# Probabilistic seismic hazard curves and maps for Italian slopes

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**Abstract.** The seismic performance of an earth slope is commonly evaluated through the permanent displacements developed at the end of an earthquake. In this paper a probabilistic approach is adopted to assess the displacement of the slope for a given hazard level using an updated database of ground motions recorded during the earthquakes occurred in Italy. The results are presented in terms of hazard curves, showing the annual rate of exceedance of permanent slope displacement evaluated using ground motion data provided by a standard probabilistic hazard analysis and a series of semi-empirical relationships linking the permanent displacements of slopes to one or more ground motion parameters. The probabilistic approach permits to take into account synthetically the characteristics of the slope through the yield seismic coefficient, the aleatory variability of the ground motions and the different subsoil classes of the recording stations. Finally, the procedure has been extended on a regional scale to produce seismic landslide hazard maps for Irpinia, one of the most seismically active regions in Italy. Seismic landslide hazard maps are very attractive for practitioners and government agencies for a screening level analysis to identify, monitor and minimise damages in zones that are potentially susceptible to earthquake-induced slope instability.

**Keywords:** Slopes, Earthquake-induced displacements, Probabilistic analysis, Displacement hazard curves, Hazard maps.

## 1 Introduction

Earthquakes often produce instability in natural slopes, causing severe human and economic losses. Therefore, several efforts have been devoted in the past decades by the geotechnical community to study the seismic response of slopes aimed at mitigating and preventing such catastrophic events.

The seismic performance of a slope can be synthetically assessed by the evaluation the permanent displacements developed at the end of the seismic event, which can be quantified through several methods. In this context, the well-known displacement-based Newmark's method [1] represents a good compromise between simplicity and accuracy of the results, in which the slope is assimilated to a rigid block sliding on a horizontal plane that undergoes permanent displacements only when the acceleration of the input motion is greater than a critical value, the latter depending on slope resistance. The integration of a set of acceleration time histories permits to link the permanent displacements to the yield seismic coefficient, representing the slope seismic resistance, and to one or more ground motion parameters, leading to a series of semi-empirical relationships [2-4]. These relationships are useful for a preliminary estimate of the expected seismic-induced displacement of slopes but they cannot account for the aleatory variability of earthquake ground motion and displacement prediction. Therefore, many researchers developed fully probabilistic-based approaches stemming from the above semi-empirical relationships to introduce the concept of hazard associated to the calculated displacement [5-7]. The results of the probabilistic approach are typically illustrated in terms of displacement hazard curves, which provide the mean annual rate of exceedance $\lambda_d$ (or the return period $T_r = 1/\lambda_d$ ) for different levels of permanent displacements.

The present study aims to contribute towards the evaluation of earthquake-induced landslides hazard for Italy, which is characterised by a high level of seismicity. The displacement hazard curves are developed for the Italian territory stemming from the seismic databased recently updated by Gaudio *et al*. (2020) [8]. Both scalar and vector probabilistic approaches are employed: in the first case the peak ground acceleration (*PGA*) is used as ground motion parameter, while the combination of *PGA* with the peak ground velocity (*PGV*) is chosen for the vector approach. Moreover, the probabilistic approach has been implemented on a regional scale using the ground motion hazard information to evaluate landslides hazard maps, that allow to identify the zones that are more susceptible to earthquake-induced slope instability and the probability of occurrence of a displacement level in a specific time interval. These results provide a useful tool for practitioners and government agencies for a preliminary evaluation of the seismic performance of slopes, stemming from the updated seismic database and the results of the semi-empirical relationships adopted in the study.

## 2 Probabilistic approach

The displacement models predict the natural log of permanent horizontal displacement *d* as a function of the natural log of one or more ground motion parameters (*GM*) or earthquake magnitude.

For the single ground motion parameter model, the expression proposed by Ambraseys & Menu (1988) [9] is adopted:

$$\ln(d) = a_0 + a_1 \ln\left(1 - \frac{k_y}{PGA}\right) + a_2 \ln\left(\frac{k_y}{PGA}\right) \tag{1}$$

where $a_0$, $a_1$ and $a_2$ are regression coefficients and $d$ is expressed in cm. The efficiency of the semi-empirical relationships is described by the standard deviation of the natural log of displacement $\sigma_{\ln}$. Eq. (1) complies with the conditions $d \to \infty$ for $k_y/PGA = 0$ and $d = 0$ for $k_y/PGA = 1$ expected for the assumption of a rigid sliding block.

The results of a probabilistic analysis are synthesised in terms of seismic displacement hazard curves, providing the mean annual rate of exceedance $\lambda_d$ for different levels of displacements given a yield seismic coefficient and a specific site. According to [7], for the single ground motion *PGA* displacement model the annual rate of exceedance $\lambda_d$ can be computed as:

$$\lambda_d(x) = \sum_i P\left[d > x \mid PGA_i\right] \times P\left[PGA_i\right] \tag{2}$$

where $P\left[d > x \mid PGA_i\right]$ is the probability of the displacement exceeding a specific value *x*, given a peak ground acceleration $PGA_i$, and $P\left[PGA_i\right]$ is the annual probability of occurrence of the ground motion level $PGA_i$ obtained through a probabilistic seismic hazard analysis (PSHA).

Ambraseys & Menu (1988) [9] suggest to modify Eq. (1) to account for the effects of other ground motion parameters. Therefore, along this track, the following semi-empirical relationship is proposed for the case of two ground motion parameters:

$$\ln(d) = a_0 + a_1 \ln\left(1 - \frac{k_y}{PGA}\right) + a_2 \ln\left(\frac{k_y}{PGA}\right) + a_3 \ln(PGV) \tag{3}$$

Eq. (3) allows to develop a vector probabilistic approach in terms of the ground motion parameters *PGA*, *PGV*, according to Rathje & Saygili (2008) [7]:

$$\lambda_d(x) = \sum_i \sum_j P\left[d > x \mid PGA_i, PGV_j\right] \times P\left[PGA_i, PGV_j\right] \tag{4}$$

Details concerning the calculation of Eq. (4) can be found in [10].

## 3 Results of the proposed approach

The results of the probabilistic approach are synthesised in terms of displacement hazard curves, plotting the mean annual rate of exceedance $\lambda_d$ for different levels of permanent displacements and in terms of hazard maps, showing the distribution of the return period $T_r = 1/\lambda_d$ for a given permanent displacement and a given yield seismic coefficient. Hazard curves and maps are developed for different zones of the Italian territory employing both the scalar and the vector approaches.

The permanent displacements are computed with the rigid sliding-block model for the simple scheme of an infinite slope assuming a constant shear strength, that is a constant $k_y$, during earthquake loading. Computation have been carried out for different values of the yield seismic coefficient, using an updated version of the Italian strong motion database. In comparison to the work by Rollo & Rampello (2021) [10], an extended range of the yield seismic coefficient is considered here

$(k_y = 0.04,\ 0.06,\ 0.08,\ 0.1,\ 0.12,\ 0.15)$ to include a higher number of slopes scenarios.

Table 1 reports the regression coefficients of the semi-empirical relationships evaluated for computed displacements greater than 0.0001 cm. Despite very small values of displacements are meaningless from an engineering perspective, they have been considered to develop semi-empirical relationships capable to fit satisfactory the data as the *PGA* approaches $k_y$. The coefficients of the semi-empirical relationships are further specialised to account for the influence of the subsoil class on the probabilistic approach.

**Table 1**. Coefficients of the semi-empirical relationships

| Subsoil class | GM parameter | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $\sigma_{ln}$ |
|---|---|---|---|---|---|---|
| All | *PGA* (g) | -1.667 | 2.017 | -2.127 | - | 1.103 |
| | *PGA* (g), *PGV* (cm/s) | -2.959 | 2.178 | -0.809 | 1.322 | 0.579 |
| A | *PGA* (g) | -2.550 | 1.799 | -2.709 | - | 1.042 |
| | *PGA* (g), *PGV* (cm/s) | -3.147 | 2.142 | -1.016 | 1.267 | 0.592 |
| B | *PGA* (g) | -1.778 | 1.975 | -2.060 | - | 1.052 |
| | *PGA* (g), *PGV* (cm/s) | -2.945 | 2.184 | -0.745 | 1.315 | 0.574 |
| C | *PGA* (g) | -1.252 | 2.124 | -2.003 | - | 1.134 |
| | *PGA* (g), *PGV* (cm/s) | -2.885 | 2.169 | -0.852 | 1.308 | 0.567 |

As reported in Table 1, the use of the two parameters semi-empirical relationship reduces significantly the standard deviation associated to the Newmark's displacements as compared to the scalar approach: an expected result as the couple of ground motion parameters *PGA*, *PGV* are more representative of the strong motion database than the *PGA* only.

The computed permanent displacements and the semi-empirical relationships are plotted in Fig. 1 against the ratio $k_y/PGA$ for the whole database and the three subsoil classes (A, B and C). The vector predictive equation is plotted for *PGV* = 8 cm/s, representing the average value associated to the recorded ground motions. It is seen that the adopted models not only predict correctly the conditions at the extrema but also nicely reproduce the non-linear variation of the permanent displacements with $k_y/PGA$. Moreover, Rollo & Rampello (2021) [10] show that the vector approach predicts about halved values of the standard deviations with respect to the scalar one, with a trend characterised by negligible biases for increasing values of $k_y/PGA$ and no relevant variation with $k_y/PGA$, hence demonstrating that the regressions adopted in this study are appropriate for the Italian ground motion database.

The displacement hazard curves shown in this paper refer to the Italian site of Amatrice, afflicted by the 2016 Central Italy seismic sequence. Information pertaining to the seismic hazard of the specific site have been extracted from the INGV interactive seismic hazard maps (http://esse1.mi.ingv.it/d2.html) that permits to query probabilistic seismic hazard maps of the Italian territory on a regular grid spaced by 0.05°.

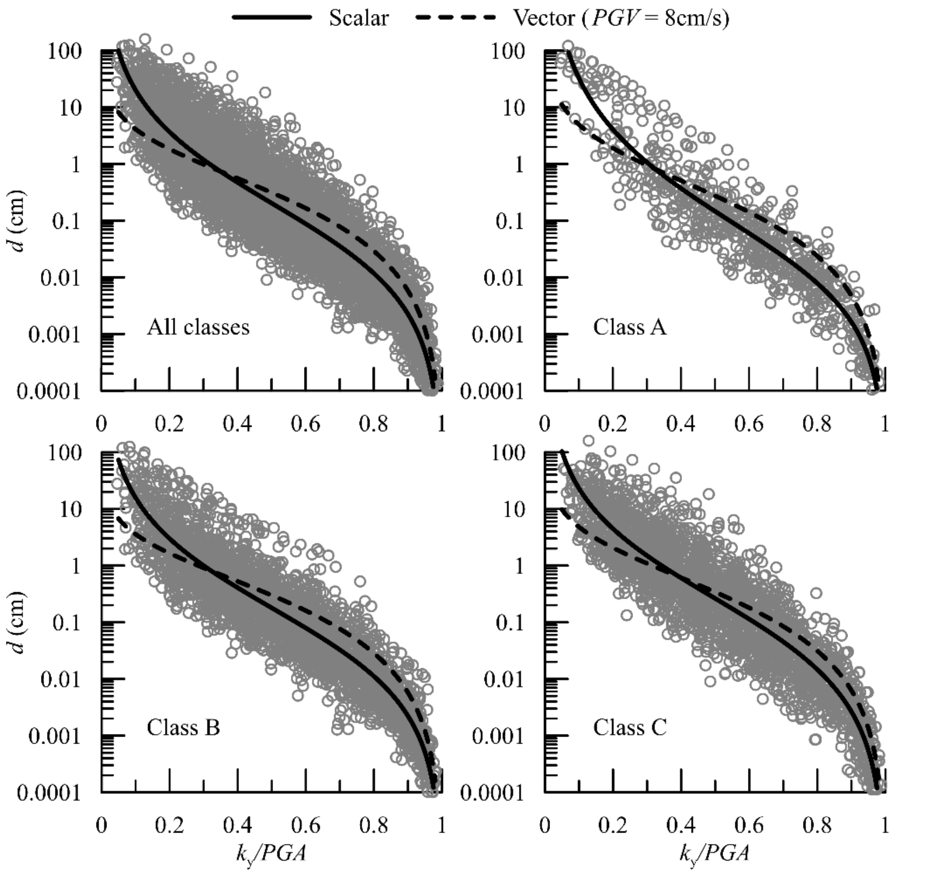


Fig. 1. Semi-empirical relationships

Fig. 2 shows the displacement hazard curves obtained through the scalar and vector approaches for different values of the yield seismic coefficient. As expected, the computed displacement hazard curves show a decreasing annual rate of exceedance with increasing permanent displacements and prove that the more stable is the slope (i.e. greater is $k_y$), the lower is the annual rate of exceedance associated to a given displacement. Furthermore, it is worth noting that the vector approach always predicts smaller values of $\lambda_d$ in the whole range of permanent displacements considered in the analysis, thus reducing the hazard estimate. This result is consistent with the outcomes of [6,7,10] and with the smaller standard deviation and median displacements computed through the vector approach as compared with the scalar one.

Fig. 3 illustrates the displacement hazard curves computed with the scalar and vector approaches for the Amatrice site, distinguishing the three subsoil classes and using $k_y = 0.08$.

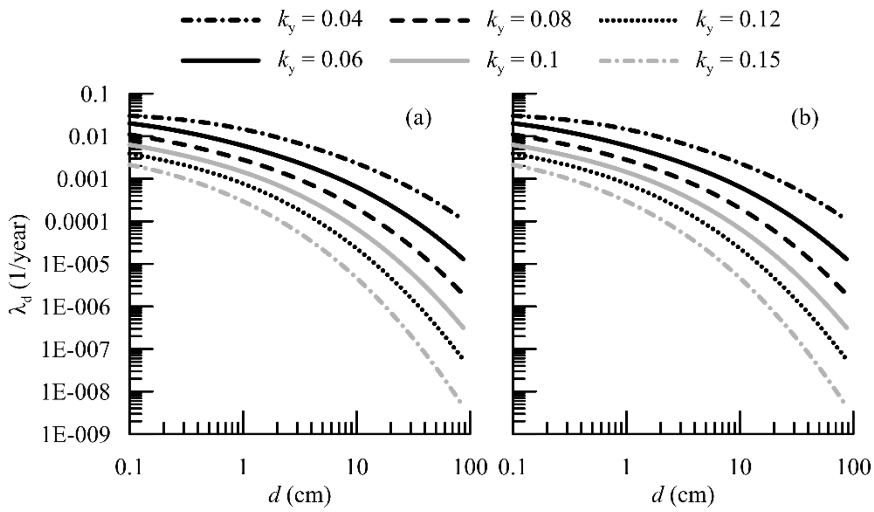


Fig. 2. Effect of $k_y$ for (a) scalar and (b) vector approaches

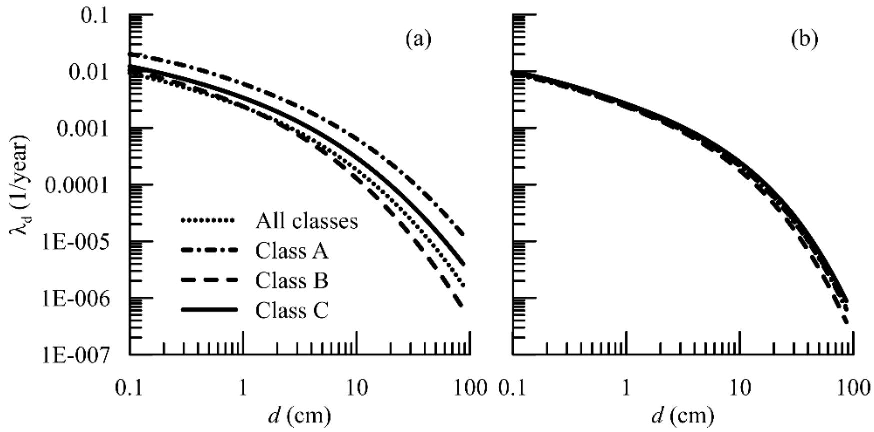


Fig. 3. Effect of subsoil classes for $k_y$ = 0.08 for (a) scalar and (b) vector approaches

It is seen that higher annual rate of exceedance $\lambda_d$ is computed for soft (class C) subsoil as compared to that of stiff (class B) subsoil or, in other terms, for class C sites the model predicts the largest displacements at fixed rate of exceedance. This is consistent with the fact that the ground motions recorded on soft soils are richer in low frequencies than those recorded on stiff soils, hence leading to larger displacements. It is less clear the trend observed for the case of rock-like (class A) subsoil, for which the smallest displacements are expected, while the obtained hazard curve lies above those computed for classes B and C. As discussed by Rollo & Rampello (2021) [10], this could be attributed to the fact that for rock-like subsoils about 50% of the records with $PGA > 0.2\ g$ are characterised by high values of the mean period $T_m > 0.4$ s, that could explain the unexpectedly high displacements computed for subsoil class A, leading the hazard displacement curve to the right of that obtained for the other subsoil classes. An analogous trend is observed for the vector approach, despite the effect of the subsoil classes is less pronounced than that observed for the scalar approach.

Finally, the probabilistic approach is used in the following to develop the hazard maps for the district of Irpinia, in the South Italy, about 50 km East of Naples and characterised by a severe seismic hazard. The hazard maps depict the contours of the return periods $T_r$ associated to different levels of seismic-induced displacement and yield seismic coefficient. Fig. 4 shows the contour maps obtained from the vector approach for a threshold displacement $d_y = 2$ cm and different values of the yield seismic coefficient.

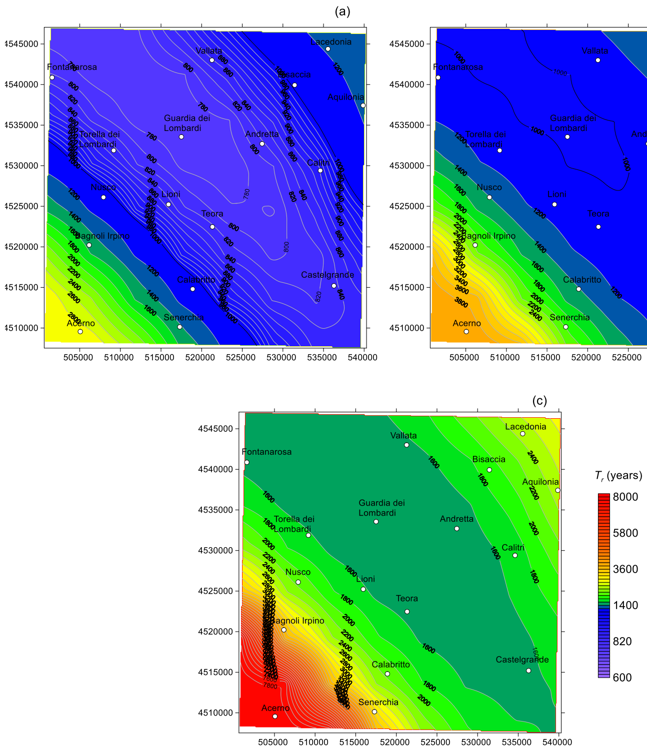


Fig. 4. Hazard maps for the Irpinia district for $d_y = 2$ cm: (a) $k_y = 0.1$, (b) $k_y = 0.12$, (c) $k_y = 0.15$

As expected, the return periods associated to a given value of $d_y$ increase with $k_y$. The variability of $T_r$ is clearly associated to the *PGA* hazard curves and disaggregation information of the region, that is more severe for the zone of the Apennines extending from North-Western to South-Eastern corners of the map. Therefore, the contour lines are nearly parallel to the NW-SE diagonal of the map, with larger return periods in the South-Western area, where hills take place of the mountains.

# 4 Conclusions

The results presented in this paper show that the probabilistic approach represents a useful tool for a preliminary evaluation of the seismic performance of slopes. The displacement hazard curves provide site-specific information, whereas the hazard maps are suitable for the analysis and the evaluation of the seismic risk of natural slopes at a regional scale. The probabilistic nature of these maps also enables them to be combined with other hazards for a more complete hazard analysis, useful for disaster management to minimise damages caused by earthquake-induced landslides.

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