 2001). The analysis is based on the sequence time series, (Graph. 1), upon which histograms relating the number of events with time, magnitude and depth distribution have been plotted. Seismic sequence is clearly constituted by two parts, showing different seismic rates. Seismicity is mainly shallow although some foci with depth greater than 10 km are located as well. Variation of depth with time supports the dynamic stress transfer from Ballaj-Kryevidhi thrust to the right lateral strike-slip fault, cutting through Bagoje's area, and then further in the north-northwest to the Karpen-Durresi backthrust. Based on magnitude distribution with time, the highest seismic energy release (M4.3), coincide with the strike-slip fault activation, nearly 72 hours prior to the Bagoje's landslide.

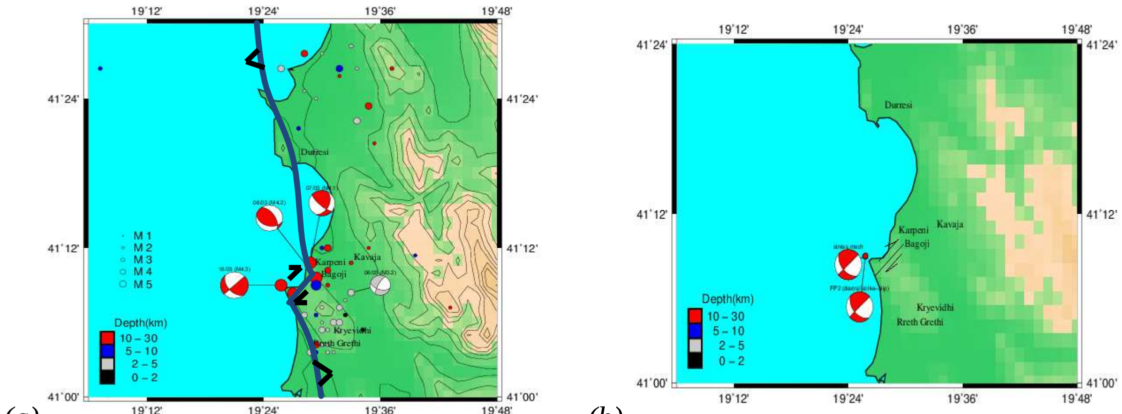


***Graph 1.** The ZMAP analysis results of the Bagoje's seismic series of 2009.*

Local stress field analysis is performed in this study, (Gipprich, L. T., et al., 2008). Only earthquakes located in the vicinity of the landslide, occurred near in time prior to the mass movement, are considered. They arerecorded by broadband (BB) stations of Albanian Seismological Network (AC). We applied the conventional first motion polarity method to resolve the focal mechanism solution (FPS), analyzing P-waves on vertical components only (Ottemoller, L., et al., 2011).Fault geometry is determined, represented as strike, dip, slip and rakeangles defining the orientation of both (FP1) and (FP2) fault planes, (Table 2). Results are plotted on the seismotectonic map, (Figure 3). Principal stress axes orientations, P-axes and T-axes namely for compressive and tensional stresses respectively, areexpressed in terms of strike and plunge angles as well, (Table 2).

Table 2. *Focal mechanism solutions (FPS), and main stress axes P and T, for the moderate events of the February- August, 2009 series, in Reth-Grethi-Durres, Periadriatic Lowland, Albania.*

Source Information					FP1/FP2			P-axes		T-axes	
Event ID	*Lat.*	*Lon*	*De*	**Ma**	*STRI*	*DIP*	*RAKE*	*STRI*	*PLUN*	*STRI*	*PLUN*
200903061	41.	19.	2	3.2	107/2	54/	-20/-	74	38	334	13
200903062	41.	19.	15	4.2	106/3	40/	58/114	38	9	285	68
200903071	41.	19.	20	4.1	131/2	75/	48/158	251	19	0.1	44
200903181	41.	19.	20	4.3	138/4	50/	0/140	100	27	355	27



(a) (b)

Figure 3. *(a)-Seismotectonics frame of the Bagoje's landslide, of 2009; (b)-March 18 (16:20 UTC), M4.3, events related to right lateral strike-slip fault.*

Applying Michael's bootstrap method (Figure 4), on FPS data(Vavryčuk,V., 2014), for March 6 (15:45 UTC), M3.2 and March 18 (16:20 UTC), M4.3 related to the transversal fault, a friction coefficient value of $\mu = 0.45$, shape ratio $R = 0.57$ and principal local stress orientation referring the principal (active) fault: σ_1 (STR = 88^0, PLUNGE = 33^0), σ_2 (STR = 229^0, PLUNGE = 50^0) and σ_3 (STR = 344^0, PLUNGE = 20^0), are determined.From stress inversion the principal fault orientation results asPFP ($228^0/89^0/-139^0$), depicted by blue cross sign on the Mohr circle diagram (Figure 2), fitting quite well the FP2 solution in table 2, for March 18, 2009 earthquake. Thus, the largest magnitude of the sequence is related to the activation of the dextral strike-slip fault, corresponding to the FP2, (Table 2; Figure 3b).

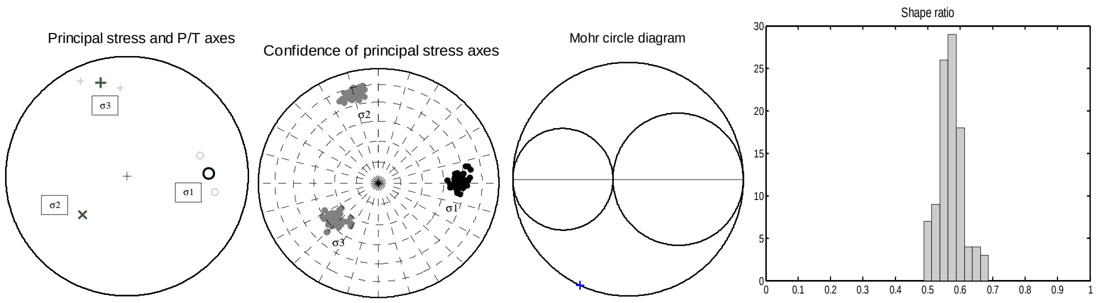


Figure 3. *Principal stress orientation analysis using Michael's bootstrap method (1984), on March 06 (15:45 UTC), M3.2 and March 18 (16:20 UTC), M4.3, events related to right lateral strike-slip fault.*

4. Discussion and conclusions

Geological, geomorphologic and hydro-geological characteristics of the region, where landslide occurred, played an important role especially in the percolation of surface and underground water towards depth, along the contact of sandy layers with clayey ones, at about 12-13 m from the surface; This contact served as the sliding bed; During this period of the year meteorological data does not show any abnormality in local precipitation values, indicating as such that atmospheric effects have played a minor role. This fact, along with the morphological patterns of the landslide shape, evidences its seismic nature. Pattern of hypocenter migration through seismicity analysis, periodic character of micro seismicity and focal mechanism solutions, support the idea of dynamic stress transfer along the activated fault segments. Stress inversion, relates the March 18, 2009 (M4.3) earthquake with the activation of the existing dextral strike-slip fault, traced northwest to the landslide location. Therefore, the prolonged micro seismic activity in the area, dynamic stress transfer and activation of the right-lateral strike-slip fault, have been found to be the major active factors that triggered the Bagoje's landslide. Shallow sliding body, long-lasting transient stress and excessive pore pressure due to water trapped at clayey layers, possibly lead to a tensile failure mechanism which triggered the delayed seismic landslide in Bagoje (Kavaja region).

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REFERENCES

Vavryčuk,V., (2014), Iterative joint inversion for stress and fault orientations from focal mechanisms, *Geophys. J. Int.* (2014) 199, 69–77, © GJI Seismology, doi: 10.1093/gji/ggu224.

Aliaj, Sh., (2012), Neotektonika e Shqiperise (*Neotectonics of Albania*), Monographs, ISBN 978-9928-4122-0-1.

Daja, Sh., Durmishi, Ç., Sinoimeri, A., Nazaj, Sh., (2011), Landslides susceptibility in central part of Albanian coast, Littoral 2010, 05003 (2011) DOI:10.1051/litt/201105003 © Owned by the authors, published by EDP Sciences, 2011

Ottemöller, L.,Voss, P., Havskov, J., (2011), Seisan-earthquake analysis software, Dep. of Earth Science, Geological Survey of Denmark and Greenland and University of Bergen.

Wartman, J., (2010), "Seismically Induced Delayed-Landslides in Homogeneous Cohesive Slopes and Embankments," https://nees.org/resources/684.

Gipprich, T. L., Snieder, R. K., Jibson, R. W., Kimman, W., (2008), The role of shear and tensile failure in dynamically triggered landslides, *Geophys. J. Int.* (2008) 172, 770–778, doi: 10.1111/j.1365-246X.2007.03681.x.

Malvick, E.J., Kutter, B.L., Boulanger, R.W. and Kulasingam, R. , (2006), Shear Localization Due to Liquefaction-Induced Void Redistribution in a Layered Infinite Slope, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No.10, pp.1293-1303.

Keefer, D.K., (2002), Investigating landslides caused by earthquakes—a historical review. Surveys in Geophysics 23, 473-510.

Wiemer, S., (2001). A Software Package to Analyze Seismicity: ZMAP, Seismological Research Letters, Vol. 72, 373-382.

Muço, B., (1995), The seasonality of Albanian earthquakes and cross-correlation with rainfall, Phys. of the Earth and Planetary Interiors 88 (1995) PEP02988.