EVALUATION OF SEISMIC DEMAND FOR EARTHQUAKE-TRIGGERED LANDSLIDES

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Abstract

Landslides are one of the most commonly observed territorial effects after a strong-motion seismic event. Although landslides are considered a secondary hazard to human lives, as compared with the safety of the buildings, they can cause significant damage to infrastructure networks that determine problems in the immediate post-earthquake during the emergency and reconstruction phases. Therefore it is important to calibrate reliable procedures for regional-scale assessment of seismic landslide susceptibility and hazard. The tools available for assessing regional-scale stability of slopes are empirically related to the earthquake intensity, yet they often provide poor useful information for practical purposes. The technical literature proposes several methods that allow for estimating slope performance under dynamic conditions or are able to evaluate effectively the parameters required for the procedures most commonly used in practice.

This note briefly outlines the criteria for extending to the regional scale the procedures proposed by Tropeano et al. (2017) for assessing the site-specific performance of slopes during a strong-motion earthquake. A preliminary application is also shown for the main events of 2016 seismic sequence in Central Italy.

1. Introduction

The seismic triggering of landslides can be generated by either an increase of inertial force in the slope mass and/or a decrease in soil strength. The latter could be the result of an increase in the pore water pressure induced by cyclic loading in the saturated soils, as well as of a cyclic degradation of soil behaviour or of the joint interfaces in rock masses.

These phenomena can be opportunely accounted for in a rigorous dynamic analysis, requiring a large number of data to characterize the geotechnical slope model and to calibrate the appropriate constitutive models. This approach is theoretically suitable for the study of a single landslide, and it cannot be easily extended to a regional scale application without introducing simplified assumptions. Hence, it is needed to identify approaches with a degree of simplification reasonable enough to reliably take into account the most significant geo-referenced variables both of the seismic motion and of the geometrical, geological and geotechnical characteristics of the slopes.

One of the most commonly adopted empirical approaches is that proposed by Keefer (1984), which defines upper bound envelopes of the maximum site-source distance of earthquake-triggered landslides as a function of the magnitude, with reference to three main categories of failure mechanisms. These relationships have been originally developed for a number of landslides triggered by a few historical earthquakes and, in principle, they need to be updated when new observations are added to the original database. Despite the straightforward use for screening analyses, these relationships are unable to provide useful practical indications. In fact, they do not allow to take account of the site-specific soil properties, of the static conditions and do not lead to any evaluation of the grade of seismic performance of the slope.

A good-working balance between simplicity and reliability is represented by semi-empirical approaches based on a large number of results obtained applying displacement-based methods. These approaches allow for estimating the cumulated sliding displacement as an indicator of the slope performance and they may account for seismic site amplification and soil deformability.

In this note, a method is proposed for evaluating on a rational basis the limit seismic demand required for assessing the slope performance at a regional scale, by applying the probabilistic relationships calibrated by Tropeano et al. (2017). A preliminary application to the main events of 2016 seismic sequence in Central Italy is also shown.

2. Method

A number of displacement-based methods suggested in the literature are derived from the Newmark (1965) rigid block model, by removing some of the basic hypotheses of the original formulation. For instance, the authors recently proposed an 'uncoupled method' that permits to account for the effects of deformability and ductility, by computing separately the seismic site response and the sliding block displacements (Tropeano et al. 2017). In principle, a dynamic uncoupled analysis should consist of two stages:

1. calculation of the time history of the shear stress, $\tau(t)$, at the depth of the real or potential sliding surface, h, by a seismic response analysis: the equivalent acceleration time history, $a_{eq}(t)$, is then defined as $\tau(t)/\sigma_v(h)$;
2. calculation of permanent displacement by double integration of the relative acceleration between the rigid landslide mass and the stable subsoil below the sliding surface.

The statistical processing of a large number of results obtained by the above two-stage analyses, with reference to a specific seismic database, leads to develop straightforward relationships for simplified displacement predictions.

Fig. 1a schematically shows the procedure of a simplified uncoupled approach, as originally proposed by Bray & Rathje (1998) and adapted to the Italian seismicity by Tropeano et al. (2017). The application needs the preliminary definition of the seismic action, in terms of peak reference acceleration, a_g, dominant frequency (represented by the mean period, T_m) and significant duration of shaking ($D_{5\text{-}95}$, defined between 5% - 95% normalized Arias intensity). In practice, such parameters can be evaluated by site-specific seismic hazard analyses or ground motion prediction equations (GMPE), such as those developed on purpose by the authors for the Italian seismicity Tropeano et al. (2017). The slope geotechnical model is characterised by the fundamental period, T_s, of the potentially unstable soil mass, and by the yield acceleration, a_y, corresponding to the onset of sliding.

Non-linear site amplification is taken into account, by expressing the surface acceleration, a_s, as a function of a_g and of the subsoil class (Fig. 1a1); thus, the maximum equivalent acceleration, a_{eq}, is obtained through a reduction factor, α_F, decreasing with the ratio between T_s and T_m (Fig. 1a2). The latter allows accounting for the effects of soil deformability, which tends to reduce the resultant of inertia forces due to the asynchronous motion within the potentially unstable soil/rock mass. Finally, the acceleration ratio a_y/a_{eq} is used to evaluate the displacement d^*, normalised with respect to the reference ground motion parameters a_{eq}, T_m and $D_{5\text{-}95}$ (Fig. 1a3).

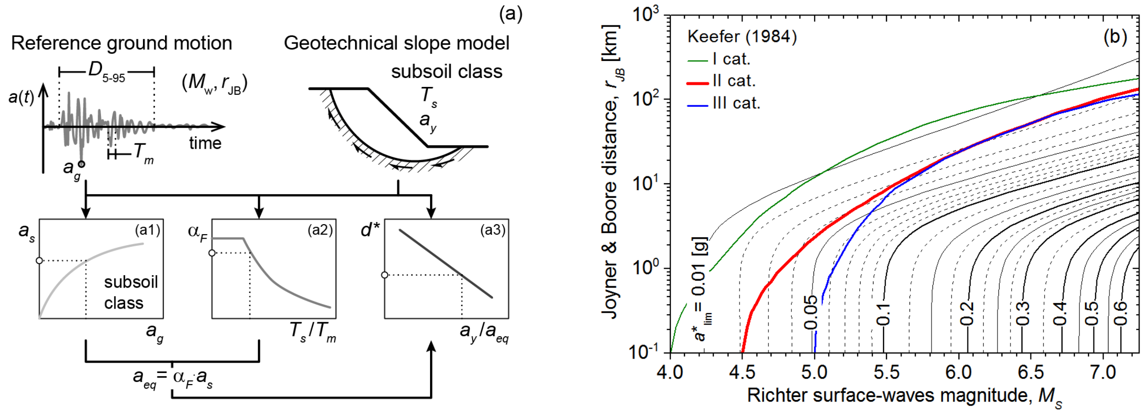

Fig. 1. (a) Flowchart of simplified decoupled approach for evaluating slope permanent displacements and (b) Chart for evaluating the reference limit acceleration from hazard evaluated in terms of magnitude and distance.

The first procedure synthetically quantifies the site-specific landslide susceptibility in terms of yield acceleration, computed with the common pseudo-static approach. This procedure cannot be easily extended to a regional scale without introducing significantly simplified assumptions about the landslide mechanism (typically, the infinite slope model, as adopted by Silvestri et al. (2016).

In the second procedure, the seismic demand for the achievement of a given damage level of the slope (specified by a threshold displacement, u_{lim}) is expressed by the 'limit acceleration' a_{lim}. The specified damage level is trespassed when a_{lim} is higher than the 'seismic capacity', represented by the yield acceleration. Alternatively, the value of a_{lim} (expressed in g) might be used as horizontal seismic coefficient in conventional pseudo-static analyses for evaluating the seismic slope stability. In fact, in the performance-based philosophy, the slope is unstable when undergoes a displacement greater than the threshold value with a given probability of exceedance. Note that, while the seismic slope capacity depends on site-specific parameters, the seismic demand can be extensively mapped at a regional scale with different probability of exceedance. Two different degrees of detail can be adopted, namely:

I. reference limit acceleration, a^*_{lim}, defined as a function of seismological parameters only i.e. magnitude, distance and error of the selected GMPE, ε, for threshold displacement u^*_{lim} = 1 cm (Fig. 1b). This possibility is yet available at regional scale, by considering geo-referenced data from Seismic Hazard Maps;

II. limit acceleration, a_{lim}, accounting for site amplification through geo-referenced maps of the soil classes and topographic categories. The frequency reduction factor, α_F, might be in principle included in the computation of a_{lim}, if information are available about the equivalent shear wave velocity and the likely depth of sliding surface (e.g. for active or dormant landslides, shallow soft colluvial covers overlying a stiff bedrock, and so on). In the lack of such information, α_F can be conservatively set equal to the maximum value, corresponding to the lowest T_s/T_m ratio (see Fig. 1b).

3. Application

In this work, the procedure proposed by Tropeano et al. (2017) was applied in fully probabilistic terms, i.e. by expressing the limit acceleration as function of a^*_{lim} as follows:

$$a_{\lim} = \alpha_F S \left\{ a^*_{\lim} 10^{0.25\varepsilon} + \frac{a_g}{3.41}\left[\log\left(\frac{\alpha_F S \cdot u^*_{\lim}}{u_{\lim}} \right) + 0.25\varepsilon + 0.45\varepsilon_{tot} \right] \right\} \tag{1}$$

where: S is the site amplification factor including stratigraphic and topographic effects, ε is the error term of GMPE and ε_{tot} is the error of prediction relationship distributed with a standard normal law.

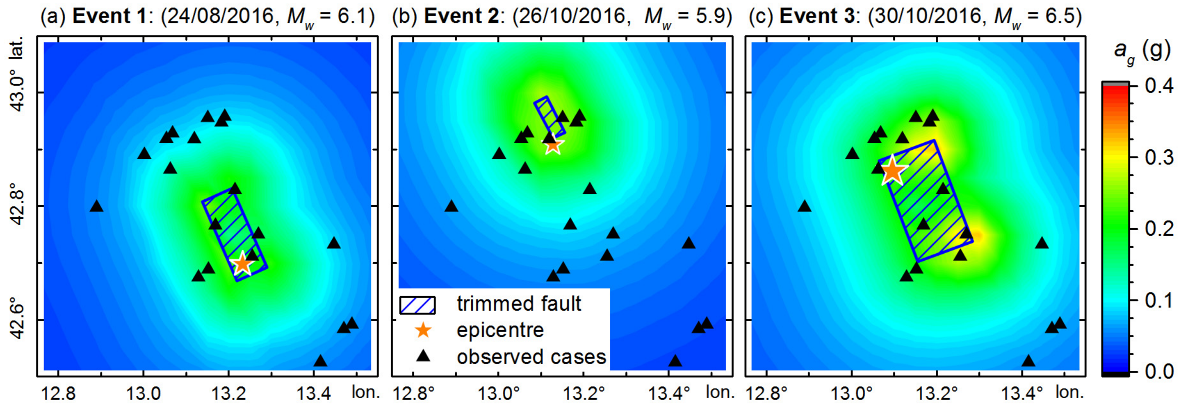

Fig 2. Areal distribution of median a_g obtained with NGA-WEST 2 GMPE for: (a) 24 August 2016 event (M6.1) (b) 26 October 2016 event (M5.9) and (c) 30 October 2016 event (M6.5).

Depending on whether reference is made to the overall regional seismic hazard or on that specifically induced by a given seismogenic source, the reference peak ground acceleration, a_g, on a flat outcropping rock site can be respectively estimated as that given by the National Hazard Map or through the GMPE adopted. The peak acceleration at surface, a_s, can be then obtained through stratigraphic and topographic amplification factors, similar to those proposed by Technical Codes, function of the soil class and topographic category, respectively.

In this work, a_g has been predicted with NGA-WEST 2 GMPE [Bozorgnia et al. (2014), Boore et al. (2014)] for the three main events occurred during August to October 2016 in Central Italy, considering the source geometry and seismological parameters reported by GEER (2016), and including the near-fault effects. The obtained areal distributions of median values are shown in Fig 2. The same figure reports with triangles the locations of the main instability cases surveyed by GEER (2016, 2017).

Figs. 3a, 3b and 3c show the areal distribution of the limit acceleration, a_{lim}, for the events of 24 August, 26 October and of 30 October 2016, respectively. A conservative prediction for a_{lim} evaluation was considered in Eq. (1), corresponding to a non-exceedance probability p = 84%.

The maps of a_{lim} are referred to the distribution of median prediction value of a_g (Fig. 2) and for rock-site conditions, being the deformability of the unstable slopes considered not significant, so that the stratigraphic amplification factor was set equal to unity. Topographic effects were accounted for in simplified manner, adopting the amplification coefficient S_T = 1.4, suggested by Italian and European technical codes for topographic category T4 (i.e. hills or mountains with a ridge width much smaller than that at the base and average inclination i > 30°) that is the typical morphology detected in most of the instability cases surveyed [see GEER (2016, 2017)]. The mean period and significant duration were considered as random ground motion parameters, defined with the above mentioned GMPEs calibrated by Tropeano et al. (2017) for the Italian seismicity.

Relatively small displacements are sufficient for triggering disrupted slides, falls and topples, which were the most frequent instability mechanisms observed in the seismic sequence: therefore, the three values of 1, 5, and 10 cm were considered for the threshold co-seismic displacement, u_{lim}.

In the maps, the areas with a_{lim} > 0.1g are highlighted with shades of white to red: in these areas, it is more likely that the seismic demand is higher than the seismic capacity of slopes. In the areas with a_{lim} < 0.1g (shading turning from white to blue), the triggering of landslides is more likely if the slope is close to the limit equilibrium conditions before the earthquake. For values of a_{lim} < 0.01g (white hatched areas), the seismic triggering requires that the slope is practically unstable in static conditions. Nevertheless, in both last cases, the possibility that a stable slope can sustain the limit displacement is an event with higher non-exceedance probability.

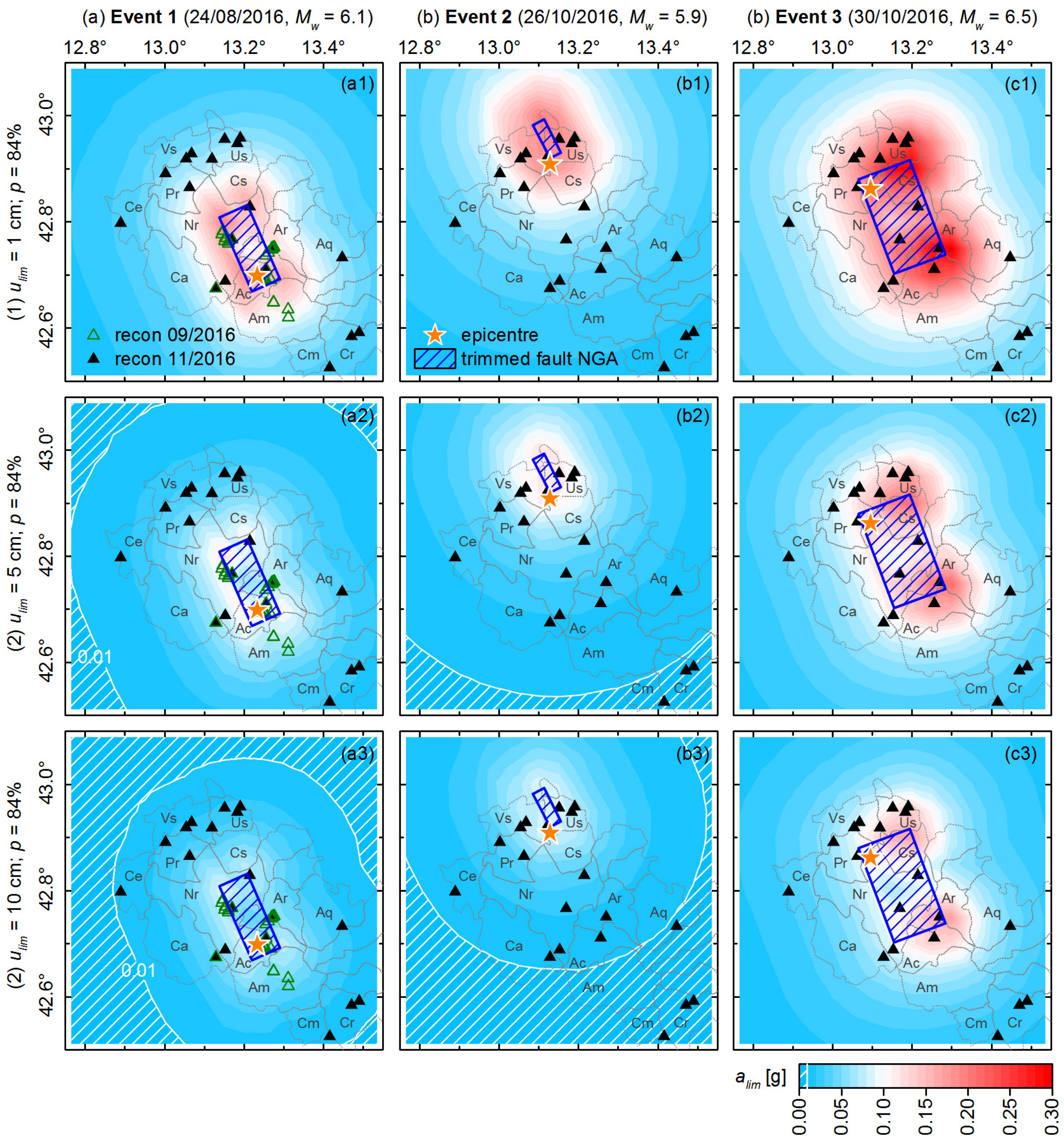

Fig. 3. 84% non-exceedance probability prediction of 'seismic demand' of slope (a_{lim}), assuming three threshold displacements (u_{lim} = 1 cm, 5 cm and 10 cm) for the three main events of the seismic sequence in 2016.

In Fig. 3a the results for seismic demand are compared with the cases surveyed by GEER (2016) during the reconnaissance of September 2016 after the first shock of 24 August 2016 (green empty symbols) and those surveyed by GEER (2017) during the reconnaissance of December 2016 (black full symbols).

The distribution of estimated a_{lim} reflects that of the prediction of a_g obtained by the GMPE (Fig. 2), with an evident increase in seismic demand in correspondence of the areas around the corner of the fault box, where the selected GMPE provides greater near-source effects on a_g estimation.

Despite the simplifications adopted for the calculation, Fig. 3 show a high seismic demand in the municipalities of Visso and Ussita (labelled as'Vs' an 'Us' in Fig. 3), where numerous disrupted rock slides, rock-falls and topples were observed. In this area, the event of 26 October has significantly contributed to the increase of the local susceptibility, resulting in an incremental damage in the unstable rock volumes following the subsequent event. For events located further away from the fault (e.g. in the municipalities of Crognaleto, 'Cr', and Campotosto, 'Cm', at about 40 km from the epicentre of 30

October event), the seismic demand does not seem enough high to activate the collapse of large rock masses observed. In these cases, geomorphological factors may have played an important role in the local amplification of the seismic motion.

4. Conclusions

This note describes the extension of the procedure proposed by Tropeano et al. (2017) to regional scale predictions.

These preliminary application to the main events of the 2016 seismic sequence in Central Italy shows that the method, although using only the seismological characterization of the source, is able to locate the areas where rock slope instability is most likely. In such a perspective, it represents a rational extension of the empirical screening criteria first introduced by Keefer (1984). However, more reliable results can be expected if the seismic demand is predicted by adequately accounting for local geomorphological and geotechnical properties, which are going to be gathered during forecoming seismic microzonation studies.

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