Reliability analysis of empirical predictive models for earthquake-induced sliding displacements of slopes

Analyse de fiabilité des modèles empiriques de prédiction des déplacements sismiques de pentes

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ABSTRACT: The goal of this study is twofold: (i) to identify the influence of the earthquake characteristics on the magnitude of the residual co-seismic slope displacements of a typical slope using different predictive analytical models and (ii) to compare the results of the analytical models with an exact fully dynamic non-linear analysis. In particular, three analytical models were used to predict the permanent slope displacements: the classical Newmark rigid block model, the decoupled Rathje and Antonakos model and the coupled Bray and Travasarou sliding block model. In addition, 2 dimensional fully non-linear numerical analyses were performed using the code FLAC for idealized sand and clayey step-like slopes considering different real acceleration time histories as input motion. All three models predict displacements that are generally in good agreement with the numerical results for the sand slope case. On the contrary, for the clay more flexible slope the correlation is not so good. However it is shown that the some crucial parameters, like the frequency content of the input motion, are not always appropriately captured in all analytical models.

RÉSUMÉ : L'objectif de cette étude est (i) d'identifier l'influence des caractéristiques du tremblement de terre sur l'ampleur des déplacements co-sismiques résiduels d’une pente, en utilisant différents modèles analytiques et (ii) de comparer les déplacments analytiques avec une analyse numérique plus élaborée. En particulier, trois modèles différents étaient utilisés pour estimer les déplacements permanents : le modèle de base de bloc rigide de Newmark, le modèle découplé de Rathje et Antonakos et le modèle couplé de Bray et Travasarou. L’analyse numérique a été effectuée sur la même pente avec le code FLAC et pour les mêmes matériaux de sol (sable et argile). Dans le cas de pente sableuse les déplacements calculés par les trois modèles analytiques sont généralement en relativement bon accord avec les résultats numériques. La comparaison est moins bonne pour la pente argileuse. Néanmoins il a été démontré que tous les modèles analytiques ne tiennent pas en compte proprement quelques paramètres importants comme la fréquence du mouvement fort des sols.

KEYWORDS: co-seismic slope displacements, Newmark-type displacement models, non-linear dynamic numerical analysis.

1 INTRODUCTION

It is common practice in geotechnical earthquake engineering to assess the expected seismic performance of slopes and earth structures by estimating the potential for seismically induced permanent displacements using one of the available displacement-based analytical procedures. Considering that (total and/or differential) displacements ultimately govern the serviceability level of a slope after an earthquake, the use of such approaches is strongly recommended. Typically, two different approaches of increased complexity are proposed to assess permanent ground displacements in case of seismically triggered slides: Newmark-type displacement methods and advanced stress- strain dynamic methods.

The sliding-block analog proposed by Newmark (1965) still provides the conceptual basis on which all other displacement-based methods have been developed aiming to yield more accurate estimates of slope displacement. This has been accomplished by proposing more efficient ground motion intensity measures (e.g. Saygili and Rathje, 2008), improving the modeling of dynamic resistance of the slope characterized by its yield coefficient (e.g. Bray, 2007) and by analyzing the dynamic slope response more rigorously (e.g. Bray and Travasarou, 2007; Rathje and Antonakos, 2011). In terms of their assumptions to analyze the dynamic slope response, displacement based methods can be classified into three main types: rigid block, decoupled and coupled. A short description of the different types of Newmark-type displacement methods as well as recommendations for the selection of the most appropriate ones is given in Jibson (2011).

Advanced stress-deformation analyses based on continuum (finite element, FE, finite difference, FDM) or discontinuum formulations usually incorporating complicated constitutive models, are becoming recently more and more attractive, as they can provide approximate solutions to problems which otherwise cannot be solved by conventional methods e.g. the complex geometry including topographic and basin effects, material anisotropy and non-linear behavior under seismic loading, in situ stresses, pore water pressure built-up, progressive failure of slopes due to strain localization. Several investigators have implemented continuum FE or FD codes to evaluate the residual ground displacements of slopes using elastoplastic constitutive models (e.g. Chugh and Stark, 2006; Lenti and Martino, 2012 etc.).

In this paper we study the accuracy of three different Newmark-type based models i.e. the conventional analytical Newmark (1965) rigid block approach, the Rathje and Antonakos (2011) decoupled model and Bray and Travasarou (2007) coupled model, classically used to estimate the expected co-seismic slope displacements, with a more refined numerical approach, considering different earthquake input motions scaled to different PGA values and compliance of the sliding surface. For the purpose of this comparative study we selected a typical configuration of a 30^o inclined sand and clayey slope.

2 IMPLEMENTATION OF NEWMARK-TYPE PREDICTIVE MODELS

The Newmark conventional analytical rigid block method is used to predict cumulative slope displacements obtained by integrating twice with respect to time the parts of an earthquake acceleration-time history that exceed the critical or yield acceleration, a_c ($k_y \cdot g$) (e.g. threshold acceleration required to overcome shear soil resistance and initiate sliding). The second approach is a two-parameter vector (PGA, PGV) model proposed by Rathje and Antonakos (2011) applied herein to evaluate co-seismic slope displacements. This model is recommended for use in practice due to its ability to significantly reduce the variability in the displacement prediction. For flexible sliding, k_{max} (e.g. peak value of the average acceleration time history within the sliding mass) is used in lieu of PGA and k–vel_{max} (e.g. peak value of the k-vel time history provided by numerical integration of the k-time history) is used to replace PGV. The third one is the Bray and Travasarou (2007) model. In this model cumulative displacements are calculated using the nonlinear fully coupled stick-slip deformable sliding block model proposed by Rathje and Bray (2000) to capture the dynamic response of the sliding mass. They use a single intensity parameter to characterize the equivalent seismic loading on the sliding mass, i.e. the ground motion's spectral acceleration S_a at a degraded period equal to $1.5T_s$, which was found to be the optimal one in terms of efficiency and sufficiency (Bray 2007).

The first goal is to study the influence of the earthquake characteristics and the dynamic response of the slope on the magnitude of the residual slope displacements using the aforementioned three predictive models. In this respect, permanent displacements as a function of the critical acceleration ratio (e.g. k_y/k_{max} or k_y/PGA) are computed using the three approaches considering different earthquake input motions and compliance of the sliding surface. Comparisons between the models allowed evaluating their reliability. Mean displacements were calculated using the Newmark rigid block model, as reference, whereas median values ±1 standard deviation and median and 16th - 84th percentiles were derived for the decoupled and coupled approximations respectively.

Table 1. Parameters describing the characteristics of the ground motions and the dynamic response of the sliding mass

Earthquake record name	*Valnerina 1979- Cascia_L*		*Northridge 1994- Pacoima Dam_L*	
Earthquake code	*Cascia*		*Pacoima*	
Moment magnitude (M_w)	5.9		6.7	
PGA (g)	0.15		0.41	
Fundamental period T_p (sec)	0.23		0.48	
Mean Period T_m (sec)	0.295		0.507	
Scaled PGA (g)	0.3	0.7	0.3	0.7
PGV (cm/sec)	10.3	30.9	14.6	43.9
Natural period of the sliding mass T_s (sec)	0.16	0.032	0.16	0.032
$S_a(1.5T_s)/PGA_{scaled}$	2.93	1.07	2.26	1.03
T_s/T_m	0.54	0.11	0.32	0.06

The seismic input consists of two real acceleration time histories recorded at rock outcropping conditions and scaled at two levels of PGA, i.e. 0.3 and 0.7g. Table 1 presents the parameters describing some basic characteristics of the ground motions and the flexibility of the potential sliding surface. The displacements were computed for nearly rigid (T_s=0.032sec) and relatively flexible (T_s=0.16 sec) sliding masses. The derived (mean or median) permanent displacements for the three different predictive models and for the different considered earthquake scenarios plotted as a function of the critical acceleration ratio, k_y/k_{max} or k_y/PGA, are illustrated in Figures 2a, 2b and 2c when considering the nearly rigid sliding surface. Moreover in Figures 3a and 3b we compared between them the three analytical models for the Pacoima 0.7g input motion for the nearly rigid and the relatively flexible sliding mass respectively.

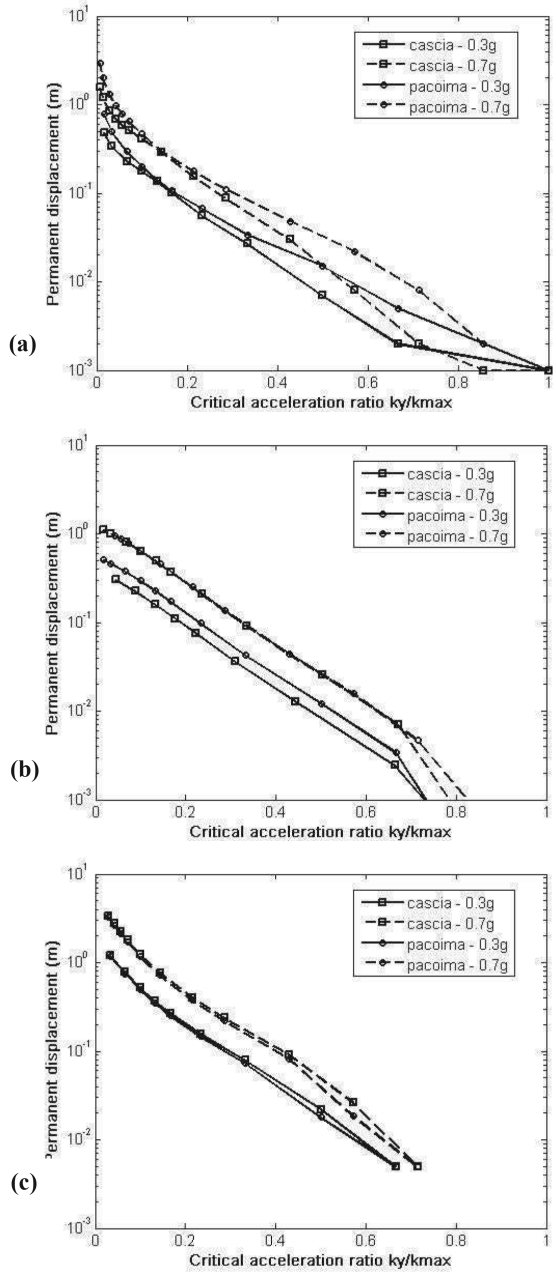

Figure 2. Newmark (a), Rathje and Antonakos (b) and Bray and Travasarou (c) displacement versus k_y/k_{max} considering a nearly rigid sliding mass for different acceleration time histories (cascia, pacoima) scaled at different levels of PGA (0.3g, 0.7g)

The results prove the important role of the amplitude and frequency content of the earthquake as well as the compliance of the sliding surface on the magnitude of the computed displacements. As it should be expected, time histories scaled at 0.7g produce larger displacements compared to those scaled at 0.3g for the same critical acceleration ratios. For the Newmark and Rathje and Antonakos models the lower frequency input motion (Pacoima- f_p=2.1Hz) generally yields larger displacements in relation to the higher frequency input motion (Cascia- f_p=4.4Hz). For the Newmark model (see Fig. 2a) this trend becomes more pronounced with the increase of the critical acceleration ratio, whereas in Rathje and Antonakos (see Fig. 2b) this trend does not seem to be influenced by the critical acceleration ratio. Contrary to the previous models it seems that the importance of the frequency content is not taken into account in the Bray and Travasarou coupled model, which predicts slightly larger displacements for the higher frequency input motion (see Fig. 2c). The latter model generally predicts larger displacements compared to Newmark rigid block and Rathje and Antonakos decoupled models. In particular, the difference in the displacement prediction is by far more noticeable for the flexible (Fig. 3b) compared to the nearly rigid (Fig. 3a) sliding mass. Displacements computed using Rathje and Antonakos predictive equations are closer to the Newmark rigid block model. The comparison is even better for the higher frequency input motion and for the lower level of shaking.

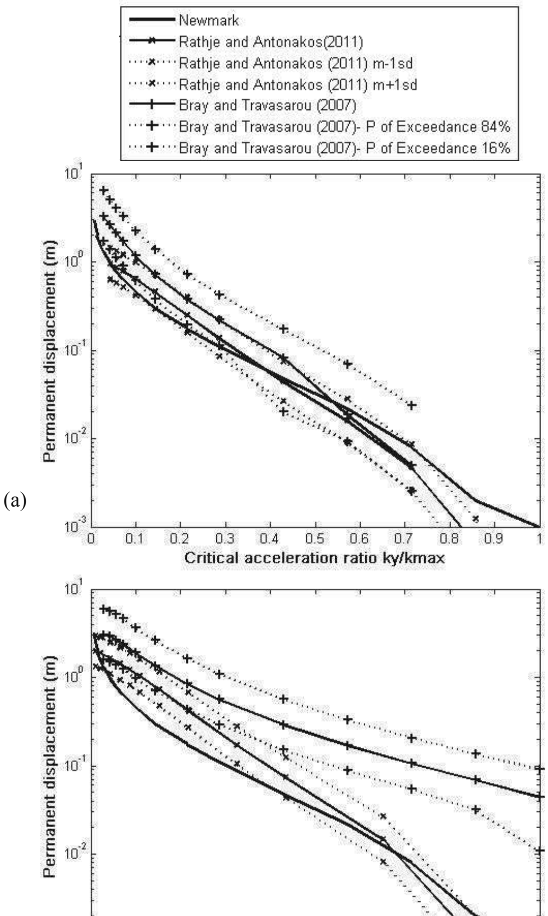

Figure 3. Comparison of the different Newmark-type models when considering a nearly rigid (a) and a relatively flexible (b) sliding mass for a certain earthquake scenario (Pacoima scaled at 0.7g)

3 COMPARISON WITH THE DYNAMIC NUMERICAL ANALYSIS

The second goal is to compare the Newmark-type analytical models with an a-priori more accurate numerical model. For this purpose a two- dimensional fully non-linear FLAC (Itasca, 2008) model has been used. The computed permanent horizontal displacements within the sliding mass for the two idealized step-like slopes, characterized by different flexibility of the potential sliding surface, are compared with the three Newmark-type models.

The geometry of the finite slope is shown in Figure 4. The discretization allows for a maximum frequency of at least 10Hz to propagate through the grid without distortion. Free field absorbing boundaries are applied along the lateral boundaries whereas quiet boundaries are applied along the bottom of the dynamic model to minimize the effect of artificially reflected waves. The soil materials are modeled using an elastoplastic constitutive model with the Mohr-Coulomb failure criterion, assuming a non-associated flow rule for shear failure. Two different soil types are selected for the surface deposits to represent relatively stiff frictional and cohesive materials. The mechanical properties for the soil materials and the elastic bedrock are presented in Table 2.

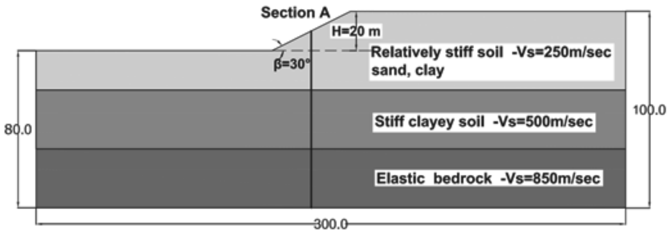

Figure 4. Slope configuration used for the numerical modeling

Table 2. Soil properties of the analyzed slopes

Parameter	Relatively stiff soil		Stiff soil	Elastic bedrock
	sand	*clay*		
Dry density (kg/m^3)	1800	1800	2000	2300
Poisson's ratio	0.3	0.3	0.3	0.3
Cohesion c (KPa)	0	10	50	-
Friction angle φ (degrees)	36	25.0	27	-
Shear wave Velocity V_s (m/sec)	250	250	500	850

Table 3. Selected outcropping records used for the dynamic analyses

Earthquake	Record station	Mw	R(km)	PGA(g)
Valnerina, Italy 1979	*Cascia*	5.9	5.0	0.15
Parnitha, Athens 1999	*Kypseli*	6.0	10.0	0.12
Montenegro 1979	*Hercegnovi Novi*	6.9	60.0	0.26
Northridge, California 1994	*Pacoima Dam*	6.7	19.3	0.41
Campano Lucano, Italy 1980	*Sturno*	7.2	32.0	0.32
Duzce, Turkey 1999	*Mudurno_000*	7.2	33.8	0.12
Loma Prieta, California 1989	*Gilroy1*	6.9	28.6	0.44

The initial fundamental period of the sliding mass (T_s) is estimated using the simplified expression: $T_s = 4H/V_s$, where H is the depth and V_s is the shear wave velocity of the potential sliding mass. The depth of the sliding surface is evaluated equal to 2m for the sandy slope and 10m for the clayey one by means of limit equilibrium pseudostatic analyses. The horizontal yield coefficient, k_y, is computed via pseudostatic slope stability analysis equal to 0.16 and 0.15 for the 30^o inclined sand and clayey slopes respectively.

The seismic input applied along the base of the dynamic model consists of a set of 7 real acceleration time histories recorded on rock outcrop (see Table 3) and scaled at PGA=0.7g. To derive the appropriate inputs for the Newmark-type methods that include the effect of soil conditions, and to allow a direct comparison with the numerical results, we computed the time histories at the depth of the sliding surfaces through a 1D non-linear site response analysis considering the same soil properties as in the 2D dynamic analysis. It is noticed that the 1D soil profile is located at the section that approximately corresponds to the maximum slide mass thickness of the slope (Section A in Figure 4). The bottom of the sliding surface is taken be consistent to the estimated fundamental period of the sliding mass (T_s) that is different for the clay and sand slopes.

Table 4 presents the computed numerical horizontal displacements together with those calculated using the different Newmark-type displacement methods. The average difference (%) of the Newmark-type models in the median (or mean) displacement estimation compared to the numerical displacement is shown in Figure 5a for both sand and clay slopes. The dispersion of the corresponding differences is presented in Figure 5b.

Table 4. Comparison between numerical, Newmark (1965), Rathje and Antonakos (2011) and Bray and Travasarou (2007) displacements for sand and clayey slope materials and for outcropping accelerograms scaled at 0.7g

Slope soil material	Earthquake code	Computed horizontal displacement (m)	Average Newmark (m)	Rathje and Antonakos Median (m)	Bray and Travasarou Median (m)
sand	*cascia*	0.6	0.64	0.40	0.60
	kypseli	0.50	0.55	0.50	0.65
	montenegro	0.90	0.70	0.37	0.42
	pacoima	0.70	0.53	0.49	0.57
	sturno	1.70	1.38	0.83	0.81
	duzce	1.10	0.94	0.36	0.57
	gilroy	0.20	0.23	0.28	0.57
clayey	*cascia*	0.50	0.36	0.16	0.57
	kypseli	0.45	0.28	0.14	0.53
	montenegro	0.82	0.47	0.16	0.72
	pacoima	0.62	0.35	0.19	0.79
	sturno	1.40	0.90	0.25	0.71
	duzce	0.85	0.48	0.16	1.16
	gilroy	0.20	0.09	0.09	0.55

4 DISCUSSION- CONCLUSIONS

In general the Newmark-type analytical models predict comparable displacements, at least in the order of magnitude, with the exact numerical analysis. The comparison is generally better for the sand slope case, while for the clayey more flexible slope the divergences are amplified. In particular Bray and Travasarou model tend to predict generally larger displacements with respect to the numerical analysis, whereas Newmark and Rathje and Antonakos models underpredict the corresponding displacements.

Among the three methods, Bray and Travasarou model was found to present the minimum average predictive error (%) in relation to the numerical analysis for both sand and clay slope cases. This is in line with the inherent coupled stick-slip assumption adopted in the method that offers a conceptual improvement over the rigid block and decoupled approaches for modeling the physical mechanism of earthquake-induced landslide deformation. However, Bray and Travasarou model presents a very large dispersion in the median displacement estimation (up to 70% for both sandy and clayey slopes). Thus, the use of $S_a(1.5\ T_s)$ seems rather insufficient to fully describe the characteristics of the seismic loading (i.e. amplitude, frequency content and duration) for site-specific applications.

Newmark analytical approach shows the minimum dispersion in the displacement prediction (less than 10-20%) with respect the numerical analysis results compared to the Bray and Travasarou and Rathje and Antonakos models. This may be justified by the fact that Newmark analytical method uses the entire time history to characterize the seismic loading as opposed to the Bray and Travasarou and Rathje and Antonakos models that use one [$S_a(1.5\ T_s)$] and two (PGA, PGV) intensity parameters respectively. As such, uncertainties associated to the selection of the ground motion intensity parameters are lower in the Newmark analytical approach.

Overall, the differences in the displacement prediction between the three models are larger for the clayey slope. Thus, the compliance of the sliding surface in relation with the way that the frequency content of the input motion is taken or not into account may produce some important errors to the estimated earthquake-induced sliding displacements of slopes. It is suggested that a better framework is deemed necessary to account for the various uncertainties in the seismic displacements prediction.

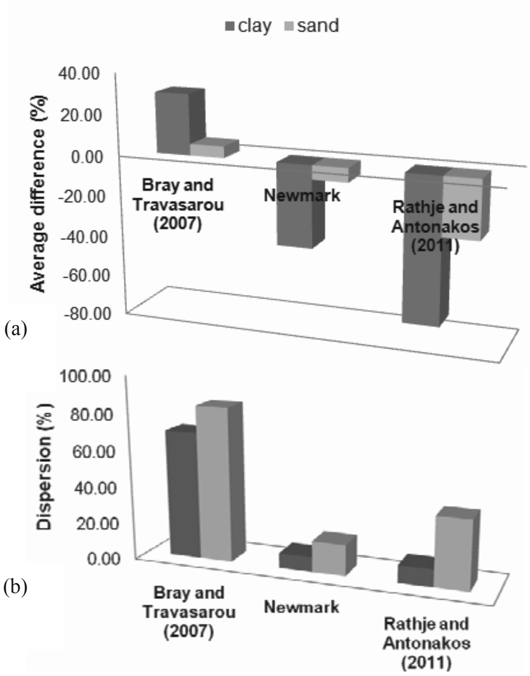

Figure 5. (a) Average difference (%) and (b) dispersion of the predictive models in the median displacement estimation compared to the corresponding numerical displacement considering nearly rigid (sand slope) and flexible (clayey slope) sliding masses

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