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Influence of cyclic strength degradation on a Newmark-type analysis

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ABSTRACT: During strong earthquakes soils develop significant deformations that may affect the stability condition of geotechnical systems, causing the activation of plastic mechanisms and the occurrence of permanent displacements. This paper focuses on the seismic behaviour of natural slopes for which the magnitude of earthquake-induced permanent displacements is noticeably affected by the cyclic behaviour of soils. Accordingly, the possibly occurring cyclic reduction of shear strength must be considered to avoid unsafe estimation of the slope seismic performance. To this purpose, a modified Newmark-type analysis is proposed in the paper assuming a time-dependent value of the slope yield acceleration coefficient k_c computed as a function of a degradation parameter R, quantifying the relative reduction of k_c with respect to its initial value, and the number of equivalent loading cycles. The results of an extensive parametric analysis were used to derive some displacement predictive models for a safe estimate of the influence of cyclic strength degradation.

1 INTRODUCTION

Earthquake-induced instabilities of natural slopes are relevant practical issues (e.g. Harp & Gibson, 1990; Biondi et al. 2004) significantly affected by the cyclic behaviour of soils possibly characterized by large reduction of the shear resistance (e.g. Biondi & Maugeri, 2005).

For the prediction of co-seismic slope displacements, the Newmark-type analysis is considered the better compromise between computational effort and results accuracy. However, this kind of analysis is generally carried out neglecting the possibly occurring cyclic degradation of the shear resistance and, thus, it is performed assuming that the slope yield acceleration coefficient k_c is constant over time. Several empirical displacement predictive models have been developed under this assumption (e.g. Madiai & Vannucchi 1997, Ausilio et al. 2007, Jibson 2007, Biondi et al. 2011). A modified Newmark-type analysis, to account for the reduction of shear resistance, was originally suggested to analyse the liquefaction-induced failure mechanisms of granular slopes (Castro, 1987). These kinds of analyses are frequently performed with reference to the infinite slope scheme (e.g. Baziar, 1991, Matasovic et al. 1997) even if, for both cohesive and cohesionless soils, the strength reduction can also be considered for slopes that differ from the infinite slope assumption (e.g. Bandini et al. 2008, 2015; Di Filippo et al. 2019).

In the framework of the work package '*WP2 - Slope stability*' of the 2017-18 ReLuis project, the research group of Messina University proposed a methodology to evaluate the co-seismic performance of slopes accounting for the possible occurring cyclic strength degradation and for the corresponding reduction of the slope critical acceleration coefficient. Some of the obtained results are presented and discussed in the paper.

2 PROPOSED MODIFIED NEWMARK-TYPE ANALYSIS

The numerical analyses presented in the paper refer to the scheme of a rigid block sliding on a horizontal plane. No effect of soil compliance is considered in the analyses which focuses only on the effect of the cyclic strength degradation. Using appropriate shape factors (e.g. Madiai & Vannucchi 1997) depending on the actual failure mechanism and on the geometrical and mechanical properties of the slope, the results presented herein can be referred to the actual slope scheme. It is worth noting that, through suitable shape factors, the results of the analyses presented in the paper can be also adopted for the seismic analyses of other geotechnical systems such as retaining walls (e.g. Biondi et al. 2014) and earth-reinforced soil slopes (e.g. Gaudio et al. 2018).

Cyclic shear strength reduction makes the critical acceleration coefficient k_c decay from an initial value k_{co} to a minimum value k_{cf}. Since only the horizontal component of ground motion is considered in the paper, k_{co} will denote the initial value of the horizontal component of the yield acceleration coefficient. k_{co} was assumed equal to a fraction of the peak horizontal acceleration coefficient k_{max} of the ground motion selected for the displacement analysis. Specifically, values of the acceleration ratio k_{co}/k_{max} in the range 0.1 ÷ 0.8 were assumed and, for each of the selected seismic records, the analyses were carried out using different values of k_{co}.

In the displacement analyses, the reduction $\Delta k_c = k_{co} - k_{cf}$ of the yield acceleration coefficient was assumed as a datum and a parametric analysis was carried out using different values of a degradation parameter $R = \Delta k_c/k_{co}$ varying in the range 0.1 ÷ 0.8. The condition $R = 0$ (i.e. $\Delta k_c = 0$), corresponding to the conventional Newmark-type analysis, with yield acceleration constant over the time, was assumed as a reference to evaluate the increment in permanent displacements due to the reduction of k_c. Obviously, a proper evaluation of the expected reduction of k_c (i.e. proper values of R) is required to adopt the predictive models presented herein.

The degradation path of the yield acceleration coefficient (from its initial value k_{co} to the final value k_{cf}) depends on the degradation path of the soil shear resistance and, thus, is strongly affected by the amplitude, frequency and duration characteristics of the loading history imposed by the ground motion. Several studies showed that the number of equivalent loading cycles N_{eq} suitably describes the energy and frequency content and the significant duration of the ground motion. Also, N_{eq} represents a robust indicator of the destructive capacity of the ground motion and allows describing the more relevant effects of the cyclic soil behaviour such as cyclic degradation and pore water pressure build-up.

The conversion procedures proposed in the literature to estimate N_{eq} aim to detect the loading cycles which mostly affect the cyclic strength degradation and, through a weighting procedure, allow establishing the contribute of each cycle to the overall strength degradation. The corresponding degradation path is defined by the time-history of the cumulated weighted cycles $n_{eq}(t)$ culminating (as a summation) in the total number of cycles N_{eq}. Accordingly, whatever the procedure adopted to estimate $n_{eq}(t)$ and N_{eq}, the ratio $n_{eq}(t)/N_{eq}$ is actually able to describe the pattern of the shear strength degradation path.

For each of the acceleration time-history selected for the displacement analysis, $n_{eq}(t)$ and N_{eq} were evaluated using the conversion procedure recently proposed by Biondi et al. (2012). According to these authors, starting from an acceleration time-history, assumed to be proportional to the time-history of the earthquake-induced shear stress, $n_{eq}(t)$ and N_{eq} can be computed through a conversion procedure in which the cycles that significantly affect the soil shear strength reduction are detected using a suitable cycle-counting method, and weighted through appropriate weighting factors derived from a large set of cyclic laboratory test results.

As an example, Figure 1 shows a horizontal acceleration time-history recorded during the recent 2012 Emilia (Italy) seismic sequence (Figure 1a), together with the cycles relevant to the conversion procedure proposed by Biondi et al. (2012), and the corresponding time-history of the weighted cycles $n_{eq}(t)$ culminating in $N_{eq} = 24.8$ cycles (Figure 1b). Other parameters relevant for the selected acceleration record are given in the figure. From the plots of Figure 1 it can be observed that despite the large time interval D_s, relevant for the selection of the loading cycles to be converted, the use of a proper weighting procedure allows the cumulation of the weighted cycles occurring in a narrow interval, close to the strong-motion duration $D_{5\text{-}95}$ between the 5 and 95% contributions of acceleration time histories to the Arias intensity I_a.

Starting from these statements, the ratio $n_{eq}(t)/N_{eq}$ was adopted herein to describe the degradation path of k_c and, in the time interval relevant for the conversion procedure (denoted as D_s in Figure 1b), the following current value $k_c(t)$ was adopted in the displacement analysis:

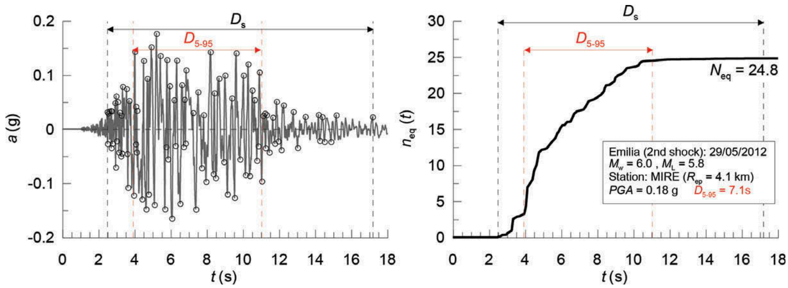

Figure 1. Evaluation of the time-history of the number of equivalent loading cycles.

$$K_c(t) = k_{co}\left[1 - \frac{n_{eq}(t)}{N_{eq}} \cdot R\right] \tag{1}$$

As a result, the reduction of k_c is assumed to occur only in the time interval relevant for the conversion procedure and depends on the cumulation of the number of those cycles whose amplitude is effective in producing the reduction of the soil shear strength.

3 SELECTED DATABASE OF RECORDS

A set of horizontal acceleration records were selected from the Italian accelerogram database ITACA v2.3; namely, accelerograms recorded during earthquakes with magnitude $M > 4$ at stations with epicentral distance $R_{ep} < 100$ km were selected. These criteria led to a set of 961 double (NS and EW) component of records, for a total of 1922 accelerograms. A detailed description of the adopted database can be found in the paper by Gaudio et al. 2018. Table 1 provides a synthesis of the relevant seismic parameters: Moment (M_w) and Richter local magnitude (M_L), epicentral distance R_{ep}, peak ground acceleration (PGA), duration ($D_{5\text{-}95}$) between the 5 and 95% of I_a and the number of equivalent loading cycles (N_{eq}) evaluated using the conversion procedure by Biondi et al. (2012). The soil class (from A to E) to which the soil deposit at the recording site belongs is indicated according to the provisions of the Italian Seismic Code (NTC18); classes A*, B* and C* denote soil deposits for which the actual shear waves velocity profile was inferred according to local geology, since no direct measurement was available.

4 PARAMETRIC ANALYSIS AND PROPOSED PREDICTIVE MODELS

The time histories of the critical acceleration coefficient were evaluated for the 1922 selected accelerograms considering 8 values of the degradation parameter R (parametrically varied in the range 0.1 ÷ 0.8), and the corresponding displacement analyses were carried out for 8 values of the acceleration ratio k_{co}/k_{max} (in the range 0.1 ÷ 0.8). For each record, both positive and negative sign were considered and the larger of the two computed permanent displacements was assumed as representative and hereafter denoted as d. Accordingly, more than 246.000 displacement analyses were performed for different slopes forced by different accelerograms.

To assess the influence of the cyclic shear strength degradation on the slope permanent displacement, a series of conventional Newmark-type analysis (i.e. $R = 0$) were also carried and the final permanent displacement, denoted as d_o, was assumed herein as a reference for a given value of the acceleration ratio k_{co}/k_{max}.

The results of the analyses which neglect (d_o) or account for (d) the degradation of k_c are represented in Figures 2a and 3, respectively, where also the average values of the dataset of results are shown together with the 84^{th} and the 90^{th} percentile of the data distribution.

Table 1. Parameters of the earthquake records adopted in this study.

Soil class	records	M_W	M_L	R_{ep}	PGA (cm/s^2)	$D_{5\text{-}95}$ (s)	I_a (cm/s)	N_{eq}
A	26	4.1-6.9	4.1-6.5	1.4-36.9	18.3-182.3	1.1-49.7	0.2-28.7	2.7-21.2
A*	224	4.0-6.9	4.0-6.5	0.7-89.9	18.3-850.0	0.8-53.0	0.2-608.6	2.7-38.4
A + A*	250	4.0-6.9	4.0-6.5	0.7-89.9	18.3-850.0	0.8-53.0	0.2-608.6	2.7-38.4
B	302	4.0-6.9	3.6-6.5	1.2-78.4	28.0-644.2	0.4-49.5	0.2-362.7	1.9-65.2
B*	634	4.0-6.9	3.0-6.5	0.6-90.4	20.8-850.8	0.4-102.3	0.2-384.2	1.9-65.2
B + B*	936	4.0-6.9	3.0-6.5	0.6-90.4	20.8-850.8	0.4-102.3	0.2-384.2	1.9-65.2
C	108	4.5-6.5	3.7-6.4	2.8-95.3	29.5-402.4	1.6-49.3	0.3-132.6	2.4-40.2
C*	484	4.0-6.5	3.7-6.4	0.4-95.3	16.3-706.8	0.7-52.8	0.15-288.8	2.4-55.2
C + C*	592	4.0-6.5	3.7-6.4	0.4-95.3	16.3-706.8	0.7-52.8	0.15-288.8	2.4-55.2
D	28	4.3-6.5	3.7-6.1	2.4-50.3	43.5-331.8	3.0-37.9	2.1-69.7	4.6-21.8
E	94	4.2-6.5	4.0-6.1	1.3-73.9	28.0-520.7	1.1-13.8	0.4-286.7	3.2-41.1
n.d	22	4.7-5.4	4.1-5.3	0.8-52.0	27.9-303.6	1.1-11.1	0.6-36.1	3.9-17.1
All	1922	4.0-6.9	3.0-6.5	0.4-95.3	16.3-850.8	0.4-102.3	0.15-608.6	1.9-65.2

A displacement predictive model based on the computed values of d_o (neglecting the possibly occurring strength degradation) is presented in the paper by Gaudio et al. 2018. The displacement ratio d/d_o can be regarded as an amplification coefficient of the earthquake-induced permanent displacements that accounts for the reduction of the yield acceleration coefficient produced by the occurrence of soil shear strength degradation during the ground motion.

The proposed procedure can be obviously combined with the predictive model by Gaudio et al. 2018, but due to its generality, the ratio d/d_o can be used also with other predictive models available in the literature; furthermore, through proper shape factors, can be applied also for the evaluation of expected permanent displacements of any geotechnical system that can be suitably represented by the Newmark sliding block model.

The computed values of the displacement ratio d/d_o are plotted in Figure 4 for each value of the degradation parameter R selected for the analyses: the average trends are also potted together with the 84th and the 90th percentile of the dataset distribution.

Comparing the plots of Figures 3 and 4 it is apparent that, whatever is the values of the degradation parameter assumed in the analyses, the variation of d/d_o with the acceleration ratio k_{co}/k_{max} is characterized by a lower dispersion. This is also confirmed by the lower values of the standard deviation described in Figure 2b for the two different set of data.

In order to provide a simple and practical tool for the displacement prediction, capable to account for the effects of the shear strength degradation, regression analyses of the computed displacement ratios d/d_o were carried out using proper functional forms to explain the distribution of the data shown in Figure 4. Specifically, a *polynomial* and an *S-shaped* functional

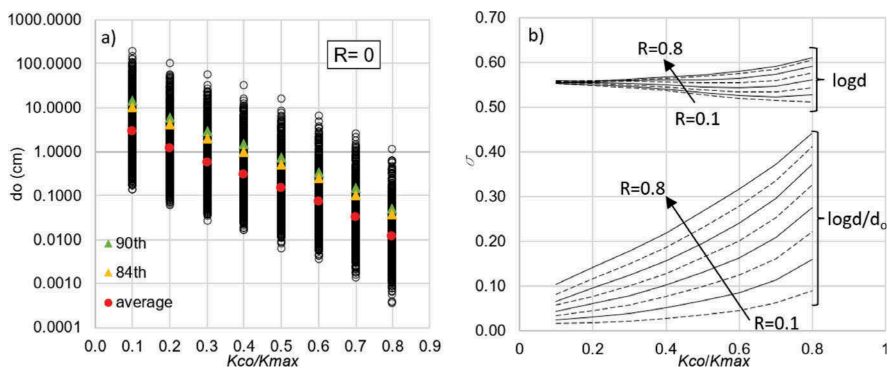

Figure 2. a) Values of the displacement d_o computed through the conventional (R = 0) Newmark-type analyses; b) values of the standard deviation computed for the displacement d and for the ratio d/d_o.

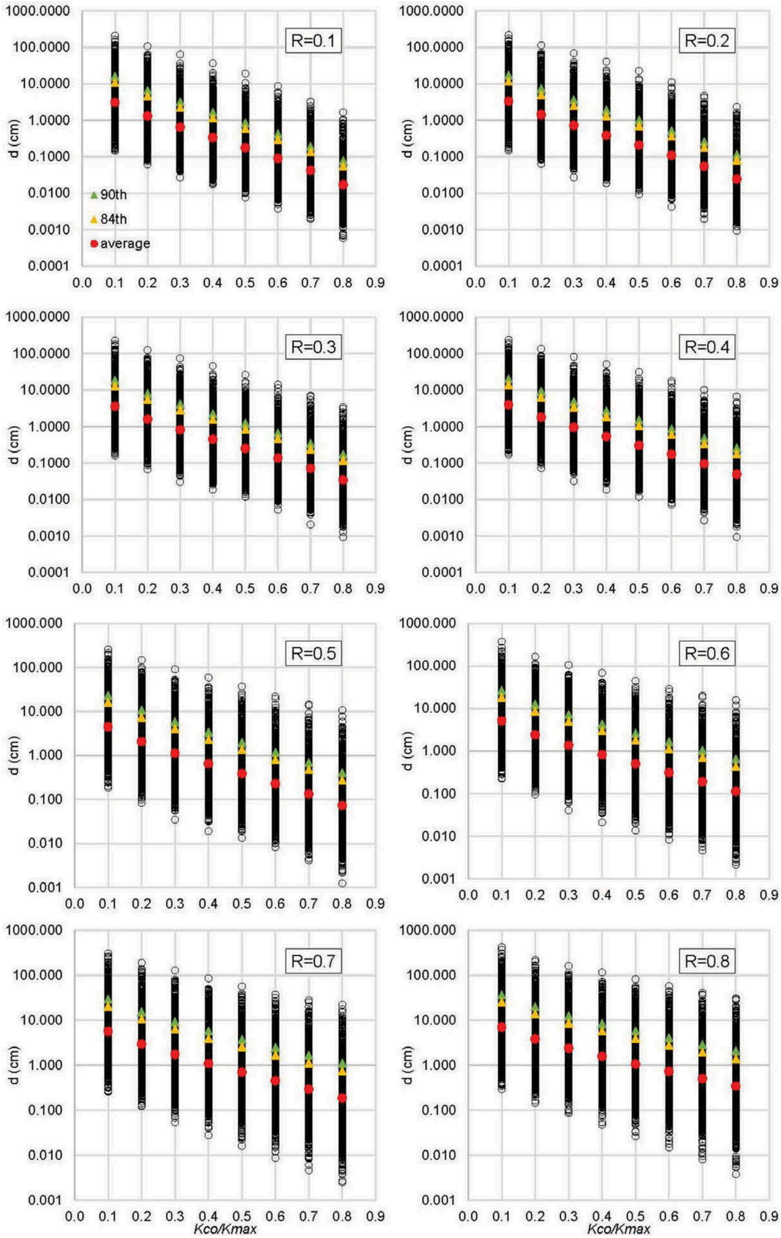

Figure 3. Permanent displacements d for various degradation parameters R and acceleration ratios k_{co}/k_{max}.

forms have been chosen to fit the average values of computed displacement ratios as well as the 84th and the 90th percentile of the dataset.

Figure 5 shows the results of the regression analyses carried out for each of the selected values of the degradation parameter *R*. Owing to the multitude of variables involved in the problem at hand, the regressions of the 84th and 90th percentile are suggested herein for a conservative evaluation of the slope permanent displacements. Furthermore, it was also verified that, regardless the values of *R* and k_{co}/k_{max}, the S-shaped model is generally characterized by a lower standard error $\sigma_{log(d/do)}$. Accordingly, only these models are presented herein.

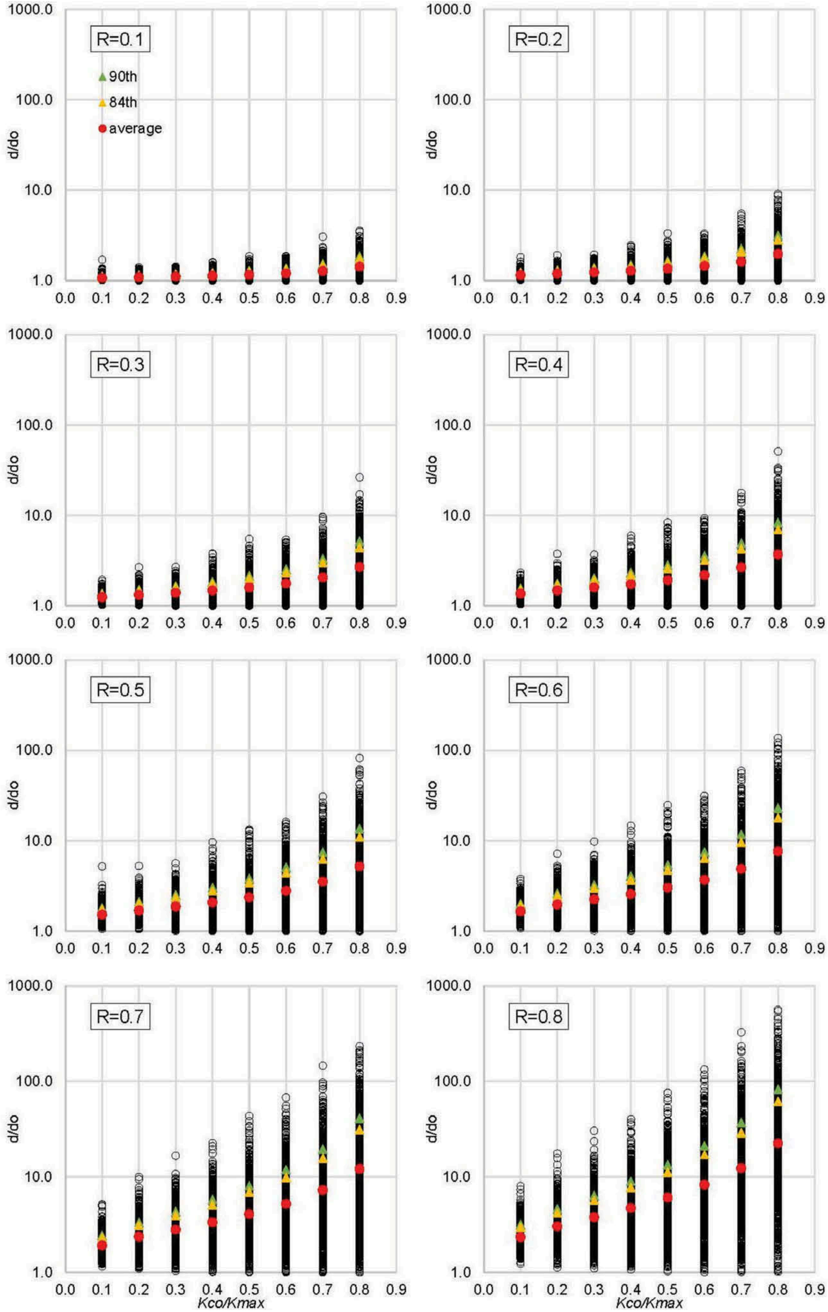

Figure 4. Displacement ratio d/d_o for various degradation parameters R and acceleration ratios k_{co}/k_{max}.

The proposed S-shaped model is described by the following equation:

$$\log\left(\frac{d}{d_o}\right) = A_k \cdot log\left(1 - \frac{k_{co}}{k_{max}}\right) + B_k \cdot log\left(\frac{k_{co}}{k_{max}}\right) + C_k \qquad (2)$$

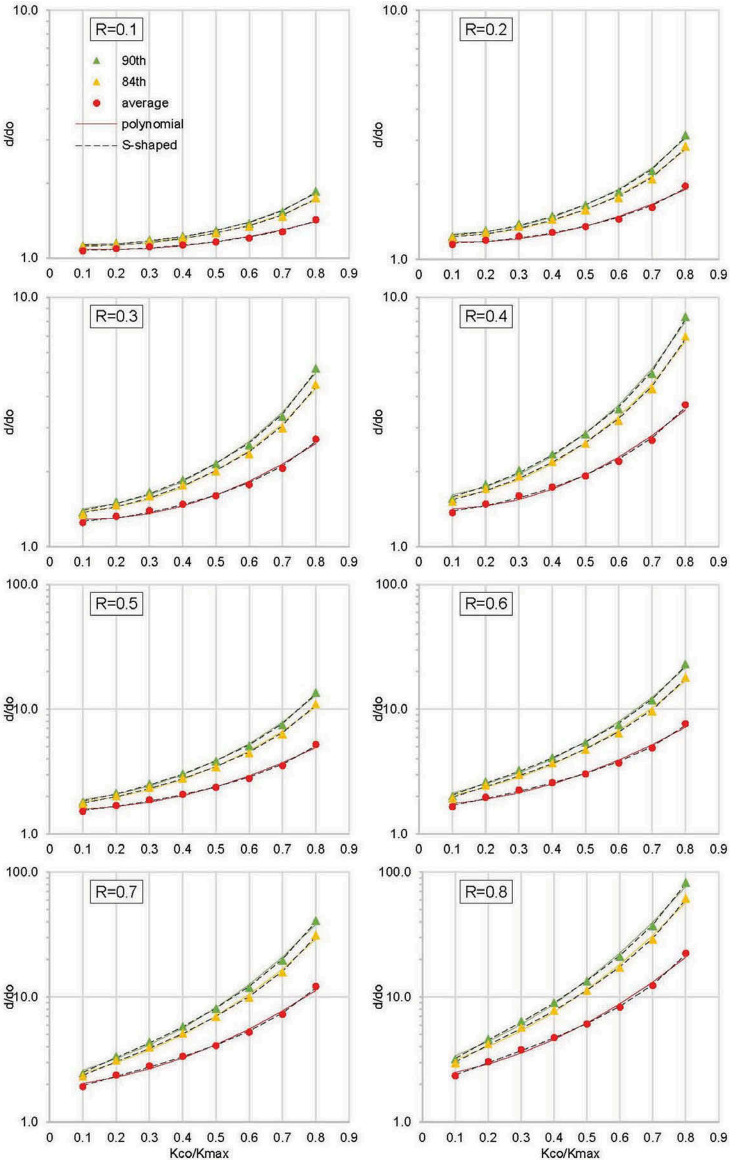

Figure 5. Empirical predictive models proposed for different values of the degradation parameter R.

where the regression coefficients A_k, B_k and C_k depend on the degradation parameter R:

$$A_k = -1.5 \cdot R - 0.1 \qquad B_k = 0.2 \cdot R - 0.1 \qquad C_k = 0.93 \cdot R^2 - 0.23 \cdot R \tag{3}$$

The ratio between the standard error $\sigma_{\log(d/do)}$ of the models proposed for the 90th percentile of the data and the corresponding values of the degradation parameter R are shown in Figure 6 for the 8 values of the acceleration ratio considered in the analyses. For k_{co}/k_{max} in the range 0.2 ÷ 06 the ratio $\sigma_{\log(d/do)}/R$ can be reasonably assumed as a liner function of the acceleration ratio and the following approximated relationship can be adopted for its prediction:

$$\frac{\sigma}{R} = 0.57 \cdot \frac{k_{co}}{k_{\max}} + 0.045 \tag{4}$$

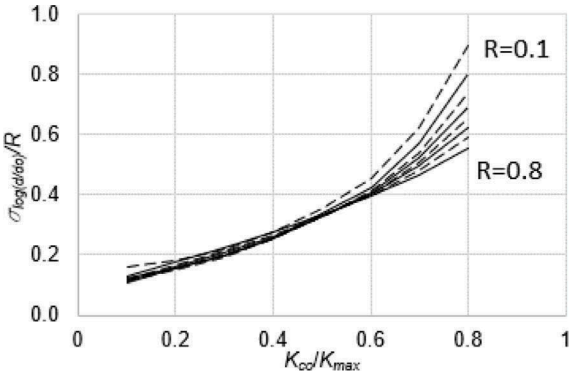

Figure 6. Standard error of the proposed empirical predictive models for the 90th percentile of the data.

5 CONCLUDING REMARKS

The paper presents a procedure to perform a modified Newmark-type analysis to account for the reduction of the yield acceleration coefficient due to the possibly occurring reduction of the soil shear strength. The reduction of k_c (starting from its initial value k_{co}) is, innovatively expressed as a function of the number of equivalent loading cycles N_{eq}, computed using a recently proposed conversion procedure, and depends on a degradation parameter $R = \Delta k_c/k_{co}$ whose proper evaluation is preliminary required to apply the proposed procedure.

The results of a large set of displacement analyses showed that the reduction of k_c remarkably affects the computed permanent displacements d which are generally larger than those (d_o) evaluated neglecting such effect. The displacement ratio d/d_o quantifies the effect of the reduction of k_c on the increase in permanent displacements and was computed for several values of the degradation parameter R and of the acceleration ratio k_{max}/k_{co}.

A predictive model for the evaluation of the displacement ratio d/d_o, have been proposed based on a best fit of the computed data. Starting from a proper estimate of d_o and R, a conservative estimate of the expected permanent displacements can be obtained using the predictive models presented herein for the 84th and 90th percentile of the data distribution. Finally, the proposed procedure, described with reference to slope stability analysis, can actually be applied to any geotechnical systems that under seismic conditions cab be assimilated to a sliding block.

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