Influence of the displacement predictive relationships on the probabilistic seismic analysis of slopes

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Abstract

Seismically-induced landslides can often cause severe human and economic losses. Therefore, it is worth assessing the seismic performance of slopes through a reliable quantification of the permanent displacements induced by seismic loading.

This paper presents a new semi-empirical relationship linking the permanent earthquake-induced displacements of slopes to one or two synthetic ground motion parameters developed considering the Italian seismicity and a comparison with existing simplified displacement models is illustrated. Once combined with a fully probabilistic approach, these relationships provide a useful tool for practicing engineers and national agencies for a preliminary estimate of the seismic performance of a slope. In this perspective, the predictive capability of different semi-empirical relationships is analysed with reference to the permanent displacements evaluated for the Italian seismicity assimilating the slope to a rigid body and adopting the Newmark's integration approach. The consequences of the adoption of these relationships on the results of the probabilistic approach are illustrated in terms of displacement hazard curves and hazard maps for different slope scenarios.

Keywords: slopes, earthquake-induced displacements, semi-empirical relationships, probabilistic analysis, displacement hazard curves, displacement hazard maps

1 Introduction

The seismic performance of a slope is often evaluated through the permanent displacements developed at the end of the seismic event (Jibson, 2011; Wasowski *et al*., 2011). A well-established method to quantify the displacements is that proposed by Newmark (1965), that consists to model the slope with a rigid block sliding on a horizontal plane that experiences permanent displacements only when the critical acceleration function of the slope resistance is lower of that of the input motion.

In the last two decades several semi-empirical relationships have been proposed, that link the permanent slope displacements computed through the Newmark's method, using different ground motion databases, to a series of ground motion parameters and the yield seismic coefficient k_y denoting synthetically the seismic slope resistance (e.g. Jibson, 2007; Saygili & Rathje, 2008; Rampello *et al*., 2010; Biondi *et al*., 2011; Song *et al*., 2017; Tropeano *et al*., 2017; Bray *et al*., 2018; Du *et al*., 2018a Bray & Macedo, 2019; Cho & Rathje, 2022). Several efforts have been made to produce more reliable semi-empirical relationships through different combination of ground motion parameters (e.g. Chousianitis *et al*., 2014; Bray & Macedo, 2019) and, more recently, to account for the influence of slope parameters variability (Du *et al*., 2018b) through machine learning algorithms (e.g. Xiong *et al*., 2019; Wang *et al*., 2020; Liu & Macedo, 2022). For instance, to better describe the properties of the earthquake, the parameters Arias intensity I_A and the mean period T_m have been adopted as they can also embody the duration and the frequency content of the ground motion. Moreover, the performance of the semi-empirical relationships increases when more than one ground motion parameter is used (Bazzurro & Cornell, 2002) as they can account for other relevant features of the ground motion that influence the displacements of the slope. These simplified relationships can be used to predict the seismic-induced displacements of specific slopes and embankments (e.g. Meehan & Vahedifard 2013, Kan *et al*., 2017) but also become a powerful and attractive tool when combined with a fully probabilistic-based approach capable to account for the aleatory variability of earthquake ground motion and displacement prediction (e.g. Rathje & Saygili, 2008, 2011; Bradley, 2012; Lari *et al*., 2014; Du & Wang, 2016; Rodriguez-Marek & Song, 2016; Song *et al*., 2018; Macedo & Candia, 2020; Macedo *et al*., 2020; Yeznabad *et al*., 2022) and the variability of the slope parameters (e.g. Wang & Rathje, 2018; Li *et al*., 2020; Wang *et al*., 2021). Within this theoretical framework, scalar and vector probabilistic approaches can be developed if one or more ground motion parameters are considered. Moreover, the probabilistic analysis can be extended at a regional scale using the ground motion hazard information to produce landslides hazard maps that allows to detect the portions of territory that are more susceptible to earthquake-induced slope instability (e.g. Saygili

& Rathje, 2009; Wang & Rathje, 2015; Chousianitis *et al*., 2016; Sharifi-Mood *et al*., 2017; Li *et al*., 2022).

Recently, Rollo & Rampello (2021) adopted this probabilistic approach for the Italian territory, obtaining hazard curves and hazard maps providing the mean annual rate of exceedance λ_d (as an alternative the return period $T_r = 1/\lambda_d$) for different values of permanent displacements and yield seismic coefficient k_y, stemming from the seismic database updated by Gaudio *et al*. (2020). In both works, Newmark's integration of the ground motions was performed for the scheme of infinite slope, using different semi-empirical relationships. Although Gaudio *et al*. (2020) show that the most efficient semi-empirical relationships are obtained for the couple of ground motion parameters (I_A, T_m), it is more convenient to adopt the couple *PGA*, *PGV*. In fact, (i) the adoption of the ratio k_y/PGA is crucial to control the behaviour of the model for displacements close to zero or with very high values and (ii) the probabilistic method adopted here requires ground motion predictions equations (GMPE) that are often developed only in terms of *PGA* and *PGV*. Moreover, (iii) the method uses the results of a standard seismic probabilistic hazard analysis (PSHA) that are usually presented in terms of peak ground acceleration hazard curves.

In this work a new semi-empirical relationship is presented, developed with reference to the Italian seismicity, along the line tracked by Rollo & Rampello (2021), assimilating the slope to a rigid sliding block. Although the Newmark's method ignores the soil deformability and the cyclic degradation of the shear strength, that would require site-specific studies, it represents an attractive tool for the screening level analysis of slopes at the regional scale. The predictive capability of this new relationship is compared with other existing formulations and proves to be more reliable for the assessment of the seismic performance of slopes in Italy. The comparison presented here aims at providing some guidance in the choice of the semi-empirical relationships, highlighting their advantages and drawbacks in predicting the displacements induced by earthquake loading in a slope, and their application within a probabilistic approach. Furthermore, in this study a wider range of yield seismic coefficients is considered with respect to what presented in Rollo & Rampello (2021), to account for a larger number of slope scenarios. The results of the probabilistic approach are first shown in terms of displacement hazard curves considering both the scalar and the vector approaches, highlighting that the results obtained through the latter are not only more reliable but also are less sensitive to the choice of the specific predictive relationships adopted for the earthquake-induced slope displacements. Finally, displacement hazard maps showing the distribution of the return period for different prescribed values of slope displacements and seismic yield coefficient are presented, aimed at clarifying the role of the adopted displacement semi-empirical relationships on the evaluation of the seismic hazard at a regional scale.

2 Displacement predictive relationships under study

The displacement relationships provide the natural log of permanent horizontal displacement *d* given the natural log of one or more ground motion parameters (*GM*). In principle, any combination of ground motion parameters can be adopted. However, as discussed by Rollo & Rampello (2021), the parameters *PGA* and *PGV* are more suitable for the development of the probabilistic approach requiring a standard seismic probabilistic hazard analysis (PSHA).

With this premise, the simplest semi-empirical relationships are those proposed by Fotopoulou & Pitilakis (2015), reported here for both the scalar and the vector approaches:

$$\begin{aligned}\ln(d) &= a_0 + a_1 \ln(PGA) \\ \ln(d) &= a_0 + a_1 \ln(PGA) + a_2 \ln(PGV)\end{aligned} \tag{1}$$

where *d* is expressed in cm and a_0, a_1 and a_2 are the regression coefficients. Eq. (1) represents linear relationships between the natural log of displacements and the natural log of the ground motion parameters *PGA* and *PGV*. Displacements *d* are computed by Eq. (1) for given values of the seismic yield coefficient k_y, so that different sets of regression coefficients are obtained depending on k_y. According to Cornell & Luco (2001), the efficiency of the semi-empirical relationships can be quantified by the standard deviation $\sigma_{\ln}$ of the natural log of displacement. Despite the simplicity and the limits of application of the linear relationships, they are employed here for comparison with more sophisticated predictive equations. Saygili & Rathje (2008) proposed a modification of Eq. (1) employing the following second-order polynomial expressions:

$$\begin{aligned}\ln(d) &= a_0 + a_1 \ln(PGA) + a_2 \left[\ln(PGA)\right]^2 \\ \ln(d) &= a_0 + a_1 \ln(PGA) + a_2 \left[\ln(PGA)\right]^2 + a_3 \ln(PGV) + a_4 \left[\ln(PGV)\right]^2\end{aligned} \tag{2}$$

with the addition of the regression coefficients a_2 and a_4, still depending on k_y, as above. Then, a functional form that encompasses the ratio k_y/PGA has been also proposed by Saygili & Rathje (2008):

$$\ln(d) = a_0 + a_1 \frac{k_y}{PGA} + a_2 \left(\frac{k_y}{PGA}\right)^2 + a_3 \left(\frac{k_y}{PGA}\right)^3 + a_4 \left(\frac{k_y}{PGA}\right)^4 + a_5 \ln(PGA)$$
$$\ln(d) = a_0 + a_1 \frac{k_y}{PGA} + a_2 \left(\frac{k_y}{PGA}\right)^2 + a_3 \left(\frac{k_y}{PGA}\right)^3 + a_4 \left(\frac{k_y}{PGA}\right)^4 + a_5 \ln(PGA) + a_6 \ln(PGV) \quad (3)$$

However, the 4th order polynomial forms of Eq. (3) do not respect the conditions $d \rightarrow \infty$ for k_y/PGA = 0 and d = 0 for k_y/PGA = 1 expected for the case of rigid block. This is why the expressions that satisfy the above conditions, proposed by Ambraseys & Menu (1988) and adopted by Rollo & Rampello (2021), are also reported:

$$\ln(d) = a_0 + a_1 \ln\left(1 - \frac{k_y}{PGA}\right) + a_2 \ln\left(\frac{k_y}{PGA}\right)$$
$$\ln(d) = a_0 + a_1 \ln\left(1 - \frac{k_y}{PGA}\right) + a_2 \ln\left(\frac{k_y}{PGA}\right) + a_3 \ln(PGV) \quad (4)$$

In this study, to improve the predictive capability of Eq. (4) while respecting the conditions at the extrema, a new semi-empirical relationship is proposed:

$$\ln(d) = a_0 + a_1 \ln\left(1 - \frac{k_y}{PGA}\right) + a_2 \ln\left(\frac{k_y}{PGA}\right) + a_3 \left[\ln\left(\frac{k_y}{PGA}\right)\right]^2 + a_4 \ln(PGA)$$
$$\ln(d) = a_0 + a_1 \ln\left(1 - \frac{k_y}{PGA}\right) + a_2 \ln\left(\frac{k_y}{PGA}\right) + a_3 \left[\ln\left(\frac{k_y}{PGA}\right)\right]^2 + a_4 \ln(PGA) + a_5 \ln(PGV) \quad (5)$$

These new relationships are simpler than those of Eq. (3) as characterised by one less term (i.e. one coefficient less to be calibrated) and still allows to predict the permanent displacements for any value of yield seismic coefficient with a unique set of coefficients.

3 Comparison of the displacement relationships for the Italian seismicity

In this section the predictive capability of the relationships described above is critically analysed with reference to the Italian seismicity. A brief description of the seismic database is reported here, and the readers are referred to Gaudio *et al*. (2020) and Rollo & Rampello (2021) for further details. The seismic database collects 954 records by 297 stations of the Italian territory and refers to 208 earthquakes occurred from 14/06/1972 to 24/04/2017 and characterised by moment magnitude $M_w \geq 4$, peak ground accelerations $PGA \geq 0.05$ g and epicentral distance $R_{ep} < 100$ km. Most of the records have peak ground acceleration ranging between 0.05 and 0.2 g while the peak ground velocity from 1 and 10 cm/s and the values of the mean period T_m between 0.1 and 0.8 s. Concerning the tectonic aspects, the normal fault with 581 events, equal to 61.3% of the total, is the most common mechanism, followed by the reverse faulting with 170 (18%), the oblique reverse with 126 (13.3%) and strike-slip with 65 (6.9%). According to the Eurocode 8, Part I (CEN 2003), the database is organised in five groups based on the subsoil class of the recording station. In detail, 123 records (13% of the total) refer to rock-like subsoil (class A), 469 (49.5%) to dense and stiff subsoils (class B), 294 (31%) to medium stiff soil (class C), 14 (1.5%) to loose and soft subsoil (class D) and 47 (5%) to weaker materials (class E). Figure 1 shows the distribution of the relative frequency of the quantities M_w, R_{ep}, PGA, PGV, T_m and $D_{5\text{-}95}$ for the subsoil classes A, B and C, while the data from the classes D and E were disregarded as the number of records is only equal to 1.5% and 5% of the total, respectively.

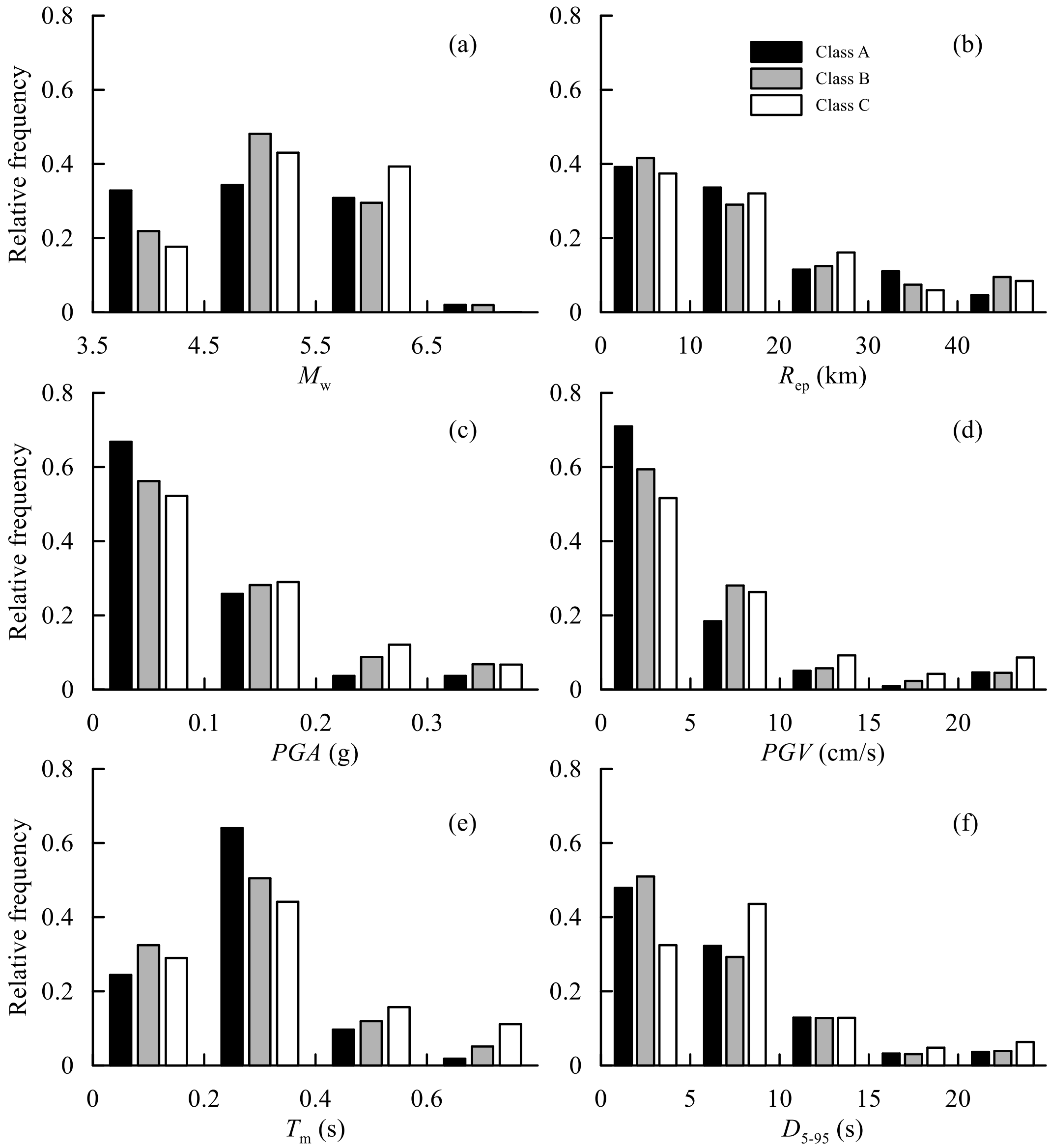

Figure 1. Frequency distribution of (a) moment magnitude, (b) epicentral distance, (c) peak ground acceleration, (d) peak ground velocity, (e) mean period and (f) significant duration for different subsoil classes (after Rollo & Rampello, 2021)

Figure 1 shows that the distributions of the ground motion parameters *PGA* and *PGV* are similar, ranging between 0.05 and 0.1 g and 1 and 5 cm/s, respectively, and, as discusses in the following, are highly correlated.

According to Gaudio *et al*. (2020) and Rollo & Rampello (2021), the permanent displacements are computed with the rigid sliding-block model (Newmark, 1965) for the simple scheme of an infinite slope for different values of the yield seismic coefficient, using the updated version of the Italian strong motion database. Additional values of the seismic coefficient have been considered here with respect to those investigated by Rollo & Rampello (2021) to increase the representativeness of the study ($k_y = 0.04, 0.06, 0.08, 0.1, 0.12, 0.15$).

The results of the predictive relationships of Eq. (1) proposed by Fotopoulou & Pitilakis (2015) (F&P15) and Eq. (2) by Saygili & Rathje (2008) (S&R08 2nd order) are first compared for $k_y = 0.04$ considering permanent displacements greater than 0.1 cm as lower values are not relevant from an engineering perspective. The regression coefficients are $a_0 = 4.761$, $a_1 = 2.456$ for the linear case and $a_0 = 5.277$, $a_1 = 3.093$, $a_2 = 0.179$ for the quadratic law, with the same $\sigma_{\ln} = 0.958$. Figure 2 shows the prediction of the relationships for the single ground motion parameter *PGA* and the dots are the permanent displacements computed using the Newmark's method.

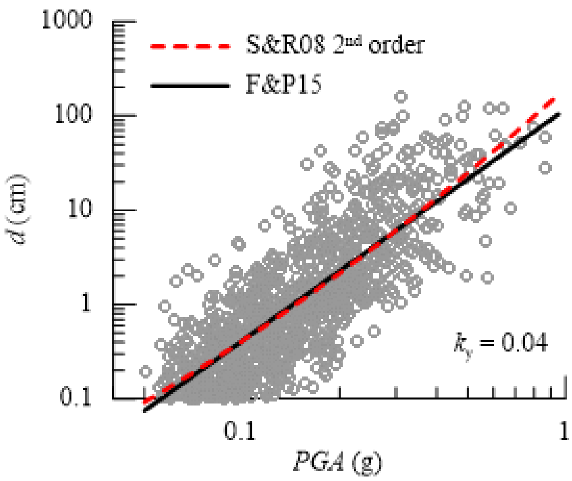

Figure 2. Comparison between the single ground motion parameter (*PGA*) semi-empirical relationships of Eqs. (1) and (2)

At a glance, the simplest semi-empirical relationships seem to reproduce satisfactorily the computed displacements when values greater than 0.1 cm are considered for earthquake-induced displacements. However, when smaller values of slope displacements are taken into account, the predictive relationships of Eqs. (1) and (2) fail at reproducing the trend of the computed permanent displacements. Figure 3 illustrates the results of the scalar relationships for different values of k_y considering displacements greater than 0.0001 cm. The linear and the quadratic relationships are too simplistic to capture with sufficient accuracy the variation of d with *PGA*, especially as the yield seismic coefficient increases. By contrast, the new expression proposed in Eq. (5), as well as the predictive relationships of Eqs. (3) and (4) proposed by Saygili & Rathje (2008) (S&R08 4th order) and Ambraseys & Menu (1988) (A&M88), respectively, can nicely reproduce the non-linear variation of the permanent displacements with *PGA* for any value of k_y, with Eqs. (4) and (5) also predicting correctly the conditions at the extrema.

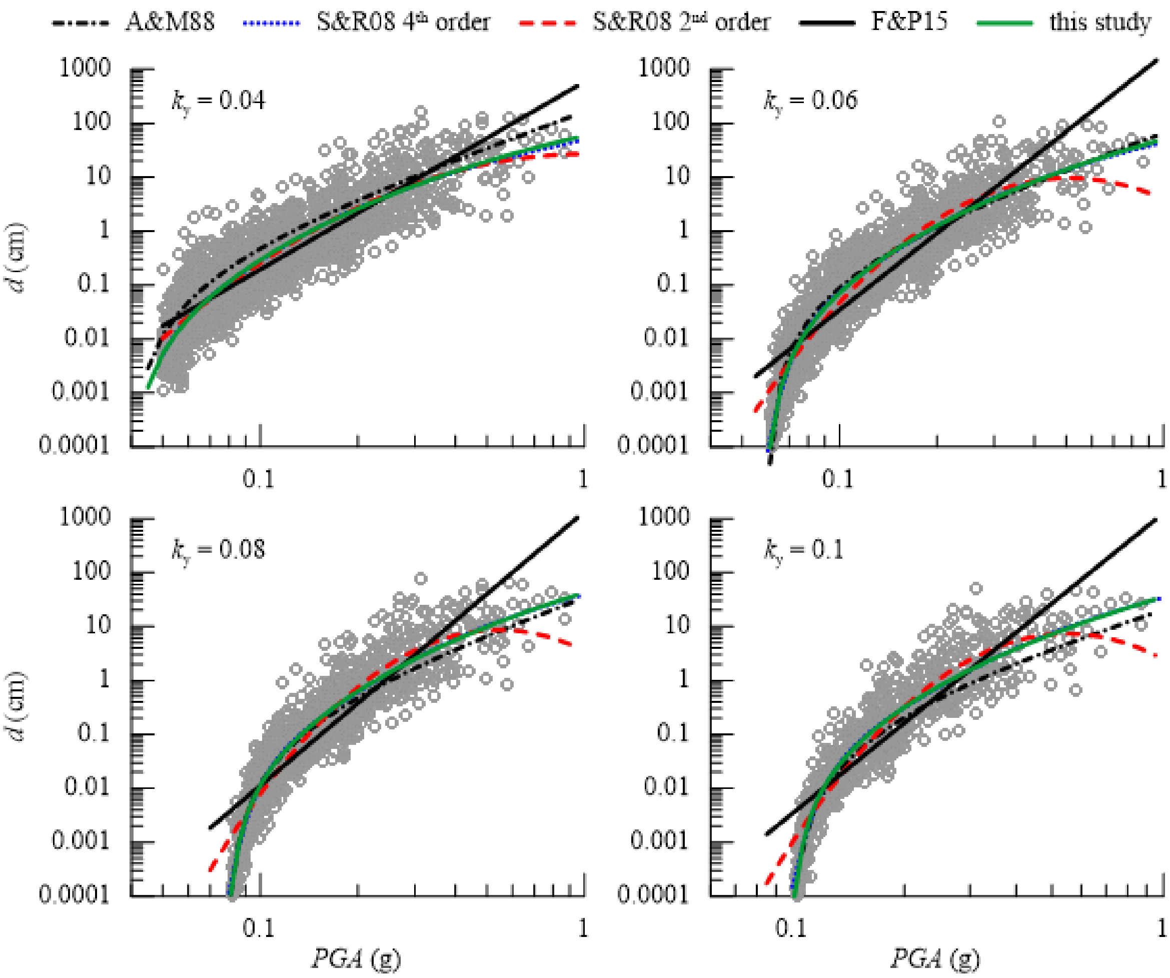

Figure 3. Comparison of the scalar semi-empirical relationships for different values of k_y

Tables 1-3 report the regression coefficients of the semi-empirical relationships evaluated for computed displacements greater than 0.0001 cm. For the relationships of Eqs. (1) and (2) different sets of coefficients must be employed for different values of k_y while Eqs. (3) - (5) provide a single set of coefficients valid for any yield seismic coefficient in the range 0.04 to 0.15.

Tables 1-3 also collect the standard deviations of the natural log of displacement $\sigma_{\ln}$, proving that for all the adopted expressions, the use of two parameters (*PGA*, *PGV*) semi-empirical relationships reduces substantially the error associated to the computed displacements as compared to the scalar approach. This result is expected as the couple of ground motion parameters *PGA*, *PGV* is more representative of the Italian seismicity than the *PGA* alone. Furthermore, the standard deviations associated to the linear and the quadratic relationships are greater than those computed for the other relationships, confirming that these latter are more reliable to predict the permanent displacements for different values of *PGA* and k_y.

Table 1. Regression parameters for Eq. (1) for different k_y

F&P15 relationship	GM parameter	a_0	a_1	a_2	σ_{ln}
k_y = 0.04	*PGA* (g)	6.378	3.48	-	1.094
	PGA (g), *PGV* (cm/s)	0.054	1.731	1.596	0.667
k_y = 0.06	*PGA* (g)	7.531	4.731	-	1.288
	PGA (g), *PGV* (cm/s)	2.163	3.25	1.355	1.059
k_y = 0.08	*PGA* (g)	7.203	5.076	-	1.267
	PGA (g), *PGV* (cm/s)	1.644	3.501	1.373	1.023
k_y = 0.10	*PGA* (g)	7.143	5.562	-	1.287
	PGA (g), *PGV* (cm/s)	1.443	3.909	1.386	1.042
k_y = 0.12	*PGA* (g)	6.967	5.938	-	1.333
	PGA (g), *PGV* (cm/s)	0.697	4.058	1.494	1.047
k_y = 0.15	*PGA* (g)	6.484	6.281	-	1.341
	PGA (g), *PGV* (cm/s)	0.279	4.453	1.491	1.026

Table 2. Regression parameters for Eq. (2) for different k_y

S&R08 2nd order relationship	GM parameter	a_0	a_1	a_2	a_3	a_4	σ_{ln}
k_y = 0.04	*PGA* (g)	3.289	0.013	-0.871	-	-	1.038
	PGA (g), *PGV* (cm/s)	-3.772	-2.505	-1.049	1.476	0.048	0.539
k_y = 0.06	*PGA* (g)	1.371	-2.67	-1.994	-	-	1.083
	PGA (g), *PGV* (cm/s)	-5.137	-5.385	-2.284	1.097	0.101	0.737
k_y = 0.08	*PGA* (g)	1.262	-2.942	-2.428	-	-	1.063
	PGA (g), *PGV* (cm/s)	-4.793	-5.362	-2.654	1.073	0.097	0.722
k_y = 0.10	*PGA* (g)	0.893	-675	-3.063	-	-	1.054
	PGA (g), *PGV* (cm/s)	-4.69	-5.762	-3.194	0.914	0.108	0.725
k_y = 0.12	*PGA* (g)	0.433	-4.631	-3.832	-	-	1.076
	PGA (g), *PGV* (cm/s)	-4.792	-6.04	-3.693	0.959	0.094	0.740
k_y = 0.15	*PGA* (g)	0.159	-5.273	-4.709	-	-	1.094
	PGA (g), *PGV* (cm/s)	-4.593	-6.369	-4.449	0.763	0.124	0.737

Table 3. Regression parameters for Eqs. (3), (4) and (5)

Displacement relationship	GM parameter	a_0	a_1	a_2	a_3	a_4	a_5	a_6	σ_{ln}
Ambraseys & Menu (1988)	*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
Saygili & Rathje (2008) 4th order	*PGA* (g)	4.104	-4.211	-19.1	41.54	-28.56	1.113	-	1.002
	PGA (g), *PGV* (cm/s)	-2.241	-1.669	-27.1	52.66	-34.04	-0.556	1.526	0.553
This study	*PGA* (g)	0.698	1.899	-1.987	-0.285	1.101	-	-	1.001
	PGA (g), *PGV* (cm/s)	-5.124	1.992	-1.736	-0.234	-0.573	1.531	-	0.547

In addition, the relationships of Eqs. (3) - (5) are more useful as they provide the permanent displacements for any value of k_y stemming from a single set of regression coefficients.

The results of the vector approach are illustrated in Figure 4 as a function of the ratio k_y/PGA (Eqs. (3) - (5)). The curves plotted in the figure refer to a value of PGV = 8 cm/s, representing the average value for the seismic database, and demonstrate that the vector approaches provide curves that plot very close each other.

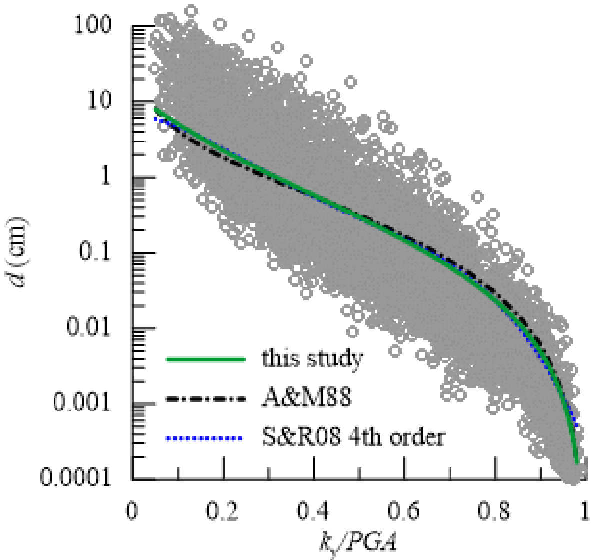

Figure 4. Displacements versus k_y /*PGA* for vector semi-empirical relationships (*PGV* = 8 cm/s)

Moreover, for both scalar and vector models, it is worth calculating the residuals of the displacements $\ln d_{\text{observed}} - \ln d_{\text{predicted}}$, with $\ln d_{\text{observe}}$ the displacement evaluated through the Newmark's method and $\ln d_{\text{predicted}}$ that predicted through the semi-empirical relationships. For the new semi-empirical relationship, Figures 5 (a, c) show the residuals over the range of k_y/*PGA* while Figures 5 (b, d) show the mean of residuals for different k_y/*PGA* bins, where the vertical bars denote the standard deviation above and below the mean values. The values of the residuals obtained through the vector approach are half of those calculated with the scalar one, with irrelevant biases and almost constant standard deviations over the whole range of k_y/*PGA*. Again, the vector approach should be preferred as it predicts lower values of the residuals with respect to the scalar one, with similar trends observed with increasing k_y/*PGA*.

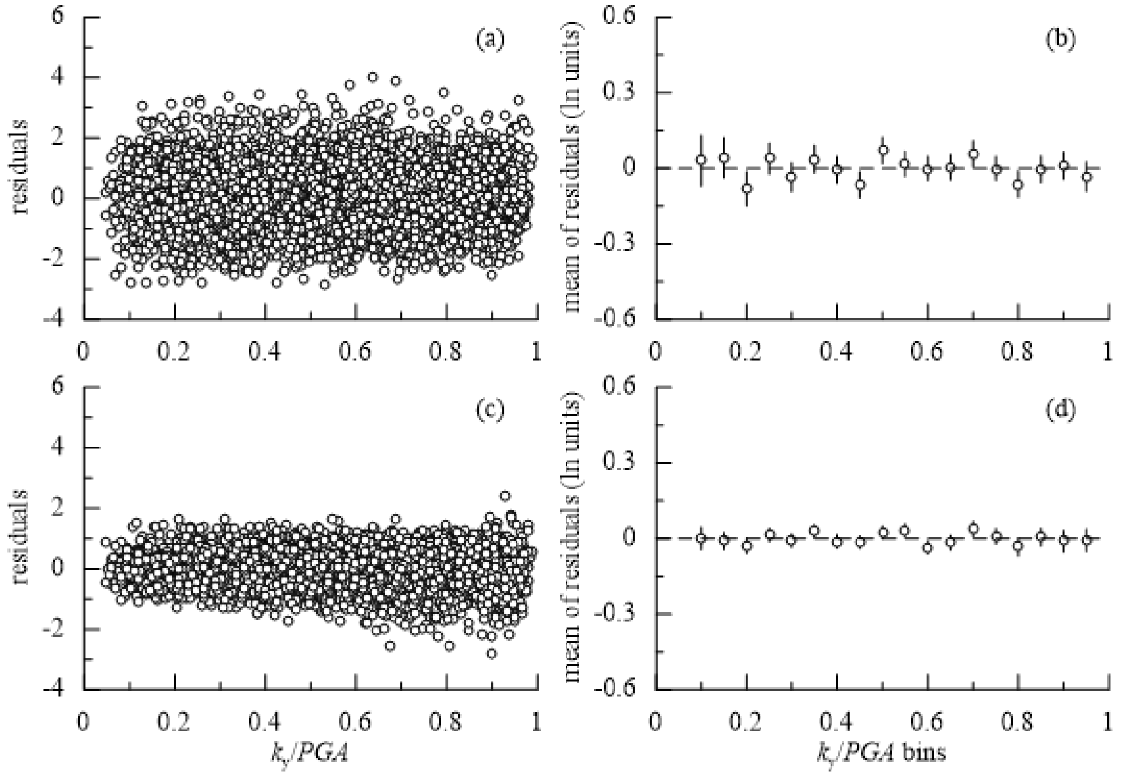

Figure 5. Mean residuals versus k_y /*PGA* for scalar approach (a, b) and vector approach (c, d) for the new relationship

For comparison, Figure 6 depicts the mean of residuals and their standard deviations obtained through the expressions of Saygili & Rathje (2008) and Ambraseys & Menu (1988), while the results of the Eq. (1) are not illustrated as it predicts much greater values of the mean of residuals than the other equations.

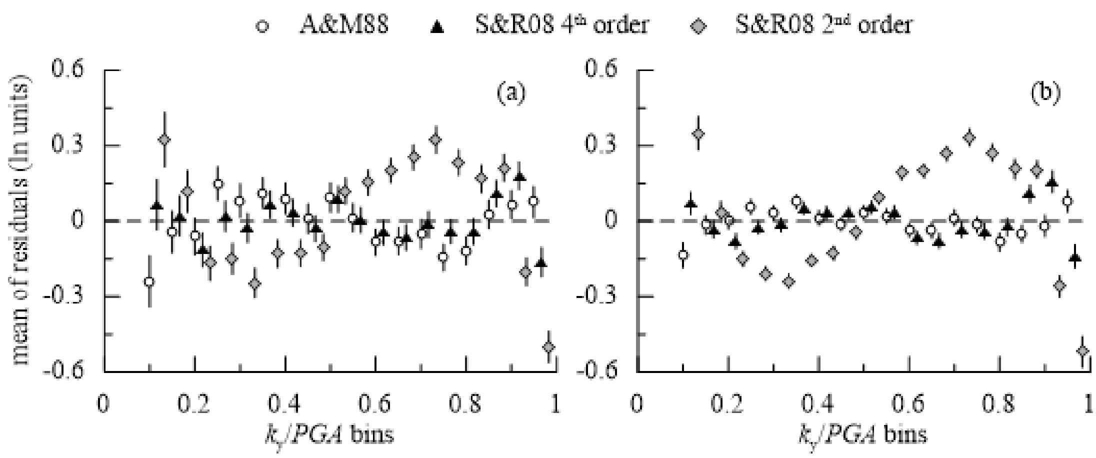

Figure 6. Mean residuals versus k_y /*PGA* for scalar approach (a) and vector approach (b) for different predictive relationships

As expected, Eqs. (3) and (4) provide comparable values of residuals that are significantly lower than those evaluated using the 2nd order polynomial of Saygili & Rathje (2008) of Eq. (2). The trends of Eqs. (3) and (4) are also characterised by negligible biases for increasing values of k_y/PGA, but similarly to what found by Saygili & Rathje (2008), bias appears for Eq. (3) when $k_y/PGA > 0.8$, though this result is not of engineering significance due to the small displacements predicted for that level of k_y/PGA. Therefore, Figure 6 shows that the use of Eqs. (3) and (4) reduces significantly the residuals as compared with the 2nd order polynomial of Eq. (2). However, the lowest values of the mean of residuals are obtained through the new relationship proposed in this work, as shown in Figures 5 (b-d), for which no bias appear for increasing values of k_y/PGA. This is also consistent with the fact that the values of $\sigma_{\ln}$ reported in Table 3 obtained through Eq. (5) are lower than those computed with Eqs. (3) and (4). This is why the new proposed relationships improve the predictive capability of the permanent slope displacements as compared to the existing ones, thus being more appropriate to describe the characteristics of the Italian strong motion database. Furthermore, Figure 7 and 8 show the variation of the residuals obtained from the one-parameter (*PGA*) and the two-parameters (*PGA, PGV*) models with M_w, *PGV*, S_a ($1.5T_s$) and R_{ep} employing the new relationships of Eq. (5), with the greyscale lines representing the mean of residuals. As expected, the vector approach provides much lower residuals for all the considered ground motion parameters, with almost constant mean values, demonstrating that the new semi-empirical relationship proposed in this work is reasonable for the study of the Italian seismicity when using *PGA* and *PGV* as the seismic loading parameters, as it is not biased when compared to the other seismic parameters.

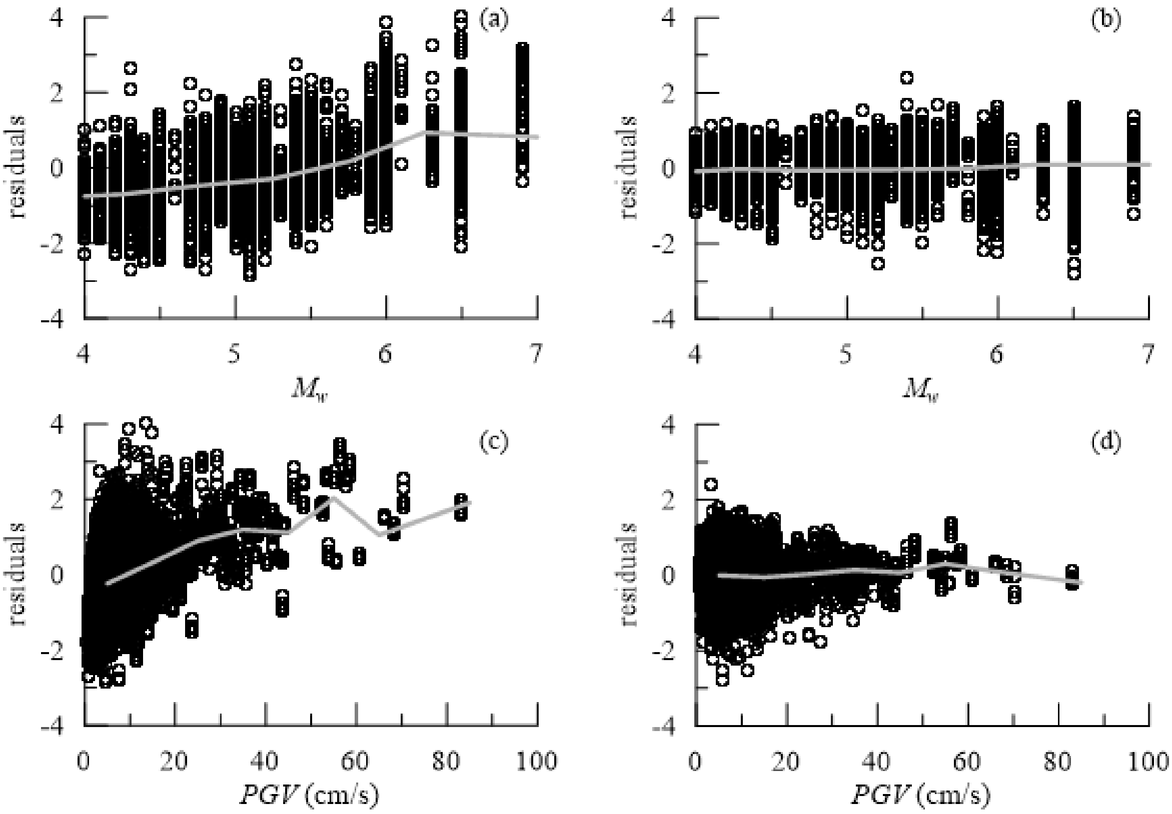

Figure 7. Residuals for scalar (a, c) and vector (b, d) semi-empirical relationships of Eq. (5) vs M_w and *PGV*

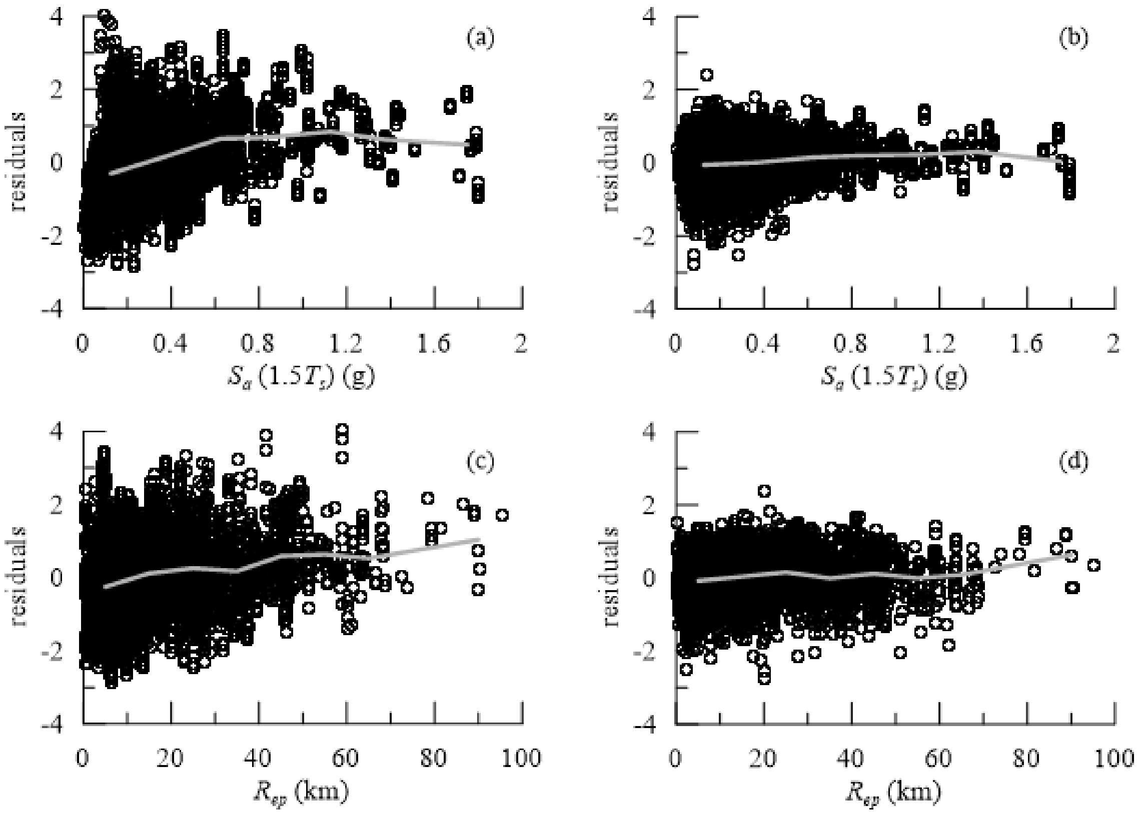

Figure 8. Residuals for scalar (a, c) and vector (b, d) semi-empirical relationships of Eq. (5) vs S_a and R_{ep}

Finally, Figure 9 gives an insight into the variation of the standard deviation with k_y/PGA for the different semi-empirical relationships: once again, $\sigma_{\ln}$ is significantly reduced when the *PGA, PGV* models are used, with the 4th order polynomial of Saygili & Rathje (2008) and the new proposal providing very similar trends and the lowest values.

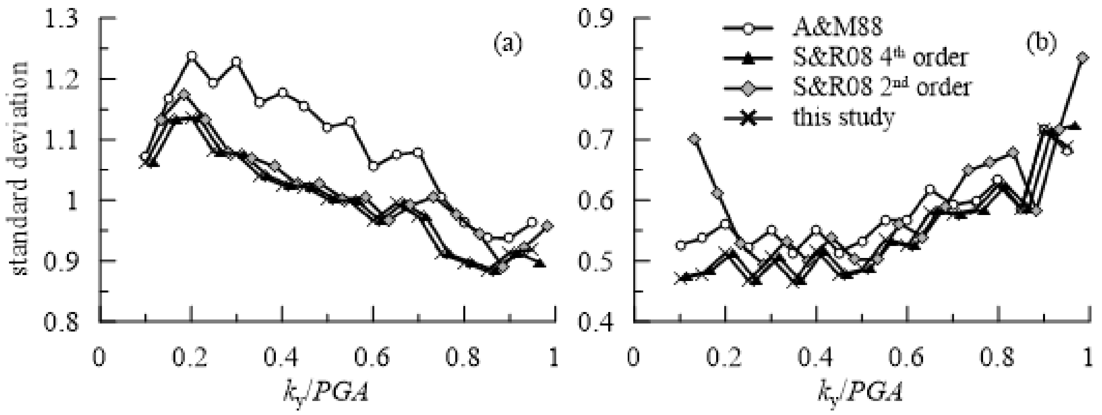

Figure 9. Variation of standard deviation ($\sigma_{\ln}$) of displacements with k_y /*PGA* for (a) scalar and (b) vector relationships

The results presented in this section are summarised as follows. The semi-empirical relationships of Eqs. (1) and (2) are too simplistic to reproduce satisfactorily the results of the Newmark's integration over a wide range of displacements and their coefficients depend on the specific values of the yield seismic coefficient. Conversely, Eqs. (3) - (5) reproduce well the calculated displacements for different values of k_y. The vector relationships provide a better description of the seismicity of the site than the scalar ones as characterised by lower values of the standard deviation. Among the presented semi-empirical relationships, the new formulation proposed in this paper should be preferred as characterised by the lowest standard deviations, by no bias in terms of residuals, while reproducing correctly the permanent displacements for k_y/PGA equal to 0 and 1.

4 Probabilistic approach: effect of the predictive displacement relationships

The displacement predictive equations are a key ingredient to develop the probabilistic approach, whose results are synthesised in terms of displacements hazard curves and maps, providing the annual rate of exceedance λ_d for a given level of displacement *d*. Here, a brief description of the probabilistic approach is presented and the reader is referred to the Appendix for further details. For the scalar approach, λ_d is calculated as:

$$\lambda_d(x) = \sum_i P\left[d > x \mid PGA_i\right] \times P\left[PGA_i\right] \tag{6}$$

with the probability of a certain displacement x $P\left[d > x | PGA_i\right]$ for a specific peak ground acceleration PGA_i, and $P\left[PGA_i\right]$ the annual probability of PGA_i provided by a probabilistic seismic hazard analysis (PSHA). In this study, the conventional scheme of PSHA proposed by Stucchi *et al*. (2011) for Italy is followed, in which the seismicity is uniformly distributed in each seismic source zone and the earthquake recurrence model follows the Poisson's distribution. A logic tree scheme is adopted in this scheme for the ground motion prediction equations (GMPE) and magnitude distribution. The readers are referred to the original work for further detail. Specifically, Stucchi *et al*. (2011) determined the values of *PGA* for more than 16000 points of a regular grid of 5 km throughout the Italian territory for nine probabilities of exceedance in 50 years (2%, 5%, 10%, 22%, 30%, 39%, 50%, 63%, and 81%) for the 16th, 50th and 84th percentiles. The results are presented in terms of *PGA* hazard curves, plotting the annual rate of exceedance of this parameter against *PGA*, as well as in terms of disaggregation of the *PGA* values for all the nine probabilities of exceedance in terms of magnitude and epicentral distance. The results are available through the webGIS interactive seismic hazard maps provided by the Italian Institute of Geophysics and Volcanology (INGV) (http://esse1.mi.ingv.it/d2.html) that allow to extract information on the Italian territory on a regular grid spaced by 0.05°.

For the vector approach one has:

$$\lambda_{\mathrm{d}}(x) = \sum_i \sum_j P\left[d > x \mid PGA_i, PGV_j\right] \times P\left[PGA_i, PGV_j\right] \tag{7}$$

where $P\left[d > x | PGA_i, PGV_j\right]$ is the probability displacements greater than *x*, given the peak ground acceleration PGA_i and the peak ground velocity PGV_j, while $P\left[PGA_i, PGV_j\right]$ is the joint annual probability of PGA_i and PGV_j. This latter term requires the disaggregation of the hazard of *PGA* and the correlation coefficient ρ between *PGA* and *PGV*. As discussed in detail in the Appendix and in Rollo & Rampello (2021), the correlation coefficient is evaluated through the ground motion prediction equation (GMPE) of Lanzano *et al.* (2019), specifically developed for the Italian seismicity, leading to $\rho = 0.843$. Further details for the computation of Eq. (7) are reported in the Appendix. The probabilistic approach has been implemented in the commercial numerical software package MATLAB.

The displacement hazard curves plot the annual rate of exceedance λ_{d} against the displacement and are presented first for the site of Amatrice (RI) in the central Italy using different yield seismic coefficients and different semi-empirical relationships: Fotopoulou & Pitilakis (2015) (F&P15), Saygili & Rathje (2008) (S&R08 2nd and 4th order), Ambraseys & Menu (1988) (A&M88) and the new expression proposed herein. This permits to investigate the role of the adopted semi-empirical relationships in the probabilistic framework. Figures 10, 11 and 12 show the hazard curves for the Italian site of Amatrice for values of $k_{\mathrm{y}} = 0.04, 0.08, 0.12$, respectively, for both the scalar (a) and vector (b) probabilistic models. For displacements smaller than 1 to 5 cm the hazard curves obtained with different predictive relationships are very similar, while for greater values some differences arise.

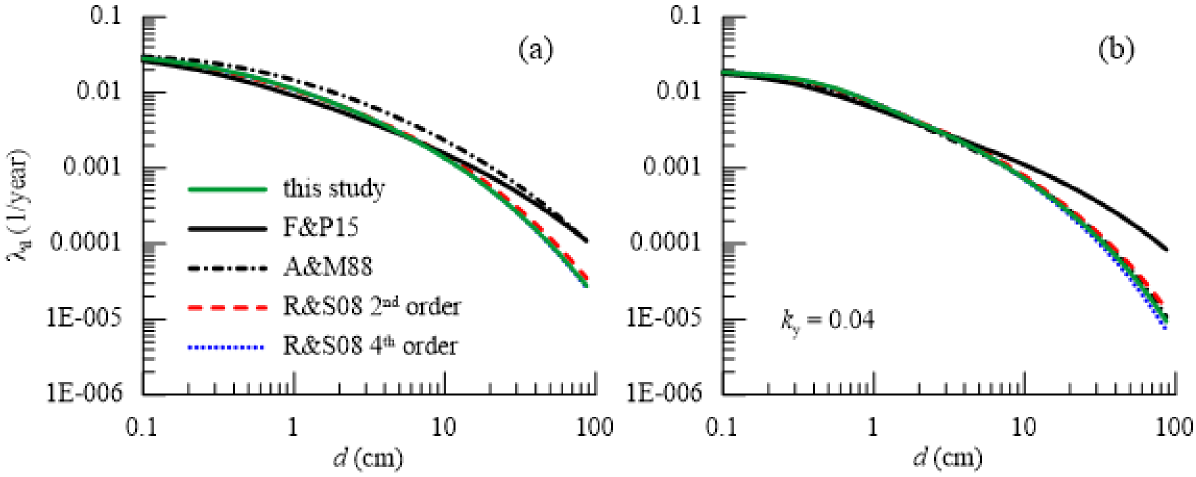

Figure 10. Displacement hazard curves for the site of Amatrice and k_y = 0.04 for (a) scalar and (b) vector models

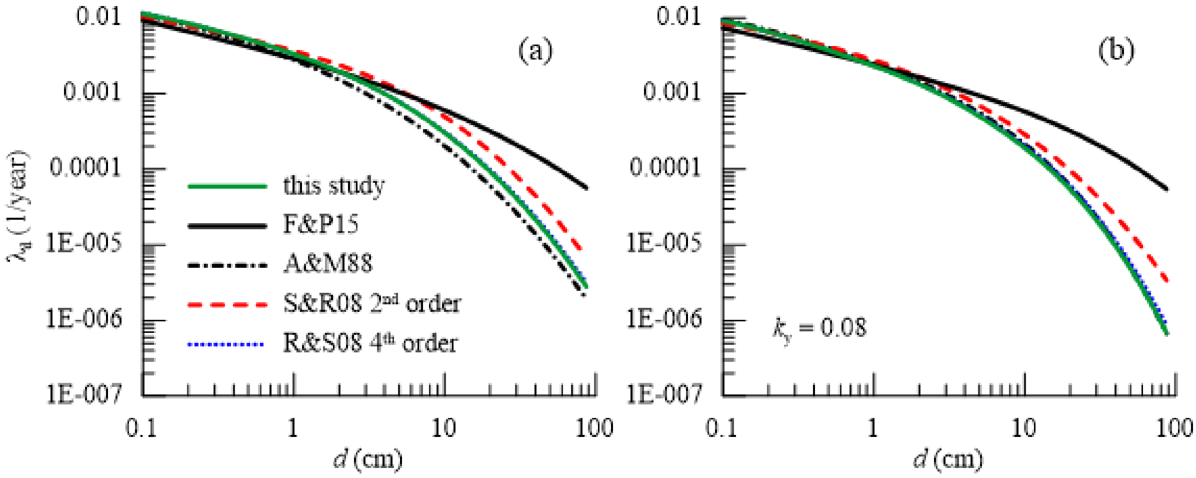

Figure 11. Displacement hazard curves for the site of Amatrice and k_y = 0.08 for (a) scalar and (b) vector models

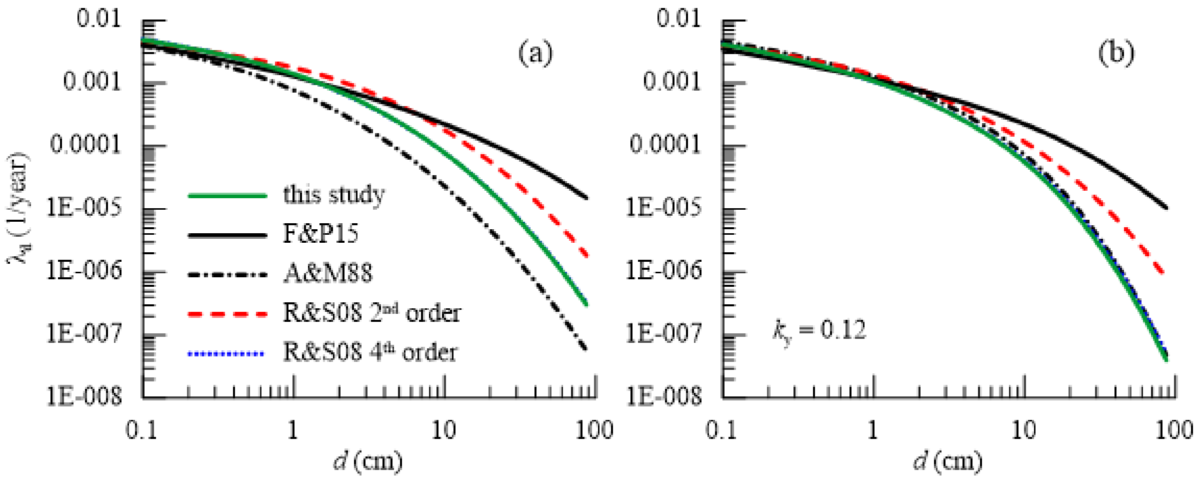

Figure 12. Displacement hazard curves for the site of Amatrice and k_y = 0.12 for (a) scalar and (b) vector models

For the Italian site considered here, the F&P15 and the R&S08 2nd order relationships lead to the largest differences in the hazard curves as compared to Eqs. (3) - (5). These results become more evident as the yield seismic coefficient increases. Among the vector models, those based on the linear and quadratic relationships overestimate the seismic hazard, in that lead to higher values of λ_d, and are substantially affected by k_y, if compared with the two-parameters models based on Eqs. (3) - (5).

Eqs. (1) - (2) are simpler and provide more conservative, though less reliable results in terms of hazard curves, as characterised by the highest standard deviations. On the contrary, the 4th order polynomial semi-empirical relationships proposed by Saygili & Rathje (2008), that by Ambraseys & Menu (1988) and the new proposed expression provide a more satisfactory estimate of the slope displacements computed through the Newmark's approach, being characterised by the lowest residuals. Moreover, it is seen that the displacement hazard curves obtained using the two-parameters relationships of Eqs. (3) - (5) are nearly coincident, demonstrating that they predict similar results when embodied in the vector probabilistic approach. By contrast, even for the two-parameters (*PGA*, *PGV*) probabilistic models, the F&P15 and the R&S08 2nd order relationships are too simplistic and are characterised by higher residuals. Furthermore, for the site of Amatrice Figures 10, 11 and 12 show that the vector approach is less sensitive to the adopted semi-empirical relationship (with the exception of Eq. (1)) and hence its adoption should be preferred when developing hazard curves and maps. To support and generalise the results presented till now, the analyses have been extended to two other sites in Italy characterised by different seismic hazard: the site of Lioni (AV) in the southern Italy and the one of Modena in the northern Italy. The displacement hazard curves obtained for k_y = 0.12 using all the semi-empirical relationships are plotted in Figures 13 and 14 for these sites, permitting to draw similar conclusions to those highlighted for the site of Amatrice. The only difference lies in the values of λ_d computed for a given displacement: in Figure 13 they are greater than those reported in Figure 12, while those in Figure 14 are lower. This is consistent with the fact that the sites of Lioni and Modena are characterised by a more and a less severe seismic hazard than the site of Amatrice, respectively.

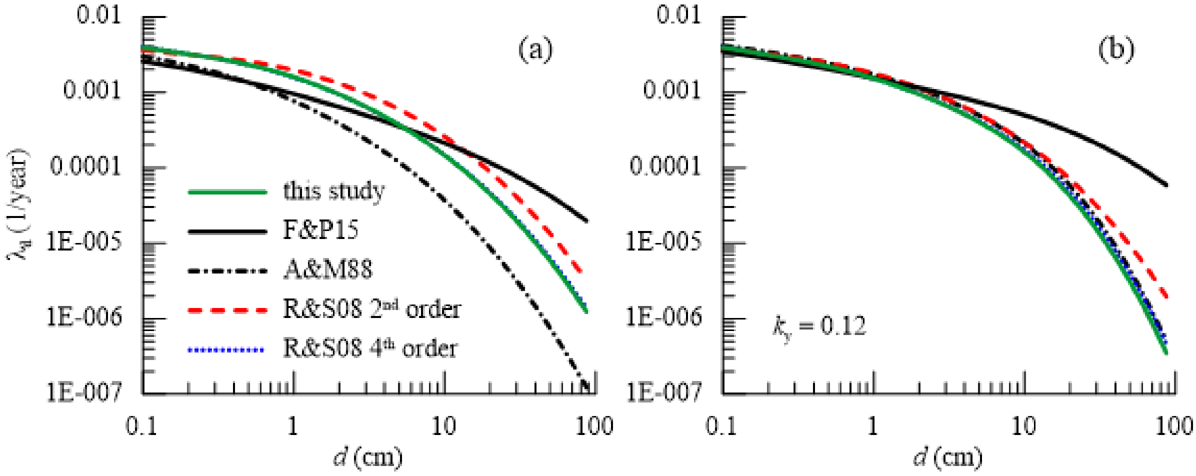

Figure 13. Displacement hazard curves for the site of Lioni and k_y = 0.12 for (a) scalar and (b) vector models

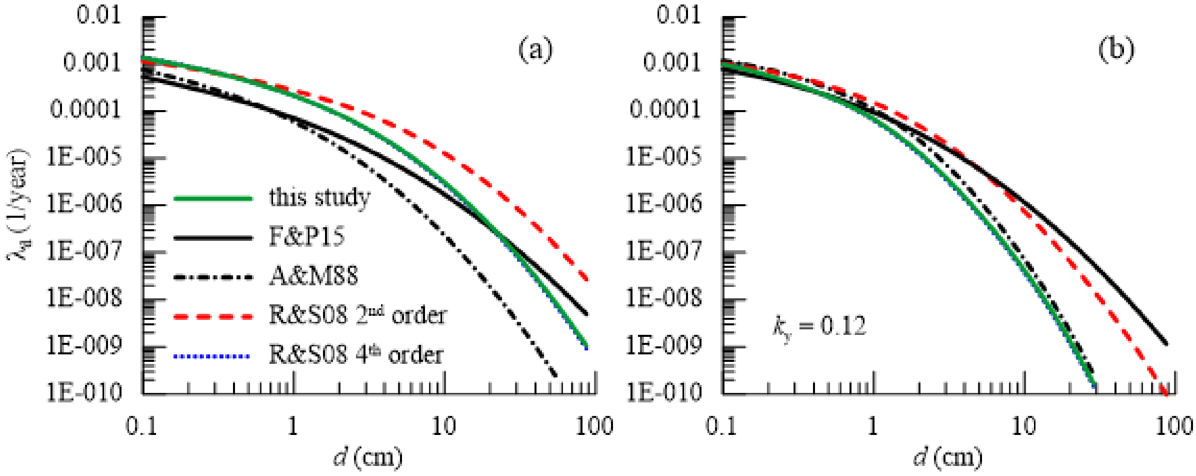

Figure 14. Displacement hazard curves for the site of Modena and k_y = 0.12 for (a) scalar and (b) vector models

The effect of the adopted semi-empirical relationships in the probabilistic approach is also investigated in terms of hazard maps showing the contours of the return periods T_r associated to different levels of seismic-induced displacement and yield seismic coefficients. The maps are obtained considering a grid of points equally spaced of 5 km. These points correspond to the sites on the national territory for which information pertaining to the seismic hazard in terms of *PGA* hazard curves and disaggregation are available. For any points of the map, the probabilistic analysis provides the displacement hazard curves for different values of k_y. Therefore, for a given value of k_y and a prescribed displacement, one get the corresponding value of λ_d (or $T_r = 1/\lambda_d$). The T_r values of the nearby grid points are linearly interpolated to obtain a representation in terms of return period isolines. Finally, to make the representation of results clearer, a logarithmic scale is adopted for T_r. It is worth mentioning that the maps do not account for the real distribution of the slope parameters and soils properties. However, if obtained for several values of the seismic coefficient k_y, they still represent a useful tool for a preliminary assessment of the slope seismic hazard. The hazard maps presented here are developed from the vector probabilistic approach for the district of Irpinia (Campania), an area of about 40x40 km^2 located in the South Italy, at 50 km from the city of Naples. It is crossed by the mountain range of Apennines and is characterised by a severe seismic hazard (Porfido *et al.*, 2002; Del Gaudio & Wasowski, 2004). The x and y axes of the map are East and North according to the reference coordinate system WGS84 and the INGV interactive seismic hazard maps (http://esse1.mi.ingv.it/d2.html) have been used to query seismic hazard information for the points of the area of interest in terms of *PGA* hazard maps and seismic disaggregation necessary for the evaluation of Eq. (7).

Figures 15 and 16 refer to $k_y = 0.08$ and to threshold displacements $d_y = 2\,\text{cm}$ (rock-like subsoil) and $d_y = 15\,\text{cm}$ (free-field ductile soil behaviour) (Idriss, 1985; Wilson & Keefer, 1985), respectively. Figure 15(a) shows the results obtained through the linear relationship of Eq. (1), while Figure 15(b) shows the results computed using the new proposed relationship. The distribution of T_r is directly related to the probabilistic seismic hazard and disaggregation information of the Irpinia district, that is more severe in correspondence of the mountainous zone of the Apennines extended from North-Western to South-Eastern corners of the map.

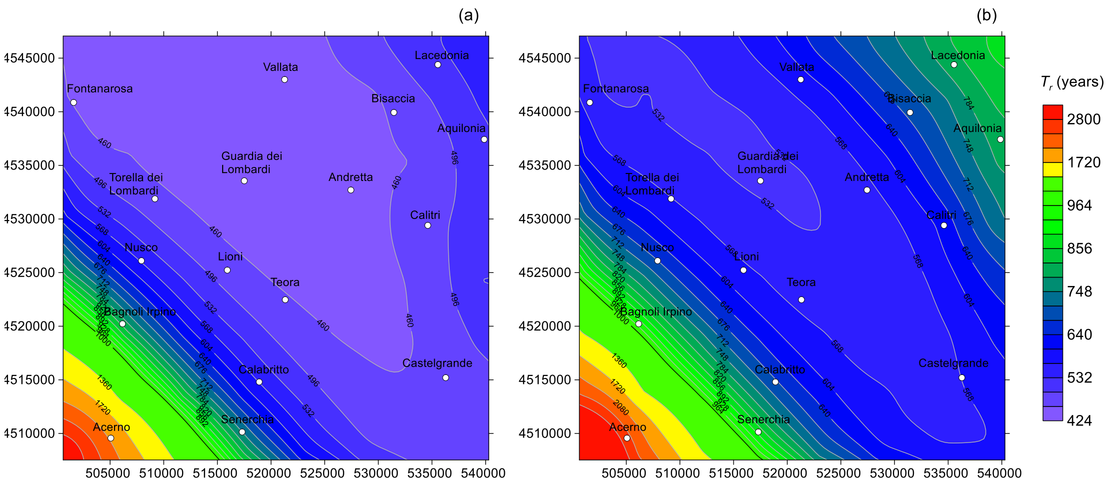

Figure 15. Displacement hazard maps for the Irpinia district for $d_y = 2\text{cm}$ and $k_y = 0.08$ for the (a) F&P15 and (b) the new proposed relationships

The new proposed relationship improves the prediction of the earthquake-induced displacements and, consistently with what observed in terms of hazard curves, leads to a lower hazard, that corresponds to higher values of the return period, as compared to the linear relationship. Specifically, Figure 15 shows that for roughly 40% of the map the return period increases from 430 years to 620 years when the new expression is included within the probabilistic framework. Moreover, the differences obtained using the two relationships become even more relevant when considering a higher threshold slope displacement d_y = 15 cm, as shown in Figure 16(a)-(b). Therefore, the linear relationships providing much lower return periods T_r may result in an excessively conservative estimate of the seismic hazard.

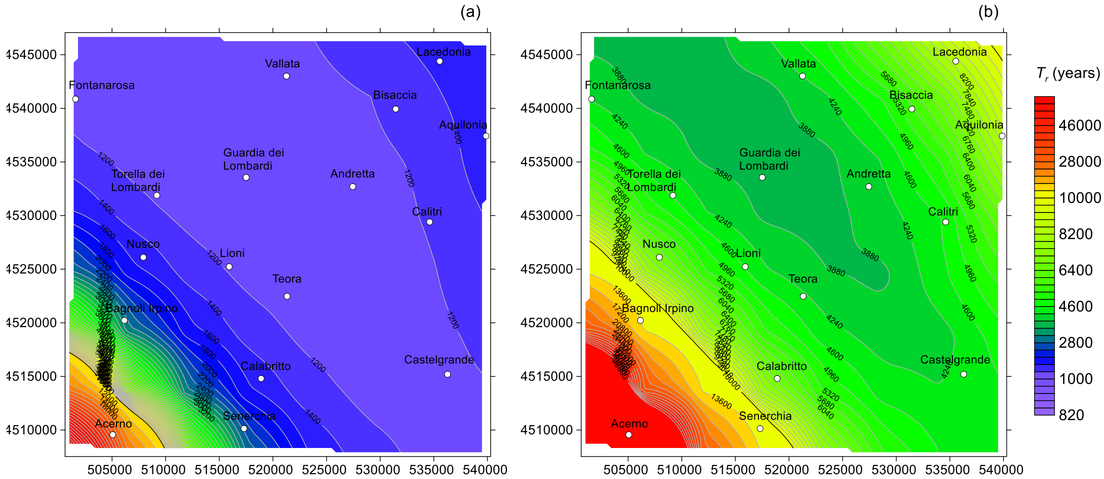

Figure 16. Displacement hazard maps for the Irpinia district for d_y = 15cm and k_y = 0.08 for the (a) F&P15 and (b) the new proposed relationships

5 Summary and conclusions

This paper presents a new semi-empirical relationship that may be used to evaluate the earthquake-induced slope displacements as a function of one or two ground motion parameters and was formulated with reference to the Italian seismicity assimilating the slope to a rigid block. Five semi-empirical relationships have been compared, linking the log of displacement d and the log of the ground motion parameters PGA and PGV: (i) the linear expression by Fotopoulou & Pitilakis (2015), (ii) the second order and (iii) fourth order polynomial by Saygili & Rathje (2008), (iv) that proposed by Ambraseys & Menu (1988) and (v) the new one. The latter not only satisfies the conditions for the permanent displacements at the extrema k_y/PGA = 0 and k_y/PGA = 1 but also proves to be more efficient than other existing formulations to predict the permanent displacements as characterised by lower residuals and standard deviations when comparing the displacements calculated through the Newmark's method and the values predicted by different semi-empirical relationships. The analysis of the mean of residuals also demonstrates that differently from the existing ones, for the new relationship no bias appear for increasing values of k_y/PGA and that the residuals are almost constant within the range of values of ground motion parameters of the Italian seismic database. Moreover, the relationships analysed in this work permit to develop a scalar probabilistic approach, characterised by the single ground motion parameter PGA, or a vector approach, using the couple of parameters

PGA, *PGV*. The result of the analysis consists in a series of hazard curves and maps providing the annual rate of exceedance associated to given values of threshold, or limit, slope displacements and given values of the yield seismic coefficient k_y. The results presented in this work show that, for both scalar and vector approaches, the hazard curves obtained using Eqs. (3) and (5) are similar but they suggest the adoption of Eq. (5) in light of the more accurate description of the permanent displacements over all the range of k_y/PGA. Moreover, the vector probabilistic approach is less sensitive to the adopted displacement semi-empirical relationship and thus, in combination with Eq. (5) provides a reliable assessment of the seismic hazard associated to a slope on the Italian territory. It is worth recalling that the results presented in section 4 refer to specific sites and areas of Italy. However, the probabilistic framework is general enough to be straightforwardly employed for any other locations in Italy once information on the seismic hazard of the site are given. In principle, this approach can be also extended to any geographical locations once the coefficients of the semi-empirical relationships are determined based on the seismicity of the country and a proper GMPE is selected. For future developments, a logic tree scheme should be introduced within the probabilistic approach to account for the epistemic uncertainty coming from the slope conditions. Moreover, the hazard maps could be integrated with GIS techniques to account for the spatial variability of regional landslide properties. However, the results presented this study in terms of displacements hazard curves and maps provide practical engineers with a powerful tool for a more rational, though preliminary estimate of the seismic hazard associated to slopes.

Appendix

According to Rathje *et al*. (2014), for the single ground motion *PGA* displacement model the annual rate of exceedance λ_{d} can be computed as:

$$\lambda_{\mathrm{d}}(x) = \sum_i P\left[d > x \mid PGA_i\right] \times P\left[PGA_i\right] \tag{A1}$$

To evaluate the annual rate of exceedance, the product of the two terms of Eq. (A1) has to be integrated over all the levels of *PGA* depending on the specific site under study. The first term can be computed adopting a cumulative lognormal distribution function for the permanent displacements, where the mean value is evaluated for a given value of k_y and different PGA_i according to one of the semi-empirical relationships reported in Section 2 and $\sigma_{\ln}$ is the standard deviation associated to the adopted equation and collected in Tables 1-3. The term $P\left[PGA_i\right]$ is obtained by differentiation of the *PGA* hazard curve available as a result of a probabilistic seismic hazard analysis (PSHA). Specifically, according to Rathje *et al*. (2014) is:

$$P\left[PGA_i\right] = \frac{\lambda\left(PGA_{i-1}\right) - \lambda\left(PGA_{i+1}\right)}{2} \tag{A2}$$

with λ the mean rate of occurrence associated with adjacent (previous and subsequent) values of *PGA* in the *PGA* hazard curve. Therefore, there is an analogy between the probabilistic approach predicting the annual rate of exceedance λ_{d} of many levels of permanent displacements and a PSHA providing the annual rate of exceedance λ for different *PGA*. Given a value of displacement, the annual rate of exceedance is computed as a summation over the whole range of PGA_i that characterise the seismic hazard curve. All the values of λ_{d} associated to the permanent displacements *d* are finally plotted to obtain the displacement hazard curve.

For the double parameters (*PGA*, *PGV*), Rathje *et al*. (2014) suggested the following expression to determine λ_{d}:

$$\lambda_{\mathrm{d}}(x) = \sum_i \sum_j P\left[d > x \mid PGA_i, PGV_j\right] \times P\left[PGA_i, PGV_j\right] \tag{A3}$$

where, again, the first term is the probability that $d > x$ given ground motion levels PGA_i and PGV_j determined through a cumulative lognormal distribution function for the displacement x, with the mean value and the standard deviation $\sigma_{\ln}$ depending on the specific adopted displacement semi-empirical relationships and computed for the couple of parameters PGA_i and PGV_j, while the second one is the joint annual probability of occurrence of PGA_i and PGV_j. In principle, the latter should be calculated via a vector probabilistic seismic hazard analysis VPSHA (Bazzurro & Cornell, 2002), but here a simplified procedure is adopted taking advantage of the results of a standard PSHA. However, Rathje & Saygili (2009) demonstrated that the simplified approach to compute the joint probability leads to the same displacement hazard curves obtained adopting the VPSHA.

$$\begin{aligned} P\left[PGA_i, PGV_j\right] &= P\left[PGV_j \mid PGA_i\right] \times P\left[PGA_i\right] = \\ &= \sum_k \sum_l P\left[PGV_j \mid PGA_i, M_k, R_l\right] \times P\left[M_k, R_l \mid PGA_i\right] \times P\left[PGA_i\right] \end{aligned} \tag{A4}$$

The conditionate probability $P\left[M_k, R_l \mid PGA_i\right]$ is evaluated from the disaggregation of the hazard of the specific site: for each value of *PGA* associated to different probabilities of exceedance, the disaggregation provides the probability for any combinations of magnitude and epicentral distance (i.e. the input is a number of *i*-matrices with *k*-rows and *l*-columns) to account for multiple seismic sources. The calculation of the term $P\left[PGV_j \mid PGA_i, M_k, R_l\right]$ requires the ground motion prediction equations (GMPE) and the correlation coefficient of *PGA* and *PGV* and is computed assuming a lognormal distribution (Bazzurro & Cornell, 2002), with specifically the mean value $\mu_{\mathrm{ln\,PGV|PGA,M,R}}$ and the standard deviation $\sigma_{\mathrm{ln\,PGV|PGA,M,R}}$ evaluated as (Rathje & Saygili, 2008):

$$\begin{aligned} \mu_{\mathrm{ln\,PGV|PGA,M,R}} &= \mu_{\mathrm{ln\,PGV}} + \rho \frac{\sigma_{\mathrm{ln\,PGV}}}{\sigma_{\mathrm{ln\,PGA}}} \left(\ln PGA - \mu_{\mathrm{ln\,PGA}}\right) \\ \sigma_{\mathrm{ln\,PGV|PGA,M,R}} &= \sigma_{\mathrm{ln\,PGV}} \sqrt{1-\rho^2} \end{aligned} \tag{A5}$$

The terms μ_{lnPGV}, σ_{lnPGV}, μ_{lnPGA} and σ_{lnPGA} are the mean values and the standard deviations of the adopted quantities and ρ is the correlation coefficient between *PGA* and *PGV*. For the first quantities the ground motion prediction equation of Lanzano *et al*. (2019) is adopted in this paper: the mean values μ_{lnPGV} and μ_{lnPGA} depend on the combination of magnitude and epicentral distance (i.e. one obtains a matrix of k-rows and l-columns) while $\sigma_{\ln \mathrm{PGV}}$ and $\sigma_{\ln \mathrm{PGA}}$ are constant and represent the standard deviations of the two ground motion parameters provided by Lanzano *et al*. (2019) that account for the epistemic uncertainty of the GMPE. For ρ the procedure by Rathje & Saygili (2008) is followed:

$$\rho = \frac{\sum_i \left(\varepsilon_{\mathrm{PGA}_i} - \bar{\varepsilon}_{\mathrm{PGA}}\right)\left(\varepsilon_{\mathrm{PGV}_i} - \bar{\varepsilon}_{\mathrm{PGV}}\right)}{\sqrt{\sum_i \left(\varepsilon_{\mathrm{PGA}_i} - \bar{\varepsilon}_{\mathrm{PGA}}\right)^2 \sum_i \left(\varepsilon_{\mathrm{PGV}_i} - \bar{\varepsilon}_{\mathrm{PGV}}\right)^2}} \tag{A6}$$

where $\varepsilon_{\mathrm{PGA}}$, $\varepsilon_{\mathrm{PGV}}$, $\bar{\varepsilon}_{\mathrm{PGA}}$ and $\bar{\varepsilon}_{\mathrm{PGV}}$ are the normalised residuals for the quantities *PGA*, *PGV* and the mean value of the observed events, respectively, such that the general expression is:

$$\varepsilon_{\mathrm{GM}} = \frac{\ln GM_{\mathrm{observed}} - \ln GM_{\mathrm{predicted}}}{\sigma_{\ln \mathrm{GM}}} \tag{A7}$$

with *GM* denoting either the ground motion parameters *PGA* or *PGV*, the term $\ln GM_{\mathrm{predicted}}$ evaluated here through the ground motion prediction equation (GMPE) of Lanzano *et al*. (2019) and $\ln GM_{\mathrm{observed}}$ depending on specific observed ground motion parameter (i.e. the values of PGA_i and PGV_j of the strong-motion database). Eq. (A6) provides a synthetic scalar value that correlates the two ground motion parameters based on the total number of observations. Given a value x of permanent displacement, the annual rate of exceedance is computed according to Eq. (A3) as a summation over the whole range of PGA_i, PGV_j, magnitude M_k and epicentral distance R_l that characterise the seismic hazard of the site.

The probabilistic scalar and vector approaches have been implemented in the numerical software package MATLAB. To summarise, the ingredients of the probabilistic approach are: (i) the values of displacements and the standard deviations predicted by any of the semi-empirical relationships (i.e. in this study one among Eqs. (1) – (5)), (ii) the *PGA* hazard curve of the site, (iii) the ground motion prediction equations for *PGA* and *PGV* in terms of mean values and standard deviations and (iv) the seismic disaggregation of *PGA*. Information pertaining to the seismic hazard of the specific site (i.e. *PGA* hazard curve and disaggregation) are provided as external input data extracted from the website of the Italian National Institute of Geophysics and Volcanology (INGV).

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Conflict of interest

Conflict of interest: authors declare that they have no conflict of interest.

Notation

GM	Ground motion parameter
$a_0, a_1, ...a_6$	Coefficients of Eqs. (1) - (4)
d	Permanent sliding displacement
d_y	Threshold permanent sliding displacement
I_A	Arias intensity
k_y	Yield seismic coefficient
M_w	Moment magnitude
PGA	Peak ground acceleration
PGV	Peak ground velocity
R_{ep}	Epicentral distance
$S_a(1.5T_s)$	Spectral acceleration computed at the degraded period $1.5T_s$
T_m	Mean period
T_r	Return period
ε_{GM}	Residual of the ground motion parameter
λ_d	Displacement annual rate of exceedance
μ_{ln}	Natural log of mean value
ρ	Correlation coefficient
σ_{ln}	Natural log of standard deviation

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