Evaluation of seismic landslide hazard based on a new displacement semi-empirical relationship

Fabio Rollo[1][0000-0003-2526-8997] and Sebastiano Rampello[1][0000-0003-0489-9589]

[1] Dipartimento di Ingegneria Strutturale e Geotecnica, Università di Roma *La Sapienza*, via Eudossiana 18, 00184 Roma, Italy
`fabio.rollo@uniroma1.it`

Abstract. This paper presents a new semi-empirical relationship that links the permanent earthquake-induced displacements of slopes to the synthetic ground motion parameter *PGA* or to the couple *PGA* and *PGV*. The displacements are evaluated under the hypothesis of a rigid sliding block performing Newmark's integrations for all the acceleration time histories of the updated Italian seismic database. The relationship reproduces well the displacements for any values of yield seismic coefficient in the whole range of peak ground acceleration. The two parameters expression is more reliable for the study of Italian slopes under seismic loading than that based on the single *PGA* parameter as characterised by a lower standard deviation. The proposed relationship is also combined with a fully probabilistic approach to produce displacement hazard curves and hazard maps for different sites and regions of Italy that represent a useful tool for practicing engineers and national agencies for a preliminary estimate of the seismic performance of a slope.

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

1 Introduction

A well-established way to evaluate the seismic performance of a slope is to determine the displacements induced at the end of the seismic event. These are often quantified through the method proposed by Newmark (1965) [1], 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 than 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. [2-7]). These simplified relationships are often employed to predict the seismic-induced displacements of specific slopes and embankments and are extremely useful when combined with a fully probabilistic-based approach capable to account for the aleatory variability of earthquake ground motion and displacement prediction (e.g.

[8]). In light of this, one can develop scalar and vector probabilistic approaches if one or more ground motion parameters are considered. Moreover, the probabilistic analysis can be extended to a regional scale including the ground motion hazard information within the probabilistic approach to produce landslides hazard maps that allows to detect the portions of territory that are prone to earthquake-induced slope instability (e.g. [9, 10]).

In this work the results of the probabilistic approach incorporating a new semi-empirical relationship proposed by Rollo & Rampello (2023) [11] are illustrated. The new semi-empirical relationship is developed with reference to the Italian seismicity, assimilating the slope to a rigid sliding block, and represents an attractive tool for the screening level analysis of slopes at the regional scale. The displacement hazard curves obtained through the vector approach for different Italian sites and yield seismic coefficients are first shown. Finally, a series of hazard maps displaying either the distribution of the return period for different prescribed values of slope displacements and seismic coefficient or the displacement variability are presented, aimed at clarifying the role of the adopted displacement semi-empirical relationship on the evaluation of the seismic hazard at a regional scale.

2 New semi-empirical relationship and probabilistic framework

The displacement relationships provide the natural log of 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, 2022) [12, 13], the parameters PGA and PGV are more suitable for the development of the probabilistic approach requiring a standard seismic probabilistic hazard analysis (PSHA). In the most general case of two strong motion parameters, the new semi-empirical relationship assumes the form:

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

that depends on the ratio k_y/PGA and on a series of coefficients $a_0 - a_5$ that are calibrated on the considered seismic database. The proposed expression respects the conditions $d \rightarrow \infty$ for $k_y/PGA = 0$ and $d = 0$ for $k_y/PGA = 1$ wanted for the case of a rigid block. The coefficients of the Eq. (1) have been calibrated based on the permanent displacements computed with the rigid sliding-block model [1] for the simple scheme of an infinite slope for different values of the yield seismic coefficient $k_y = 0.04, 0.06, 0.08, 0.1, 0.12, 0.15$. The Newmark's computation has been performed for all the recorded acceleration time histories of the Italian strong motion database [14]. The regression coefficients and $\sigma_{\ln}$ values are reported in Table 1. The coefficients as well as the standard deviation modify whether the ground motion parameter

PGV is taken or not into account. The two ground motion parameters relationship is characterised by lower standard deviation as it describes better the characteristics of the seismic database and the predicted displacements as compared to the single parameter *PGA*. Fig. 1 shows the comparison between the computed displacements and the scalar semi-empirical relationship for different values of yield seismic coefficient.

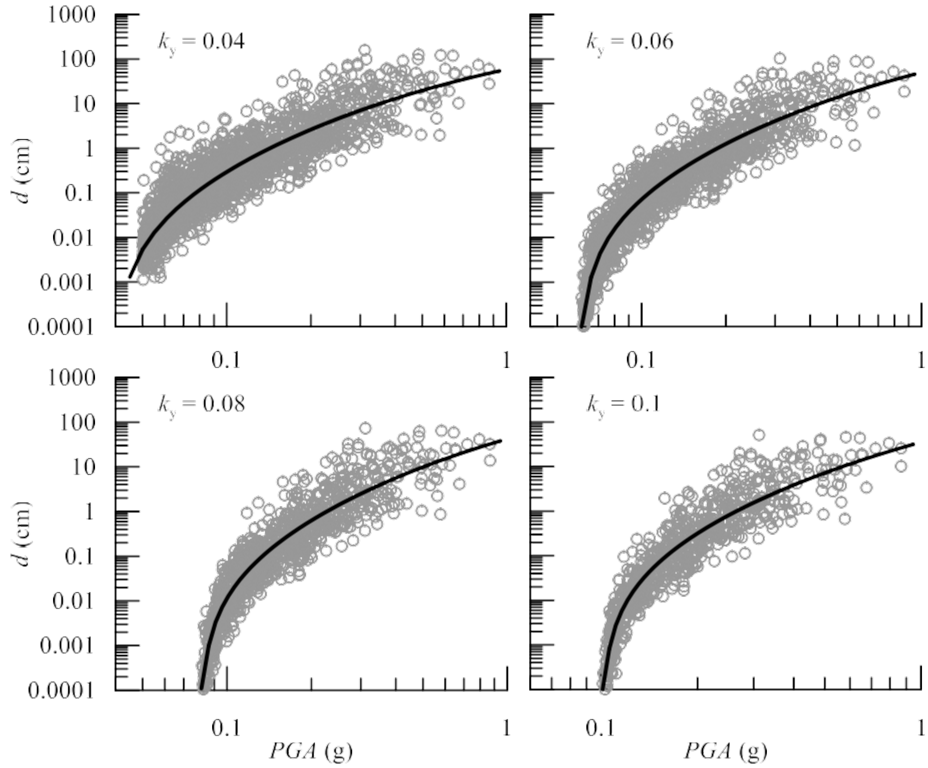

Fig. 1. Comparison between Newmark's displacements and scalar semi-empirical relationship for different values of k_y.

Table 1. Regression coefficients

Approach	a_0	a_1	a_2	a_3	a_4	a_5	σ_{ln}
Scalar	0.698	1.899	-1.987	-0.285	1.101	-	1.001
Vector	-5.124	1.992	-1.736	-0.234	-0.573	1.531	0.547

As shown by Rollo & Rampello (2023) [11], 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 is reasonable for the study of the Italian seismicity when using *PGA* and *PGV* as the seismic loading parameters. Moreover, it represents a good alternative with respect to a series of existing semi-empirical relationships. Fig. 2 shows the Newmark's displacements with the ratio k_y/PGA while the curve indicates the result of the vector semi-empirical relationship for a value of PGV = 8 cm/s, that is the average value for the seismic database

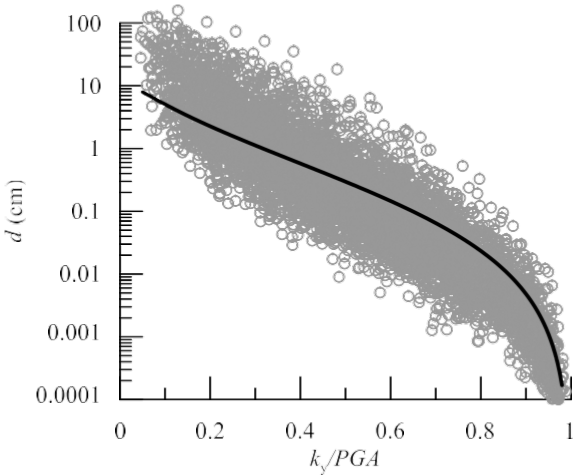

Fig. 2. Displacements versus k_y/PGA for the vector semi-empirical relationship (with PGV = 8 cm/s).

The displacement predictive equations are a key tool 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, only a brief description of the probabilistic approach is presented and the reader is referred to [11] for further details. For the vector approach, λ_d is calculated as:

$$\lambda_{\mathrm{d}}(x) = \sum_i \sum_j P\left[d > x \mid PGA_i, PGV_j\right] \times P\left[PGA_i, PGV_j\right] \quad (2)$$

where the first term is the probability of occurrence of displacements greater than a value x, given the peak ground acceleration PGA_i and the peak ground velocity PGV_j, while the second term is the joint annual probability of PGA_i and PGV_j. The former term requires the disaggregation of the hazard of PGA and the correlation coefficient between PGA and PGV. The correlation coefficient is evaluated through the ground motion prediction equation (GMPE) of Lanzano *et al*. (2019) [15], leading to a value of 0.834. The probabilistic approach has been implemented in the commercial numerical software package MATLAB. Details about the Italian seismic database and the implementation technique can be found in [11, 12].

3 Displacement hazard curves and maps

The displacement hazard curves plot the annual rate of exceedance λ_d against the induced slope displacement and are obtained for different sites in Italy and for different yield seismic coefficients. Fig. 3(a) shows the displacement hazard curves for the site of Amatrice (RI) and three values of k_y: as the seismic resistance of the slope increases the annual rate of exceedance decreases at a given displacement *d*, as expected. Fig. 3(b) shows the results for the sites of Amatrice (RI), Lioni (AV) and Modena in the central, southern and northern Italy, respectively. The displacement hazard curves refer to k_y = 0.12 and allow to investigate the site effect: Lioni and Amatrice are located in two more severe seismic regions than Modena and thus the curves are characterised by higher values of λ_d for a given permanent displacement.

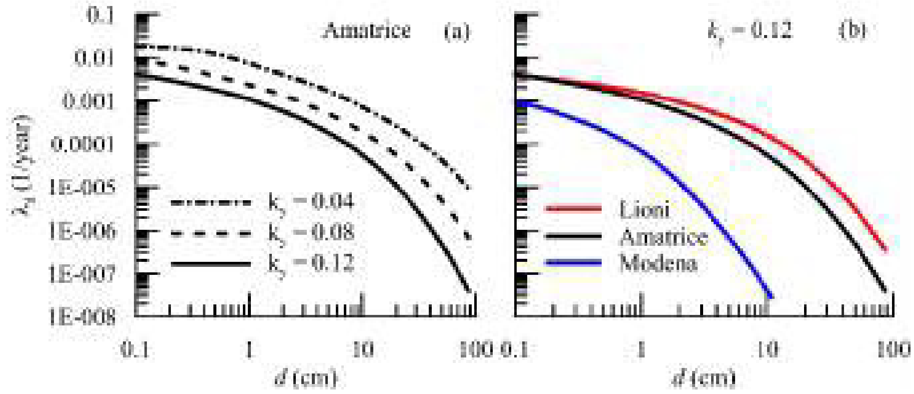

Fig. 3. Displacement hazard curves for (a) the site of Amatrice and different values of yield seismic coefficient and (b) different sites in Italy for a fixed value of k_y.

The results of the probabilistic approach are also described in terms of hazard maps showing the contours of the return periods T_r associated to different levels of earthquake-induced slope displacement and yield seismic coefficients. The maps are obtained considering a grid of points equally spaced of 5 km. Information pertaining to the seismic hazard in terms of *PGA* hazard curves and disaggregation are available in correspondence of these sites on the national territory. For any point 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 gets 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 contours, with a logarithmic scale adopted for the sake of convenience. The maps do not account for the real distribution of slope parameters and soils properties. However, they represent a useful tool for a preliminary assessment of the slope seismic hazard. The hazard maps presented here are developed using the vector probabilistic approach for the district of Irpinia, in the Campania region, an area of about 40x40 km^2 located in the South Italy, at 50 km from the city of Naples. This is a mountainous area crossed by the Apennines and characterised by a severe seismic hazard. The coordinates of the map are East and North according to the reference coordinate system WGS84. *PGA* hazard curves and disaggregation corresponding to the grid points of the area under study are extracted from the INGV interactive seismic hazard maps (http://esse1.mi.ingv.it/d2.html).

Fig. 4 shows the displacement hazard maps in terms of contours of the return period for a fixed value of the yield seismic coefficient and varying threshold displacements d_y = 2cm (rock-like subsoil) and d_y = 15cm (free-field ductile soil behaviour) according to [16].

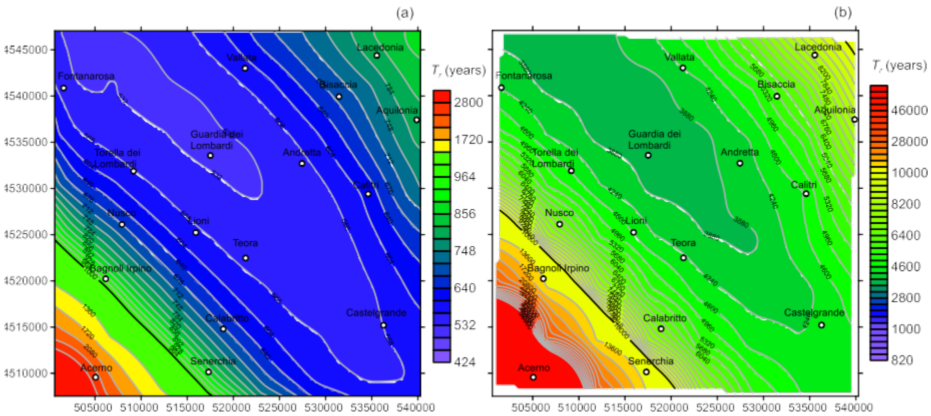

Fig. 4. Displacement hazard maps for the Irpinia district for (a) d_y = 2cm and (b) d_y = 15cm for k_y = 0.08.

The distribution of T_r follows the probabilistic seismic hazard and disaggregation information of the Irpinia district: the hazard is more severe in correspondence of the mountainous zone of the Apennines extended from North-Western to South-Eastern corners of the map. In that area, the occurrence of a certain threshold displacement is more frequent and hence characterised by lower values of return period. As expected, the return period increases drastically when higher value of threshold displacement is considered.

The hazard maps can be also plotted in terms of contours of permanent displacements for a fixed value of return period and yield seismic coefficient, as illustrated in Fig. 5. The displacements are determined directly from Eq. (1) stemming from the areal distribution of *PGA* associated to a return period T_r = 475 years obtained from a standard probabilistic seismic hazard analysis (PSHA) and an average value of PGV = 8 cm/s. The return period of 475 years corresponds to a 10% probability of exceedance in 50 years, that represents an Ultimate Limit State (ULS) according to the Italian building code (NTC18). As expected, the displacements decrease for increasing values of k_y but in any cases a common pattern of the contours can be recognised.

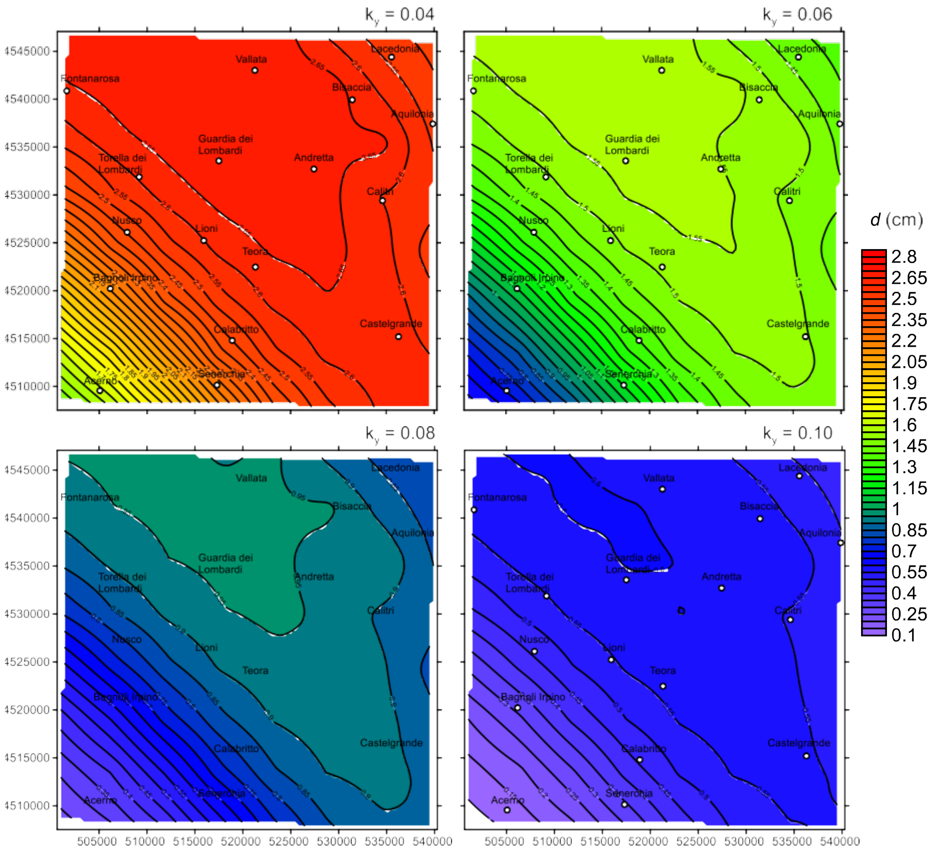

Fig. 5. Displacement hazard maps in terms of displacement contours for the Irpinia district for different values of k_y and $T_r = 475$ years.

4 Conclusions

This paper presents a new semi-empirical relationship for the evaluation of the earthquake-induced slope displacements as a function of the ground motion parameters *PGA* and *PGV* and the yield seismic coefficient k_y. The new expression was formulated and calibrated with reference to the Italian seismic database, assimilating the slope to a rigid sliding block according to the Newmark's method and well predicts the computed permanent displacements. Moreover, when incorporated within a probabilistic approach, the semi-empirical relationship allows to produce a series of hazard curves and maps providing the annual rate of exceedance to given values of slope displacements and yield seismic coefficient k_y. The probabilistic framework can be employed for any locations in Italy and hazard maps expressed either in terms of return periods or in terms of permanent displacements provide with a powerful tool for a more rational, though first estimate, of the regional landslide seismic hazard.

Acknowledgements

The research was funded by the Italian Department of Civil Protection, ReLUIS research project, WP 16: *Geotechnical Engineering*, Task Group 2: *Slope stability.*

References

1. Newmark, N. M.: Effects of earthquakes on dams and embankments. Geotechnique, 15(2), 139-160 (1965).
2. Jibson, R. W.: Regression models for estimating coseismic landslide displacement. Engineering geology, 91(2-4), 209-218 (2007).
3. Saygili, G., Rathje, E. M.: Empirical predictive models for earthquake-induced sliding displacements of slopes. J. of Geotech. and Geoenv.. Eng., 134(6), 790-803 (2008).
4. Rampello, S., Callisto, L., Fargnoli, P. (2010). Evaluation of slope performance under earthquake loading conditions. Rivista Italiana di Geotecnica, 44(4), 29-41 (2010).
5. Biondi, G., Cascone, E., Rampello, S.: Valutazione del comportamento dei pendii in condizioni sismiche. Rivista italiana di geotecnica, 45(1), 9-32 (2011).
6. Song, J., Gao, Y., Rodriguez-Marek, A., Feng, T.: Empirical predictive relationships for rigid sliding displacement based on directionally-dependent ground motion parameters. Engineering Geology, 222, 124-139 (2017).
7. Du, W., Wang, G., & Huang, D.: Evaluation of seismic slope displacements based on fully coupled sliding mass analysis and NGA-West2 database. Journal of Geotechnical and Geoenvironmental Engineering, 144(8), 06018006 (2018).
8. Lari, S., Frattini, P., Crosta, G. B.: A probabilistic approach for landslide hazard analysis. Engineering geology, 182, 3-14 (2014).
9. Sharifi-Mood, M., Olsen, M. J., Gillins, D. T., Mahalingam, R.: Performance-based, seismically-induced landslide hazard mapping of Western Oregon. Soil Dynamics and Earthquake Engineering, 103, 38-54 (2017).
10. Li, C., Wang, G., He, J., & Wang, Y.: A novel approach to probabilistic seismic landslide hazard mapping using Monte Carlo simulations. Eng. Geology, 301, 106616 (2022).
11. Rollo, F., Rampello, S. (Forthcoming): Influence of the displacement predictive relationships on the probabilistic seismic analysis of slopes. Journal of geotechnical and geoenvironmental engineering (2023). https://doi.org/10.1061/JGGEFK/GTENG-11162.
12. Rollo, F., Rampello, S.: Probabilistic assessment of seismic-induced slope displacements: an application in Italy. Bull Eart Eng. (2021). https://doi.org/10.1007/s10518-021-01138-5.
13. Rollo, F., & Rampello, S.: Probabilistic Seismic Hazard Curves and Maps for Italian Slopes. In Conference on Performance-based Design in Earthquake. Geotechnical Engineering (pp. 1348-1355). Springer, Cham. (2022). https://doi.org/10.1007/978-3-031-11898-2_116.
14. Gaudio, D., Rauseo, R., Masini, L., & Rampello, S.: Semi-empirical relationships to assess the seismic performance of slopes from an updated version of the Italian seismic database. Bulletin of Earthquake Engineering, 18(14), 6245-6281. (2020).
15. Lanzano, G., Luzi, L., Pacor, F., Felicetta, C., Puglia, R., Sgobba, S., D'Amico, M.: A Revised Ground-Motion Prediction Model for Shallow Crustal Earthquakes in Italy. Bulletin of the Seismological Society of America, 109(2), 525-540 (2019).
16. Wilson, R.C., Keefer, D.K.: Predicting areal limits of earthquake-induced landsliding. In: Ziony ED (ed) Evaluating Earthquake Hazard in the Los Angeles Region. US Geological Survey, Reston, pp 317–345 (1985).