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DYNAMIC NUMERICAL ANALYSIS OF THE GIANT VOKHCHABERD LANDSLIDE (ARMENIA)

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ABSTRACT

A dynamic numerical analysis of the Vokhchaberd giant landslide (Armenia) has been performed through the FDM code FLAC 5.0 in order to evaluate the influence of the seismic input, in terms of frequency content and peak ground acceleration, on both landslide reactivation and induced displacement field. The landslide is located close to the well known Garni fault-line and about 20 km east of Yerevan city. Some villages, housing about 1000 people, are located in the landslide area. It shows a roto-translational mechanism involving Oligo-Miocene stiff clays and Mio-Pliocene tuff stone in an area about 3 km long and 1.5 km wide (estimated volume 450Mm^3). The Vokhchaberd landslide is an active phenomenon with a recurrent style; both rainfalls and earthquakes can be regarded as responsible for major reactivations. The dynamic properties of the pre-existing landslide shear zones were derived starting from laboratory tests on stiff clay samples. The spectral analysis of the records obtained by a 3D velocimetric array, installed by USGS near Garni village, pointed out the main frequency contributions of the felt seismicity. A numerical model was implemented starting from two engineering-geology sections, respectively representing the right side and the left side kinematism of the landslide mass. The simulations were performed with an equivalent input corresponding to a M=4-5 earthquake.

The results show a significant stiffness decay along the rupture surface and a total displacements up to about 1 m; moreover, a relevant difference in the kinematic behaviour is obtained between the right-side and the left-side sections.

Keywords: seismically-induced landslide, dynamic numerical modeling, equivalent input, Armenia

INTRODUCTION

In the region of Kotayk Province (Armenia), close to the villages of Vokhchaberd, Garni, Gokht, Ghegadir and Hatsavan, there are large and active landslides named as Vokhchaberd-Garni landslide group (Fig.1). The origin of these landslides can be related to the active Garni fault, a right-lateral strike-slip and reverse fault located 1.5-2km away, and some of their reactivations could have been seismically induced by earthquakes located along the fault itself (GEORISK Company, 1999). Large seismically induced landslides are reported to have occurred in the village of Garni. Continuous reactivations of rock falls and sliding movements within this landslide repeatedly destroyed roads between Yerevan, Garni village, Avouts-Tar, Akhchocvank and Airivank (Geghard) monasteries; the

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latter was covered with debris up to the monastery dome. Investigation of the caves close to the S-E margin of the Vokhchaberd village also indicated their destruction by the July 4, 1679 Garni earthquake (estimated magnitude M=7.1), due to a reactivation of the Vokhchaberd landslide (GEORISK Company, 1999) in agreement with C^{14} dating of samples from below a fallen rock block of Garni landslide.

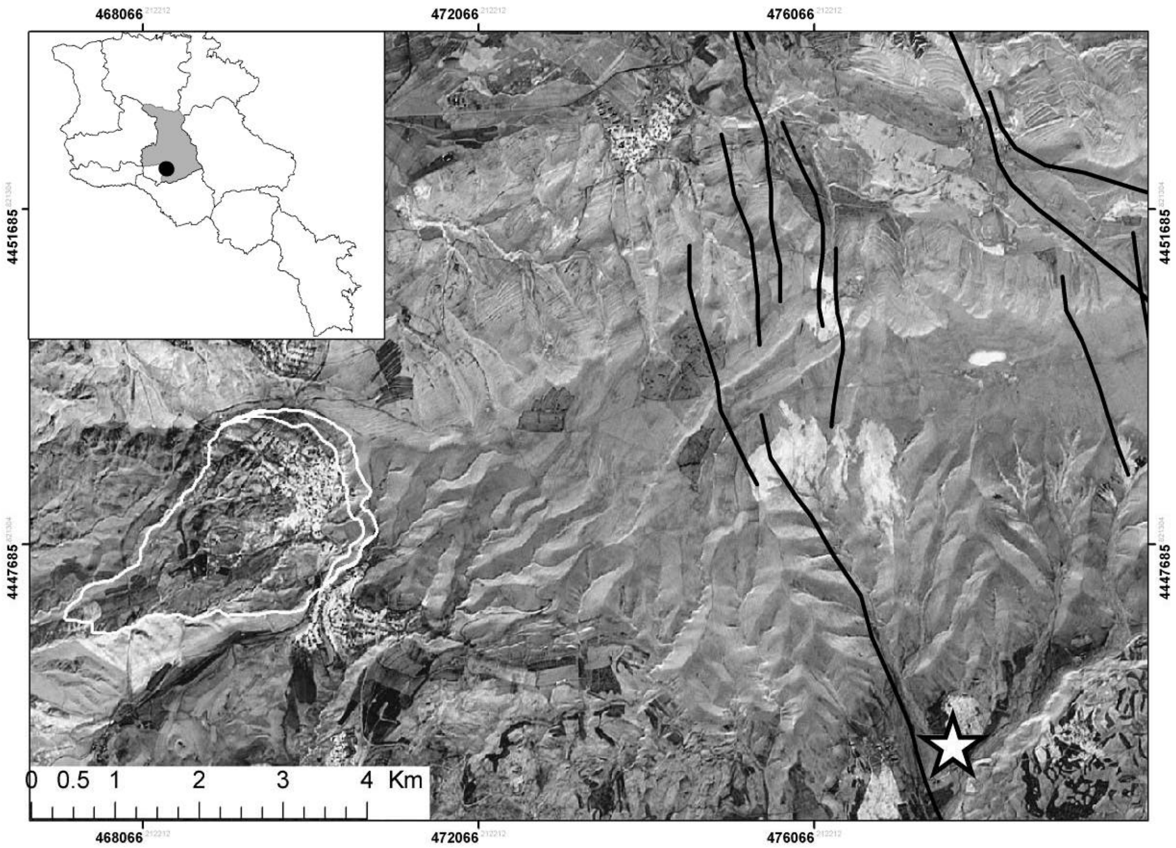

Figure 1. Satellite image of the study area: the white line borders the Vokhchaberd landslide; the black lines are segment of the Garni-fault; the star shows the location of the USGS Garni array

Within the Vokhchaberd-Garni landslide group, the giant Vokhchaberd landslide (20 km east of Yerevan city) was selected to assess seismic induced deformations since it involves an inhabited area housing about 1000 people (Fig. 2).
Pseudostatic stability analyses were performed by GEORISK Company in order to evaluate the possible earthquake-induced displacements; the obtained results indicate coseismic displacements up to 63 cm for a horizontal acceleration value of 0.55g (corresponding to a maximum expected magnitude M=7.2).
In the present paper we report the results of a dynamic numerical stability analysis, performed through the FDM code FLAC 5.0 (Itasca, 2005), taking into account the frequency content of the expected earthquakes as well as their PGA from USGS records and applying a cyclic equivalent input.

SEISMICITY OF THE VOKHCHABERD LANDSLIDE AREA

The Armenian territory is located in a seismically active zone corresponding to the complex tectonic setting related to the suture zone of the Alpine-Himalayan orogen due to the collision of Arabian and Eurasian plates, in particular. This zone includes the states of Armenia, Georgia, Eastern Turkey, Iran and Azerbaijan. The Garni fault zone is located just in the central part of the suture zone and is responsible for strong historical earthquakes with estimated magnitudes larger than 7, as testified by the mentioned 1679 event which almost destroyed Yerevan city.

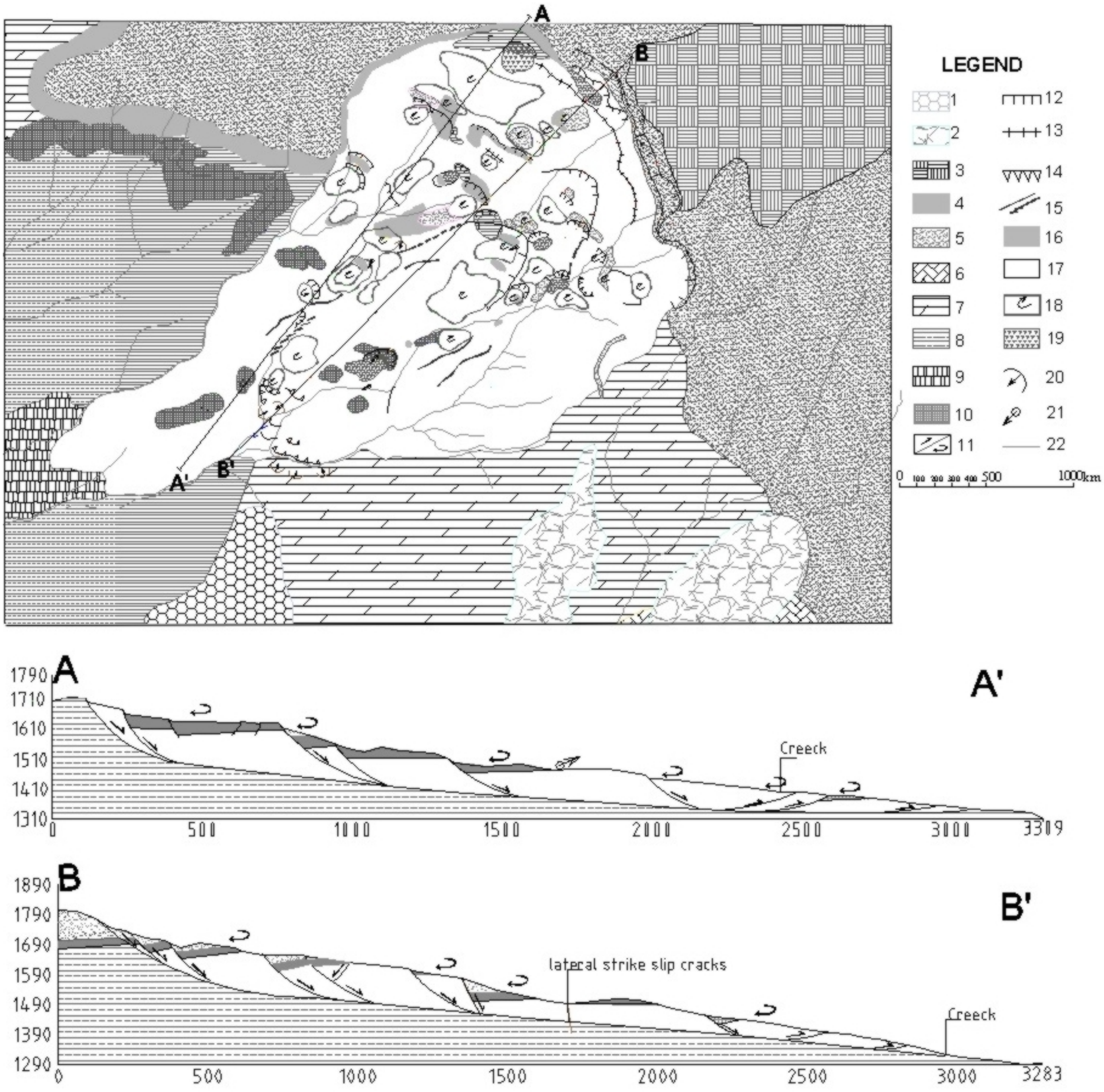

Figure 2. Geological sketch of the Vokhchaberd landslide area: 1) Conglomerates of the first Noubarashen terrace; 2) Conglomerates of the high Terrace (Nubarashen suite); 3) Volcanoclastic formations (Tsakhkounyats suite); 4) Clay-silty tuff (Yerevan suite); 5) Volcanoclastic formations (Vokhchaberd suite); 6) Conglomerates and sandstones (Hatsavan suite-the lower part); 7) Sandstones and clays (Shorakhpiur suite-upper subsuite); 8-9) Tuff stones and gypsiferous clays, (Shorakhpiur suite-middle sub-suite); 10) tuff stones of Shoraghbiur suite; 11) movement directions; 12) scarps; 13) cracks; 14) compression ridges; 15) lateral strike slip cracks; 16) swamps; 17) Vokhchaberd landslide mass; 18) terraces; 19) landslide debris; 20) small internal landslides; 21) springs; 22) streams.

Following the catastrophic M=7.0 Spitak earthquake that occurred in 1988, seismic hazard and risk assessment studies (Balassanian et al., 1999b) have been developed aiming at mitigation strategies. According to the proposed seismic zonation of the Armenian territory (Balassanian et al., 1999a), a 0.4-0.5g maximum horizontal acceleration value should be considered for the Vokhchaberd area.

Since June 1990, a 3D velocimetric array, deployed by USGS, has been operating at a geophysical observatory near Garni, to study the local seismicity associated with the Garni fault. The array is made of 10 three-component sensors, located at ground level and inside a horizontal tunnel, dug in the tuff stones; only the records obtained by stations G1A (tunnel) and G4A (surface, above G1A) were considered for this analysis

From the on-line data (http://nsmp.wr.usgs.gov/geos/garni/garni.html), recorded in the time interval 1990-1992, 10 earthquakes were selected according to epicentral distance, magnitude and source area. In particular, the selected events have magnitude in the range 5-7, epicentral distance up to 300 km and belong to five different sources (Table 1).

Table 1. Data of the analysed earthquakes

date	time	code	M	epic.dist.	depth	source area
				km	km	
16/12/1990	15:46	350	5.2	161	33	Turkey-USSR border region
27/03/1991	22:17	86	4.3	70	33	Eastern Caucasus
27/04/1991	03:32	117	4.2	86	10	Turkey-USSR border region
29/04/1991	10:53	119	7.2	272	17	Western Caucasus
02/05/1991	02:07	122	4.3	139	10	Eastern Caucasus
03/06/1991	10:23	154	5	159	28	Turkey-USSR border region
08/06/1991	01:12	159	4.2	138	33	Turkey-USSR border region
15/06/1991	00:59	166	6.3	266	9	Western Caucasus
12/11/1991	20:36	316	4.3	94	33	Armenia-Iran border region
18/02/1992	01:40	49	4.5	183	33	Georgia-Armenia-Turkey border reg.

The downloaded records were FFT transformed into the frequency domain and normalized to their maximum value (Fig.3). The Fourier spectra of the records obtained from the same events in the two considered stations are very similar and allow to exclude local amplification effects in the surface station. Moreover, the spectral analysis points out a significant difference in the frequency content of the records, which appears to depend on earthquake magnitude and to be unrelated to the source area. In particular, the records of M=4-5 earthquakes show a main frequency content between 0.5 and 2.5 Hz with a peak at about 1.5 Hz, while the earthquakes with larger magnitude show a main frequency content close to 0.5 Hz.

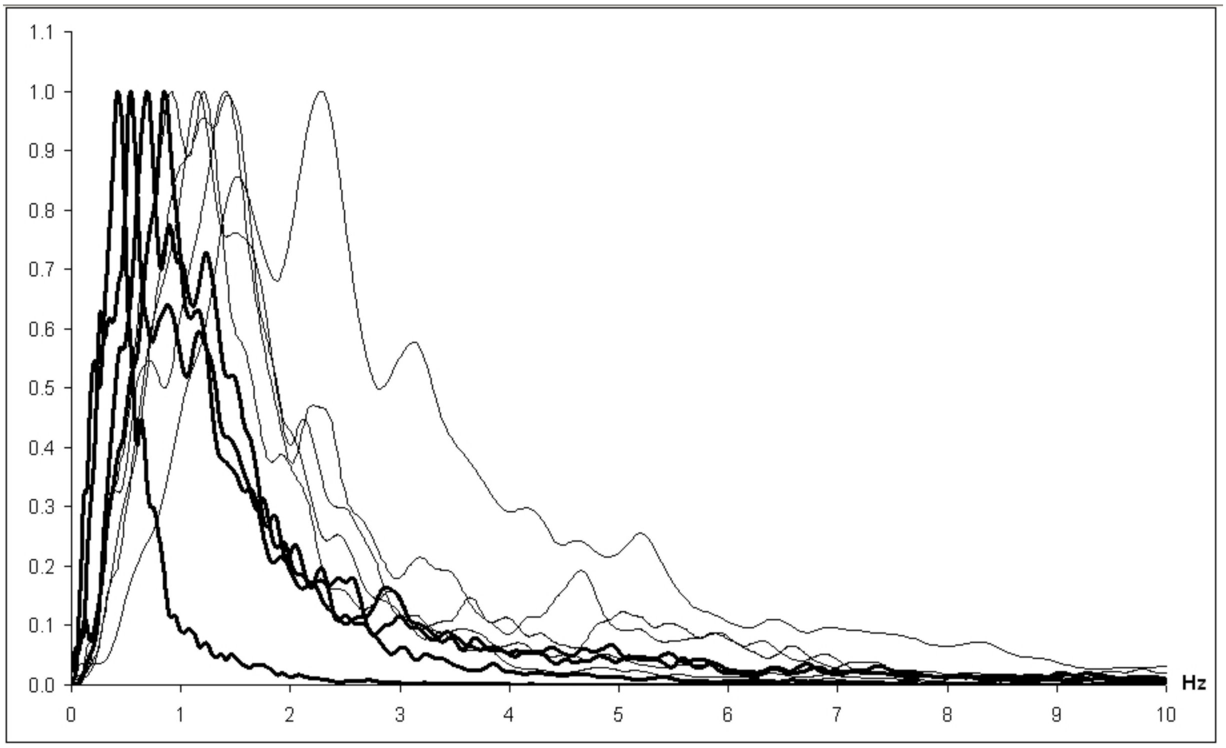

Figure 3. Normalized Fourier spectra for the analyzed earthquakes (bold lines are referred to M>5 earthquakes)

The high-magnitude events recorded by the Garni array are located at epicentral distances larger than about 250 km; nevertheless, historical and paleo-seismic studies (GEORISK, 1999) show that M=7 events can occur along the Garni fault, very close to the Vokhchabertd landslide area.

GEOLOGICAL MODEL OF THE VOKHCHABERD LANDSLIDE

The landslide bedrock is formed by Lower Oligocene clays, sandstones and tuff stones (Shorakhpiur suite) overlaid by tuff breccias (Fig. 2, 4, 5), conglomerates and clays of Lower Pliocene (Vokhchaberd suite) (Fig. 2, 4). The landslide shows a roto-translational mechanism involving an area about 3 km long and 1.5 km wide (estimated volume 450 Mm^3) (Fig.1).

Figure 4. Outcropping tuff breccias close to the landslide crown (left); detail of the longitudinal main crack alignment (see white arrows) in the downslope portion of the landslide mass (right)

Many geomorphological features such as counterslope terraces, scarps, bulging and cracks can be observed all over the landslide area (Fig. 2, 5). In particular, the landslide is characterised by roto-translational mechanisms with different kinematics on the right side and on the left one. This difference is responsible for the longitudinal main crack alignment which can be found in the downslope portion of the landslide mass. This alignment can be therefore regarded as a main kinematic element for the landslide (Fig. 2, 4).The sliding surface mainly involves the stiff clays, inducing a downhill displacement of the tuff layers and a consequent spring migration.

Figure 5. Main scarp of the Vokhchaberd landslide with outcropping tuff stones and man-made caves (left); view of the main landslide terrace from the landslide crown (right)

The Vokhchaberd landslide can be considered as an active phenomenon with a recurrent style; both rainfalls and earthquakes can be regarded as responsible for major reactivations. At this regard,

according to chronicle sources, the 1679 Garni earthquake caused the formation of numerous wide and persistent ground ruptures, the failure of mountains and rocks, numerous rock-falls and landslides that dammed valleys and destroyed roads.
The Vokhchaberd landslide belongs to constantly moving creep-type landslides. Comparison of the 1948 and 1987 air photos, made by GEORISK, indicates differential landslide displacements during the analysed period. In particular, starting from 1960-1965, an increasing activity of the landslide can be observed.
After the 1965, the activity has developed to a particularly high, disastrous level probably related with the exploitation of new irrigation system. Moreover, after the 1988 Spitak earthquake another reactivation phase has been testified by the village inhabitants; in the same period no significant change in the mean annual precipitation rate has been recorded (about 400 mm/year). A recent reactivation of the landslide is leading to the ongoing damage of the Yerevan-Garni main road, while the village of Vokhchaberd will soon be destroyed, so that its evacuation to a new place is being taken into account by the local administration.
Detailed studies by GEORISK Company allowed to establish that the downslope portion of the Vokhchaberd landslide is the most active. The data collected during the 1999-2000 time interval show, at the S-E segment of the scarp, zones of gravity-induced failures that reach 1-to-2 m in vertical displacements. Moreover, an average horizontal rate was estimated at 1 m/yr, while the average vertical rate resulted to be 1.5-2 m/yr. After the data obtained during the same time interval, an average resultant rate of the Vokhchaberd landslide of about 1.7 m/yr can be inferred. A new phase of reactivation can be defined for the period 2003-2005 as it can be observed from the retrospective analysis of photos taken from the same places.

DYNAMIC NUMERICAL MODELLING

Numerical model project

The dynamic analysis of the Vokhchaberd landslide stability conditions was performed along two geological sections, respectively in the right (A) and in the left (B) side of the landslide, where displacement fields, referred to different kinematisms, were pointed out by in site investigations.
Starting from each geological section, an engineering-geology model was obtained by zoning the stiff clay formation below the sliding surface, the landslide mass itself and the tuffs (without their heterogeneities). Moreover, based on the observed geomorphological features, pre-existing shear surfaces (primary sliding surface as well as secondary scarps) were distinguished. Both physical and mechanical properties were attributed to the numerical model, selecting a Mohr-Coulomb elastic-perfectly plastic constitutive law and considering homogeneous and isotropic media (Table 2). The values of the parameters related to the stiff clays were derived from laboratory tests and physical characterisation on samples from the landslide main scarp, while bibliographic values were assumed for the tuff stones parameters.

Table 2. Input parameters used in the numerical modeling

	Constitutive law	γ_n	**E**	**G**	**B**	**$G0_{dyn}$**	**$B0_{dyn}$**	**ten**	**c**	φ	ν
		kN/m^3	GPa	GPa	GPa	GPa	GPa	kPa	kPa	°	
Tuff stones	Mohr-Coulomb /Griffith	17	2.00	0.86	1.01	8.55	10.10	490	980	35	0.17
Clay (rupture surfaces)	Mohr-Coulomb	20	0.12	0.05	0.07	0.46	0.77	0	0	17	0.25
Stiff clay (landslide mass)	Mohr-Coulomb	20	0.12	0.05	0.07	0.46	0.77	24.8	10	22	0.25
Stiff clay (bedrock)	Mohr-Coulomb	20	1.15	0.46	0.77	4.60	7.67	24.8	10	22	0.25

Numerical simulation was performed through the finite-difference software FLAC 5.0, using a 25 m square mesh resolution, consistent with the frequency content of the applied dynamic input. Starting from the equilibrium achieved under static conditions, a stress-strain analysis was carried out under dynamic input, simulating the action of seismic shaking. In particular, the dynamic input was simulated by a single-frequency wave function. The function was deduced from the data recorded by USGS Garni array. As a first stage of the numerical modelling, M=4-5 earthquake features were considered to obtain an equivalent input. A sinusoidal cyclic pulse (Seed and Idriss, 1969; Martino and Scarascia Mugnozza, 2005), characterised by a 1.5 Hz frequency, was deduced from the spectral analysis of the records with an epicentral distance up to 100 km; a 0.1g amplitude was derived as 65% of the mean of the recorded PGA values, and a duration of 2.66s (corresponding to 4 equivalent cycles) was estimated as an empirical function of the considered magnitude.

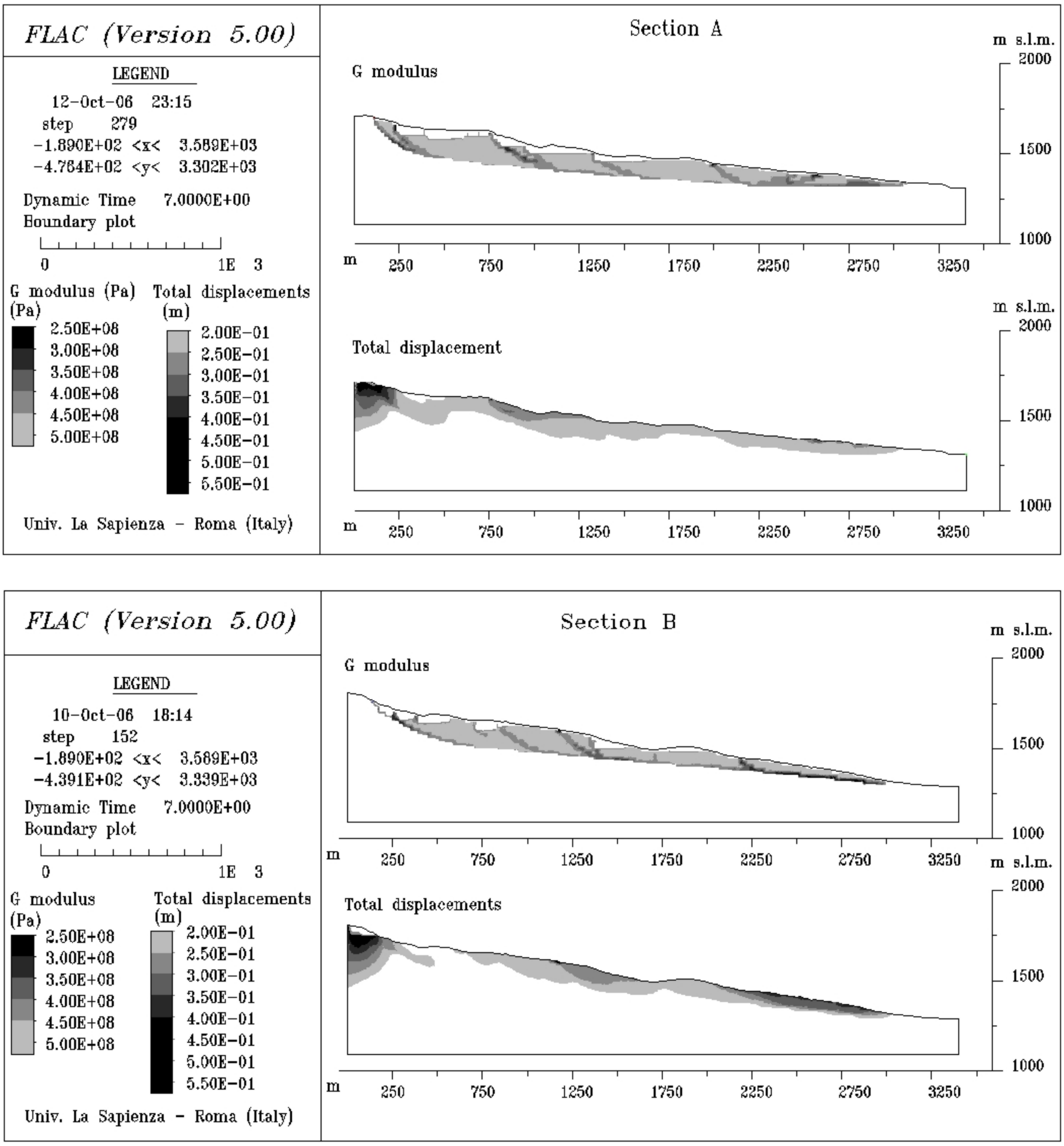

Figure 6. Stiffness decays and displacements by numerical model

While-stepping functions of G/G_0 and D/D_0 versus cyclic shear strain allowed the stiffness and the damping coefficient to decay during the shaking as a consequence of the shear strain along the pre-existing rupture surfaces; a Rayleigh Damping function (for both mass and stiffness) with constant values was used for the other involved lithologies. The G/G_0 and D/D_0 versus cyclic shear strain curves were obtained according to the ones proposed by Vucetic and Dobry (1991) for a plasticity index PI=50. The so performed dynamic solution is a nonlinear incremental analysis.

Results

Both models obtained along sections A and B show a shear modulus decay along the main preexisting rupture surface and the secondary scarps up to a 0.66 G/G0 value. The main decays along the rupture surfaces result to be located close to the toe of the landslide. Along section B a gradually increasing G/G0 decay was obtained from the top to the bottom of the slope, while along section A the G/G0 values are much more similar from the top to the bottom of the slope. Moreover, along section B, the obtained decays are larger, particularly in the middle and lower portion of the slope.

The total co-seismic and post-seismic displacements reach about 0.25 m along section A and about 0.35 m along section B (Fig.6). Moreover, the maximum total displacement values are located downslope section B (Fig.6) and close to the main crown of the landslide, where local instabilities due to plasticity states were induced by dynamic shaking (Fig.6). A widely uniform distribution of total displacement can be instead observed along section A (Fig.6), with local instabilities close to the main secondary scarp (downslope the landslide main terrace). By comparing sections A and B along the lower portion of the slope significant seismically induced differential displacements, up to some tens of centimeters, are obtained: this outcome justifies the in-site evidences of strike-type cracks (see Fig.4).

The obtained results are consistent with a differential kinematic behaviour within the landslide mass between the left and the right sectors. The seismic input widely induces differential total displacements along the left portion of the landslide, while uniform total displacements are induced along the right portion.

The resulting style for the landslide is a complex retrogressive and progradational one for the left side, where the main crown, with outcropping tuffs, as well as the bottom of the slope, with widely outcropping stiff clays, are mainly involved. On the contrary, a simple progradational style results in the right flank of the landslide, where stiff clays widely outcrop. As a consequence, the main instabilities are located downslope the secondary scarps which bound the main landslide terraces.

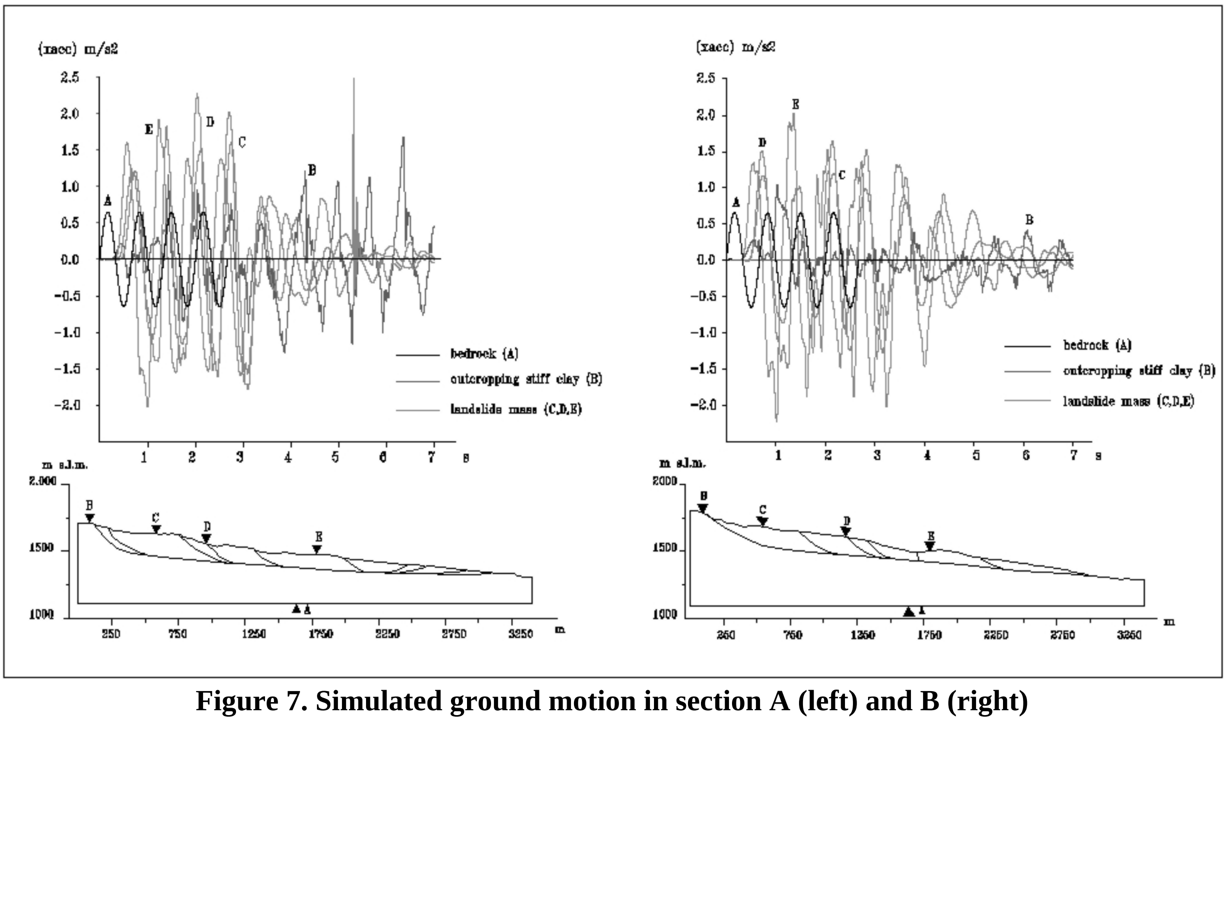

Figure 7. Simulated ground motion in section A (left) and B (right)

Moreover, for both sections, the simulated ground motion (horizontal acceleration time-histories, Fig.7) within the landslide mass (points C,D,E) shows PGA values up to 0.2g, significantly higher than the lower-boundary dynamic input (point A) and the values obtained in the outcropping stiff-clay bedrock (point B).

FINAL REMARKS

The Vokhchaberd landslide is particularly prone to earthquake triggering due to the high seismicity of Armenian Kotayk district, where 0.4-0.5 g maximum acceleration values can be expected, and to its location, few kilometres away from the active Garni fault; actually, seismically induced activations of the landslide are reported in historical chronicle sources. The field evidences point out a ground crack pattern strictly related to a differential kinematic behaviour between the right side and the left side of the landslide. Historical and instrumental seismic data show that the site is affected by different near and far sources, able to generate earthquakes with a magnitude larger than 7. The spectral analysis of the available records, obtained by a USGS local velocimetric array, points out that earthquakes with M=4-5, at distances between 70 and 180 km, induce a main frequency response in the range 0.5-2 Hz, while larger earthquakes (epicentral distance of about 270km) seem to induce a lower frequency response, close to 0.5Hz. A dynamic numerical analysis was performed along two engineering-geology sections, respectively related to the right and the left side of the landslide mass; an 1.5Hz equivalent input was applied constistent with the expected frequency site response to a M=4-5 earthquake with an epicentral distance up to 100 km.
The obtained results show maximum displacements up to about 0.35m within the landslide mass and confirm the differential mechanism between its right and left sides. As the models reach a new post-seismic equilibrium, a recurrent activity can be assumed for the landslide; this finding is consistent with cumulative displacements as a consequence of more earthquakes. Moreover, the simulated PGA values obtained along the landslide mass surface, up to 0.2g, point out a significant increase with respect to the outcropping bedrock.
Further numerical simulations are being performed in order to analyse the effects of a multi-frequency equivalent input as well as of the maximum expected earthquake.

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