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Seismic induced displacements of "La Sorbella" landslide (Italy)

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ABSTRACT: "La Sorbella" landslide is a deep-seated landslide that affects a segment of a new national road in central Italy and for this reason it is continuously monitored by fixed-in-place inclinometer probes. Inclinometer profiles highlighted a sliding mass moving on a well-defined and narrow shear band, where the mobilized shear strength is at residual. Historical average rate of movement is very slow (1.0-1.5 cm/year) with trends related to the rainfall seasonal regime. After the three main earthquakes of the 2016 central Italy seismic sequence, a fixed-in-place inclinometer probe clearly registered some permanent displacements experienced by the landslide. This kind of evidences, so rare in the scientific literature, offers a precious opportunity to study the response of large active landslides under seismic conditions. After a description of the site and the registered data, a preliminary back-analysis of the observed phenomenon is pointed out by using the well-known Newmark's method. Moreover, some considerations about the behaviour of the landslide under strong earthquakes are developed.

1 INTRODUCTION

Effects of earthquakes on natural slopes, earth dams, solid-waste landfills, cut slopes and embankments are usually evaluated in term of seismic-induced displacements. Such approach establishes a design criterion for the infrastructures under seismic load for which the traditional concept of safety is shifted on the evaluation of post-earthquake serviceability. In other term, it is admitted that the earthquake shaking determines a permanent deformation without compromise the serviceability or the stability of the earth systems. It is evident that the reliability of the method depends on the accuracy to evaluate the displacement exhibited by the soil mass after an earthquake. The founder of such approach has been Newmark (1965) who introduced the "sliding block method", then modified by several Authors to improve its capabilities.

To validate these methods, it is very important to compare predictions with real observations. Unfortunately, especially with reference to seismic-induced displacements of landslides, real data are very rare. Al-Homoud and Tahtamoni (2000) collected 7 case histories of landslides activated by earthquakes where some post-earthquake displacements were measured or estimated. Crespellani et al. (1996) and Chang et al. (2005) carried out back analysis of the large displacements occurred to two landslides induced by strong earthquakes.

In this paper original data of seismic displacements of a large landslide in central Italy are presented and analyzed. The data come from in-place continuously monitored inclinometer that sensed the seismic sequence that struck central Italy from August to October 2016, causing severe damage to several towns and hundreds of victims. "La Sorbella" landslide is located in the municipal district of Valfabbrica (Umbria region). It is a deep-seated landslide that affects a segment of the new SS 318 national road and its activity is testified by the inclinometer monitoring carried out before and after the construction works. After the three main earthquakes of the 2016 central Italy seismic sequence (24th of August, 26th and 30th of October), a fixed-in-place inclinometer probe clearly registered some permanent displacements experienced by the landslide as the consequence of the seismic motion.

The available data, so rare in the present scientific literature, offers a unique opportunity to study the behaviour of large active landslides under seismic conditions. Moreover, using the strong-motion data set made available by the Italian Accelerometric Network (RAN), a preliminary back analysis of the observed phenomenon has been carried out by following the Newmark's method.

2 "LA SORBELLA" LANDSLIDE

"La Sorbella" landslide is a large landslide that affects a slope along the East side of the valley formed by the Chiascio River. The site of interest is located in a hilly territory, belonging to the Apennines chain area. The landslide affects a gentle slope hillside (average inclination equal to 8°), North-West oriented, between the elevation of 257 and 354 m on medium sea level (m.s.l.). The body of the landslide has a planimetric shape of a fan, with a longitudinal length of 550 m and a transversal maximum width, close to the toe, of 600 m. The direction of movement is oriented towards North-West. Geotechnical survey identified the thickness of the landslide body that presents a maximum value of about 35 m in the center and tend to thin moving towards the edges. In the lower portion of the landslide, a layer of alluvial deposit has been identified between the basal part of the landslide and the underlying firm soil. The soil that constitutes the body of the landslide present a chaotic arrangement and no evident internal structure has been recognized. Available information allows identifying the old origin of the landslide: it is reasonable that paroxysmal event of sliding took place in a climatic condition different from the current one.

Under a geological point of view, the rock basement is the Marnoso-Arenacea Formation (MAF), a Miocenic foredeep turbidite succession outcropping along the north-central Apennines. The tectonic evolution of the area produced a migration towards north-east of the basin and a vertical superposition of the sediments. The result of this process is a layered structure, 4.000 m thick that nowadays constitute the subsoil of the hills. In the area of interest, it has been possible to distinguish three lithofacies of the MAF which, starting from the bottom, are: MA3 – pelitic lithofacies, mainly formed by marl, calcareous marl and over-consolidated silt of grey color; MA2 – arenaceous lithofacies, formed mainly by yellow-grey sandstone, with rare layer of marl and over-consolidated silt; MA1 – lithofacies mainly pelitic with calcarenite. In the higher portion of the slope the MA2 outcrops, while in the lower one MA3 is encountered. At the toe of the slope, close to the Chiascio River, alluvial deposits are present. It is worth to note that the MA2 and MA3 are separated by a direct fault; however, due to the weathering of the cover soil, such fault cannot directly be observed.

Figure 1 shows the plan view of the landslide with investigations and the longitudinal representative cross section A-A' along the slope. Boreholes, inclinometer readings and aerial images allowed detecting the shape of the landslide body. It results that the contact between the sliding mass and the firm soil is irregular, thus suggesting the occurrence of a complex movement where different independent bodies can exist. The landslide exhibits a roto-translational movement with only little internal deformations.

Inclinometers profiles are showed in Figure 2a. It is evident that the sliding mass is moving on well-defined and narrow shear band with depth ranging from 20 m to 36 m. Such kinematic determines a drop of the friction angle on the sliding surface until its residual value, as typically observed on several deep-seated landslides in complex clayey formation (Segato et al., 2015; Ruggeri et al., 2016). Because of the construction of the new road that crosses the hillside, the landslide has been monitored by fixed-in-place inclinometer probes along two verticals that are AI11 and AI12. Figure 2b shows the position of the probe along the vertical AI11, considered in this paper.

Rate of movement, showed in Figure 2c, is very slow (1.0-1.5 cm/year) and substantially synchronous for all the verticals in the medium and upper parts of sliding mass. Differently, the lower part of the landslide, even if it is not intensively monitored, does not show the same trend of displacement. This fact is compatible with the complex arrangement of large and old landslides. It is worth to note that, thanks to the continuous inclinometric reading, it has been possible to point out that the landslide movement is closely related to the rainfall seasonal regime.

The piezometer monitoring indicates a groundwater level generally located close to the ground surface, with seasonal oscillation ranging from 2 m to 6 m below the surface. In the

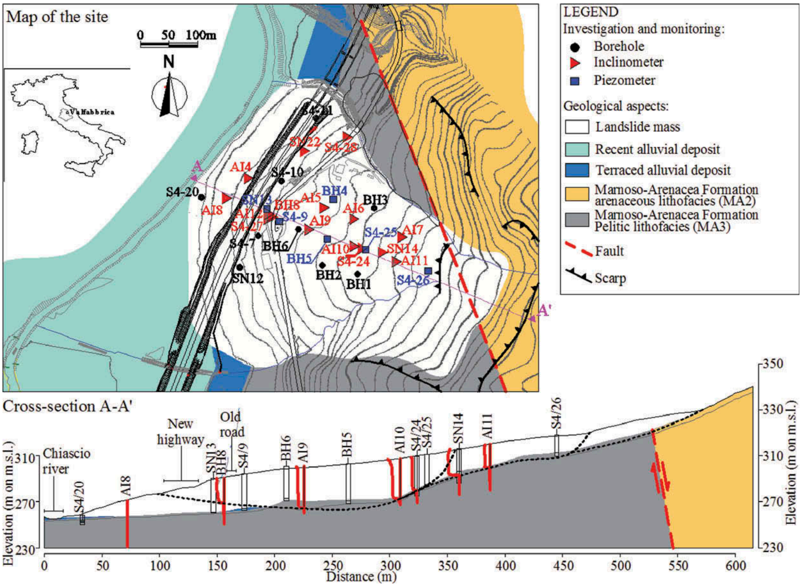


Figure 1. Plan view of the landslide with a longitudinal representative cross section A-A' along the slope.

lower part of the landslide the presence of the alluvial deposit below the sliding mass probably affect the hydraulic of the subsoil. In any case the heterogeneous composition of the landslide body and the limited number of piezometers does not allow to recognize an exact picture of the groundwater flow pattern.

The geotechnical characterization of the material has been based on some laboratory testing of undisturbed samples taken from the landslide body. The intrinsic heterogeneity of the original formation makes the geotechnical characterization of the soil very difficult, so that the representativeness of each single result has to be always evaluated.

The particle size distribution indicates a mainly fine graded composition (70-90% of silt and clay). Atterberg limits, according to Casagrande plasticity chart, allow classifying the samples as CL (clay of low plasticity) and ML (silt of low plasticity). In any case, samples mainly sandy are sometimes recovered. The estimated failure envelope can be described with a negligible cohesion and a friction angle of 28°- 32°. However, some samples exhibit higher strength parameters. The residual shear strength was estimated by shear tests, both direct and ring shear. A failure envelope with a negligible effective cohesion and a friction angle ranging from 14° to 18° was found. Unfortunately, specific tests on samples taken close to the sliding surface of the landslide are missing. Considering the presence of smoothed surfaces on some boreholes coring samples, this actual friction angle on the sliding surface need to be better investigated.

3 THE 2016 CENTRAL ITALY SEISMIC SEQUENCE

The seismic sequence started at the end of August 2016, producing more than 26.000 earthquakes during the first four months, as recorded by National Accelerometric Network (RAN) managed by the National Institute of Geophysics and Volcanology (INGV).

The three mainshocks of the sequence, that are considered in this paper, occurred in August 24 near the town of Accumoli (M_w 6.0), in October 26 near the village of Visso (M_w 5.9) and in October 30 close to the town of Norcia (M_w 6.5). "La Sorbella" landslide is located at 45 km far from Visso, 50 km from Norcia and 65 km from Accumoli. Figure 3 shows the map of central Italy with accelerometric seismic stations (triangles), epicenters of the three mainshocks (red

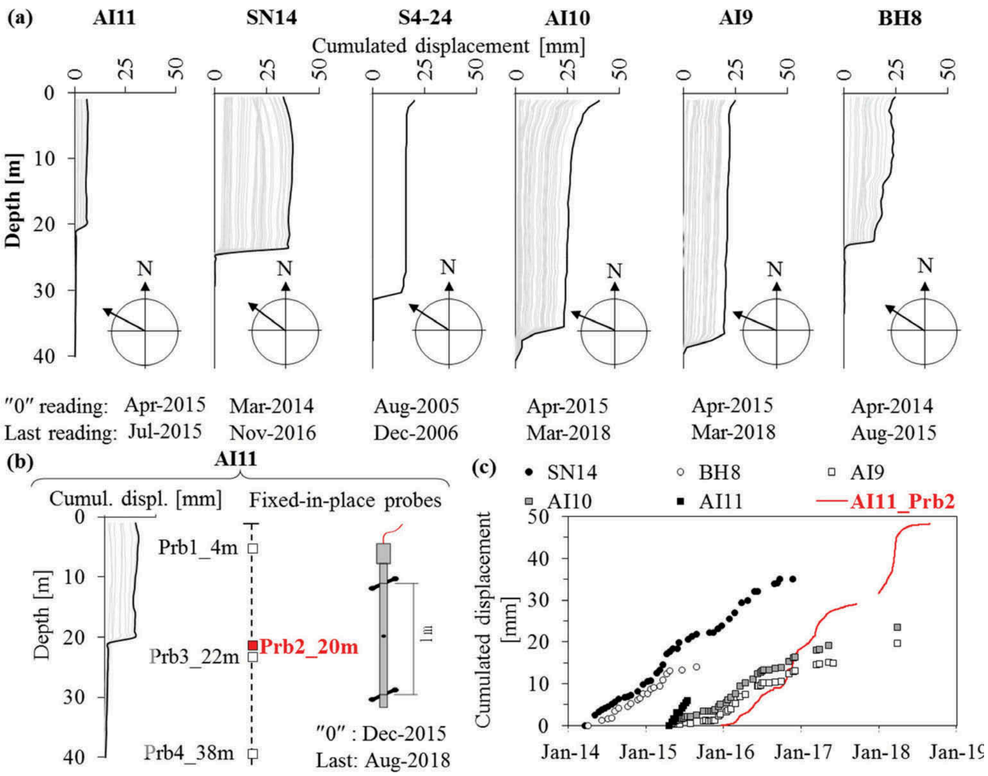
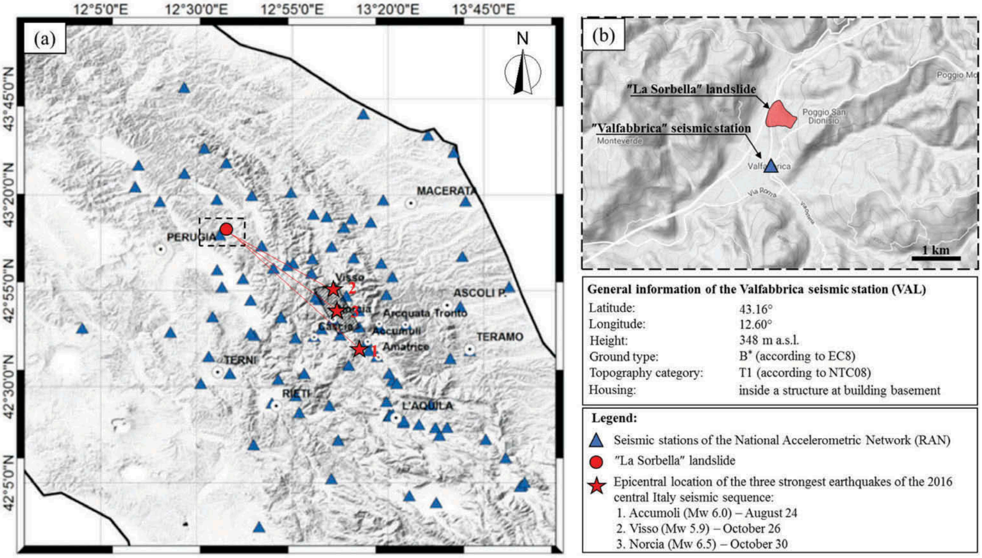


Figure 2. (a) Inclinometer readings; (b) Position of the fixed-in-place inclinometer probes along the AI11; (c) Cumulated displacement of the different inclinometers.



General information of the Valfabbrica seismic station (VAL)

Latitude:	43.16°
Longitude:	12.60°
Height:	348 m a.s.l.
Ground type:	B* (according to EC8)
Topography category:	T1 (according to NTC08)
Housing:	inside a structure at building basement

Figure 3. (a) Map of central Italy with accelerometric seismic network (triangles), epicenters of the three mainshocks (red stars) and location of "La Sorbella" landslide; (b) zoom of the dashed rectangle in the map with indication of the landslide and the closest accelerometric station of "Valfabbrica".

Table 1. Characteristics of the three earthquakes considered and main features of the seismic signals recorded at the "Valfabbrica" station.

Characteristics of the earthquakes					Main features of the signals registered by VAL station						
Earthquake	Date	hh/mm/ss (UTC)	Mw	d [Km]*	Ed [Km]♦	PGAE [g]	PGAW [g]	PGAN [g]	PGAS [g]	PGAU [g]	PGAD [g]
Accumoli	2016-08-24	01:36:32	6.0	8.1	71.5	0.04	0.06	0.03	0.04	0.01	0.01
Visso	2016-10-26	19:18:05	5.9	7.5	50.7	0.04	0.04	0.04	0.04	0.03	0.03
Norcia	2016-10-30	06:40:17	6.5	9.2	54.6	0.07	0.07	0.07	0.06	0.03	0.03

taken from http://cnt.rm.ingv.it * Depth

taken from http://ran.protezionecivile.it ♦ Epicentral distance

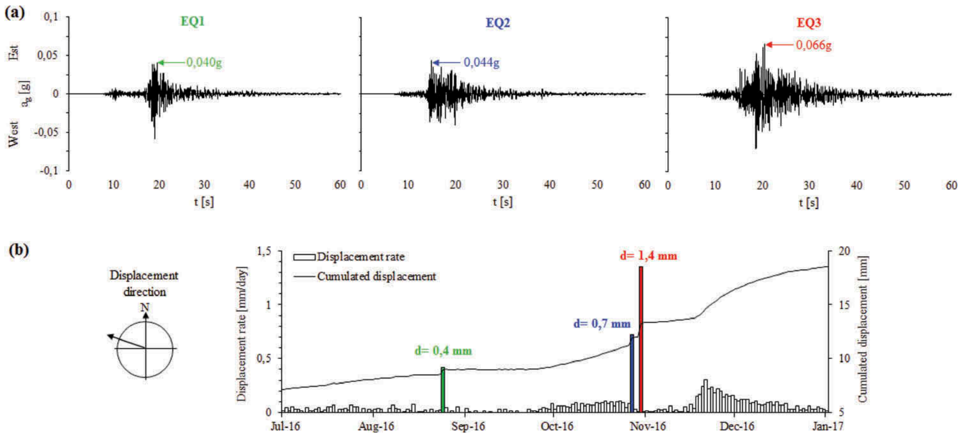


Figure 4. (a) East-West seismic signals of the three mainshocks recorded at the "Valfabbrica" station. (b) Daily displacement rate and cumulative displacement recorded by the AI11-Prb2.

stars) and location of "La Sorbella" landslide. The accelerometric station named "Valfabbrica" (VAL) is the closest one to the considered landslide, being located at a distance less than 1 km. Therefore, as first approximation, it is assumed that the seismic signal recorded by "Valfabbrica" station is representative of the shaking motion experienced by the landslide.

Table 1 summarizes the main features of the seismic signals recorded at the "Valfabbrica" station during the three mainshocks. It can be noted that peak accelerations registered in the area of the landslide range from 0.04g to 0.07g, which are small values if compared with epicentral ones (higher than 0.4g). Figure 4a shows the East-West seismic signals recorded by the "Valfabbrica" seismic station during the three events considered. This component of the seismic motion appears to be more significative to evaluate the response of the landslide due to the orientation towards West of the sliding direction.

4 SEISMIC RESPONSE OF THE LANDSLIDE

The daily reading of the fixed-in-place probes provided a very detailed evolution of the landslide displacements. This allowed distinguishing the response of the landslide to the seismic motion from the general evolution of the phenomenon. The significant readings belong to the probes located in the AI11 boring. In particular, the probes placed at 20.0 m and 22.0 m recorded a sudden increase of the displacement, while those at 4.0 m and 38.0 m did not indicate any movement.

Focusing on the data recorded by the probe at 20.0 m, which is located very close to the known sliding surface, the three seismic events produced the displacements showed in Figure 4b.

In particular a daily displacement of 0.4 mm, 0.7 mm and 1.4 mm have been observed after the three mainshocks mentioned before, respectively. Such values seem small, but the three spikes in the displacement rate graph assure the relevance of the detected measures. Moreover, the displacements developed suddenly and no relevant effects have been observed in the following days.

It is worth to note that the displacement recorded by the probe at 22.0 m has not been considered because, at the current level of knowledge, it results located out of the observed shear zone and moreover, the corresponding displacements direction is uncertain.

5 PRELIMINARY BACK ANALYSIS WITH THE NEWMARK'S METHOD

A preliminary back-analysis of the observed phenomenon has been carried out by using the Newmark's method, based on the pseudostatic analysis of the slope. Although it is well known that Newmark's method has several limitations (Kan, 2017) and that many Authors proposed to overcome some basic assumptions, in order to take into account the deformation of the soil mass (Makdisi and Seed, 1978; Kramer et al., 1997) or the effect of directionality and the vertical component of ground motions (Du, 2018), it still represents a straightforward for first analysis attempt.

Newmark's sliding block analysis is the pioneering method to estimate the permanent displacements of earth dams, natural slopes and embankments under seismic load. Newmark (1965) assumes that permanent displacement take place when the inertial forces induced by an earthquake on a potential sliding mass exceed the resisting forces that result from mobilization of shear strength along the failure surface. By assuming the material above the failure surface to be rigid, Newmark showed that the seismic slope stability problem was analogous to the problem of rigid block resting on an inclined plane. The block slides only if the earthquake acceleration becomes larger than the critical acceleration of the block. The critical acceleration, a_y, can be evaluated by a limit equilibrium analysis of the system, adding an inertial horizontal and vertical acceleration of the block mass to gravity. The displacement of a block under earthquake loading can be evaluated by double integration of the earthquake acceleration exceeding the yield acceleration of the block.

Following this framework, it is possible to evaluate the permanent displacement, d, induced by an acceleration time history as a function of the ratio a_y/a_{max}, where a_{max} is the peak acceleration of the considered time history. If the relationship between the displacement d and the ratio a_y/a_{max} is known, is possible to forecast the permanent displacement exhibited by a slope characterized by a certain critical acceleration. On the contrary, if the displacement exhibited by a sliding mass after an earthquake is known, the critical acceleration can be estimated under the hypothesis of rigid-perfectly plastic behavior of the sliding body (i.e. no hardening or softening evolution of the strength happened during the displacement).

In the present case study, the three considered seismic signals at the "Valfabbrica" station have been double integrated following the outlined procedure to obtain the relationship between permanent displacement and ratio a_y/a_{max}, obtaining the curves showed in Figure 5a. The double integration had been performed using NEWMARK-TRPX (Tropeano, 2010), after a basic baseline correction of the seismic signal (i.e. the mean value of the pre-event records has been subtracted to the accelerograms). Moreover, as first attempt, no deconvolution of the seismic signal has been considered.

Now, the displacements measured by the inclinometer probe AI11_Prb2 can be used to estimate the critical acceleration of the landslide that results equal to 0.031g, 0.024g and 0.037g for the Accumoli, Visso and Norcia earthquake respectively. Such values appear to be each other close enough to define a unique critical acceleration for the considered landslide phenomenon, equal to 0.03g. Despite the large number of simplified hypothesis, the absolute value appears to be meaningful because it agrees with the results of Crespellani et al. (1996) that, back analyzing a large landslide activated by the Irpinia earthquake (1980, South Italy), estimated an initial critical acceleration ranging from 0.017g to 0.045g.

Just to make a comparison, the three considered signals have been scaled at 0.05g and compared in Figure 5b with the graph published by Rampello and Callisto (2008), using the

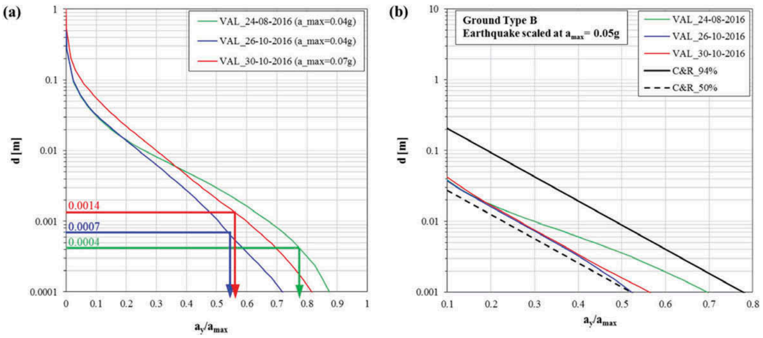


Figure 5. (a) Relationship between permanent displacement and ratio a_y/a_{max} of the seismic signals recorded at the "Valfabbrica" station; the arrows show the estimation of the critical acceleration related to the observed displacement of the landslide; (b) Relationship between permanent displacement and ratio a_y/a_{max} of the recorded seismic signals and average median and 94th-percentile of previous graph.

Italian database accelerograms recorded on ground type B and scaled at 0.05g. The three signals match very well the expected median trend of the comparable Italian seismic events.

Thanks to the knowledge of the critical acceleration it is possible to forecast the displacement induced by a hypothetical large earthquake that could happen with epicenter close to the landslide. To do so the seismic signals recorded by the "Norcia" (NRC) station during the three main earthquakes have been considered. The NRC station is located within 15 km far from the epicenters of the three events and it recorded a peak acceleration equal to 0.33g, 0.21g, and 0.42g for Accumoli, Visso and Norcia earthquake, respectively. As shown in Figure 6a, the estimation of the landslides displacement results equal to 0.30 m, 0.05 m and 1.20 m. Such large difference is related both to the different intensity of the considered earthquakes and to the well-known effect of frequency content and duration of the three accelerograms.

For engineering purposes, it is useful to consider the earthquake related to a pre-determined return period. Such event is usually considered in the hazard map of technical codes.

Considering a return period of 475 years and a ground type B the Italian hazard map provides an expected maximum acceleration on the ground surface equal to 0.274g at "La Sorbella" site.

By using the Rampello and Callisto (2008) graph for earthquakes scaled at 0.25g on ground type B (Figure 6b) and assuming again a critical acceleration of 0.03g, the displacement expected for "La Sorbella" landslide result equal to 0.10 m under an average median earthquake and 1.00 m under an earthquake related to the 94th-percentile of the statistical distribution. Such

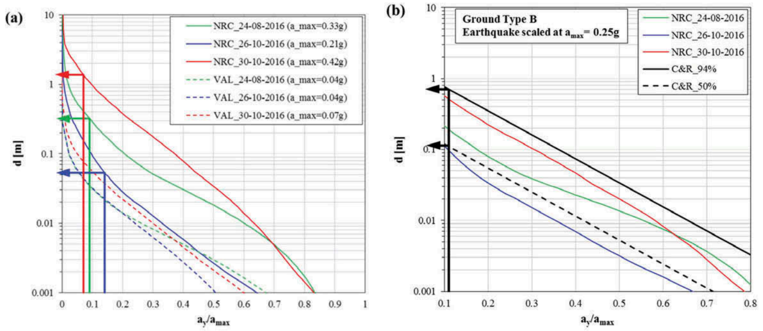


Figure 6. (a) Estimation of displacement by using the earthquakes recorded at the "Norcia" station. (b) ULS estimated seismic displacement according to the Italian technical code at the site of "Valfabbrica"

results have only speculative meaning at the current level of knowledge, because little variations of the critical acceleration determine large variations on the forecast displacements.

6 CONCLUDING REMARKS

A case history concerning seismic displacements induced on an active landslide in the Miocenic Apennines formation is presented. The landslide displacements were continuously monitored through inclinometer probes for a safe use of the highway that crosses the lower part of the sliding mass.

During the 2016 seismic sequence that affected central Italy an inclinometric probe of the monitoring system recorded displacements induced by the three main events. The observed seismic displacements are small but consistent with the low values of the peak acceleration experimented by the landslide. The observed displacements and the availability of a seismic station close to the site has allowed to estimate the critical acceleration of the sliding mass following the Newmark's approach. The uncertainties related to geotechnical characterization of the sliding surface and the exact geometry of the unstable volume do not allow to make reliable conclusions and detailed analysis are ongoing. In any case, taking into account the current level of knowledge of the phenomenon, a consistent framework to estimate the displacements caused by strong earthquakes has been outlined and some numerical forecasts have been presented.

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