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EFFECT OF SOIL PROFILE CHARACTERISTICS ON THE SEISMIC SLIDING DISPLACEMENT OF SLOPES

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Abstract

In earthquake analyses, usually the seismic displacement is estimated by the sliding-block model, where a rigid block rests on an inclined plane and every time that the applied horizontal acceleration is larger than the critical horizontal acceleration value for relative motion, the block slides. This model is used for the prediction of permanent seismic movement of slopes along a predefined slip surface, by appropriately selecting the equivalent critical and applied acceleration values of the rigid block. However, the input seismic motion is usually specified at the underlying bedrock and the seismic displacement along a slip surface depends not only on the resistance along the slip surface, but also on the dynamic characteristics of the soil both above and below the slip surface. Based on the above, the present work investigates and proposes expressions relating the ratio of the seismic displacement of slopes along a slip surface and the corresponding displacement of the sliding-block model for similar applied acceleration and critical acceleration of the slip surface in terms of characteristics of the soil profile both above and below the slip surface. The proposed expressions were obtained based state-of-the-art description of the dynamic response and results of previous dynamic seismic sliding displacement analyses. Parametric analyses using a recently developed numerical code were performed to calibrate and validate the proposed expressions. In these analyses, different acceleration histories measured at rock sites are applied below soil layers with a slip surface with varying critical acceleration value and dynamic properties both above and below the slip surface.

Keywords: slopes, sliding-block model, dynamic response, seismic displacement, slip surface, coupled analyses

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1 INTRODUCTION

The seismic displacement of slopes usually occurs along a slip surface [1]. Engineers usually assess the seismic safety of slopes using the dynamic factor of safety calculated from loads. However, evaluations based on the dynamic factor of safety have the serious drawback that they do not consider the seismic displacement, which is directly related to damage. In earthquake analyses, usually the seismic displacement is estimated by the sliding-block model [2], where a rigid block rests on an inclined plane and every time that the applied horizontal acceleration is larger than the critical horizontal acceleration value for relative motion (ac), the block slides. This model is used for the prediction of permanent seismic movement of slopes and retaining structures along a predefined slip surface, by appropriately selecting the equivalent critical and applied acceleration values of the rigid block [1, 3].

Different empirical expressions have been proposed predicting the seismic displacement of the sliding-block model, in terms, primarily, of the ratio of the maximum acceleration of the applied seismic motion by the critical horizontal acceleration for sliding [3]. In addition, some of these expressions use other than the maximum acceleration parameters of the seismic motion, such as the maximum velocity or the Arias Intensity, or parameters of the earthquake that produced the seismic motion, such as its earthquake magnitude or its earthquake fault distance [4,5]. Furthermore, region-specific empirical expressions have been proposed predicting the seismic displacement of the sliding-block model, as different regions have different earthquake faults and geological profiles conditions, and thus potentially different applied seismic motions characteristics [6].

However, the input seismic motion is usually specified at the underlying bedrock and the seismic displacement along a slip surface depends on both the dynamic characteristics of the sliding mass, and the soil profile below [8]. Based on the above, it is of interest for practicing engineers, to relate the seismic displacement along slip surfaces, not only on characteristics of the applied seismic motion and the critical horizontal acceleration for sliding of the slip surface, but also to the dynamic soil properties both above and below the slip surface. Expressions have been proposed predicting the seismic displacement of slopes in terms of not only characteristics of the applied seismic motion and the critical horizontal acceleration for sliding, but also on the dynamic characteristics of the sliding mass [7]. Furthermore, Katsenis et al [9] proposed empirical expressions relating the ratio of the seismic displacement of slopes along a slip surface and the corresponding displacement of the sliding-block model for similar applied acceleration and critical acceleration of the slip surface considering the dynamic soil profile characteristics both above and below the slip surface. Their relationships are in terms of the soil profile type of the slope according to Eurocode 8 [10] and the depth of the slip surface. Yet, the dynamic response of soil layers is related to its dominant period [7, 8], and Eurocode profile types provide only an approximate prediction of the actual dynamic response.

The present work extends the Katsenis et al. [9] work by proposing an empirical expression predicting the seismic displacement of slopes where the soil profile has any shear velocity value and depth both above and below the slip surface. In order to achieve this goal, below, first a critical literature review of the dynamic effect on the seismic displacement of slopes is presented. Then, based on this critical review, equations simulating the dynamic effect on the seismic displacement of slopes are proposed. Following, a data base of seismic motions measured at rock sites is obtained, mainly recorded in the European-Mediterranean regions and using this data base an evaluation of the model parameters of the proposed equations and an assessment of the accuracy of the model is performed. Finally, the paper discusses further validation and application of the proposed equation.

2 CRITICAL LITERATURE REVIEW OF THE DYNAMIC EFFECT ON THE SEISMIC DISPLACEMENT OF SLOPES

2.1 Eurocode

According to Eurocode 8 (European Standard, 2003), as illustrated in Fig. 1, the dynamic response of elastic systems (S) depends on the critical period of the system (Ts) according to the following equations:

$$Ts<Ta \qquad S(Ts)=1+ A\ Ts/Ta \qquad (1)$$

$$Ta \geq Ts \geq Tb \qquad S(Ts)=1+A$$

$$Ts>Tb \qquad S(Ts)=(1+A)\ (Tb/Ts)^{B}$$

Where the parameters A and B typically equal 0.25 and 2/3 respectively and the parameters Ta and Tb depend on the underlying soil type and for rock sites they equal Ta=0.10s Tb=0.40s.

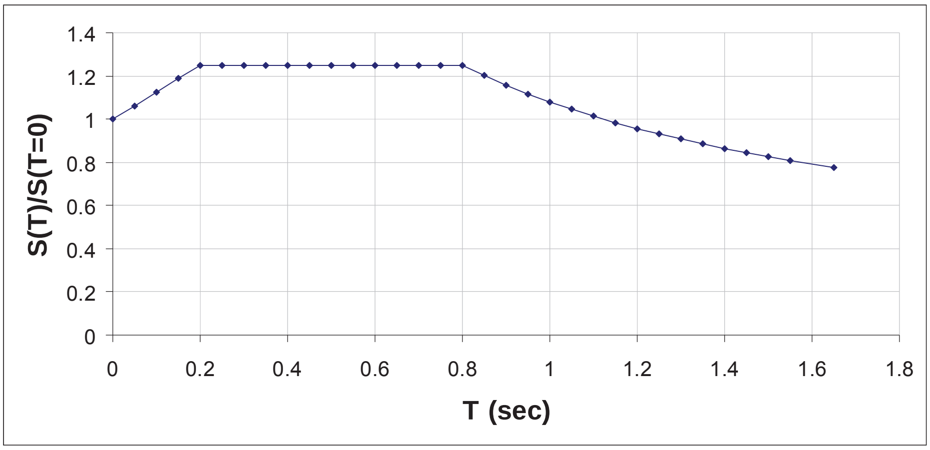

Figure 1: Seismic response in terms of Ts as predicted by Eurocode 8 (European Standard, 2003) for rock sites.

2.2 Work by Rathje and Bray [7] and Bray and Travasarou [13]

The effect of the dynamic response of the sliding mass on the seismic displacement along slip surfaces has been modelled among others by Rathje and Bray [7]. They consider the 1-dimensional geometry of Fig. 2a where a horizontal shear wave propagates vertically above a slip surface with critical acceleration ac at a body with height h and shear wave velocity Vs and identify the critical period of the system, as

$$Ts = 4h / Vs \qquad (2)$$

Fig. 2b presents typical predictions of their model: The variation of sliding displacement with Ts/Tm, where Tm is the mean period of the applied seismic motion, for the Aegion 1995 seismic motion with ac=0.5m/s^2, h= 15m, ρ= =2 Mg/m3 and damping λ=0.15 is presented. In Fig. 2b it can be observed that, similarly to Fig. 1, the effect of dynamic response (a) does not exist for Ts=0, (b) as Ts increases, the dynamic effect increases and it produces maximum response approximately when Ts=Tm and (c) as Ts further increases beyond Tm, it decreases the final seismic displacement along the slip surface (u_f) towards zero.

Consistently, Bray and Travasarou [13] proposed empirical expressions relating the seismic displacement, in addition to the critical acceleration ac and characteristics of the applied seismic motion such as the earthquake magnitude u_f, to Ts.

(a)

(b)

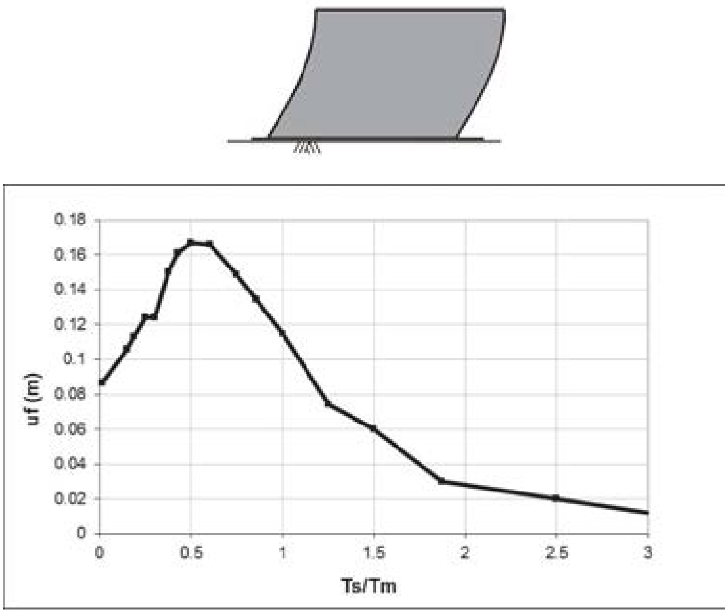

Figure 2: (a) The Rathje and Bray [7] model and (b) typical predictions of the model: Variation of sliding displacement with Ts/Tm for rigid and dynamic analyses. The Aegion 1995 seismic motion with ac=0.5m/s2, h= 15m, ρ= 2 Mg/m^3 and λ=0.15 is presented.

2.3 The Katsenis et al. [9, 11] model

In the analyses described above the effect of the soil profile below the slip surface on the seismic displacement has not been studied. The Katsenis et al [9, 11] model, is a cost-effective model which can study it: As shown in Fig. 3b, it considers the 1-dimensional dynamic response of a horizontal soil profile of depth (h_1+h_2) with a slip element at depth h_1. Different shear wave velocities (V_{s-1}, V_{s-2}), densities (ρ_1, ρ_2) and damping (λ_1, λ_2) may exist above and below the slip element. The slip element simulates the seismic displacement of the conventional sliding-block model, where its resistance is defined by the critical horizontal value (a_c), for which relative movement in only one direction occurs. The two bodies move a horizontal distance x_i, velocity x'_i and acceleration x''_i, where i takes the values 1 and 2 for bodies 1 and 2 respectively. The corresponding field configuration is that of a slope with a slip surface where seismic displacement may accumulate as a result of a horizontal shear wave, illustrated in Fig. 3a

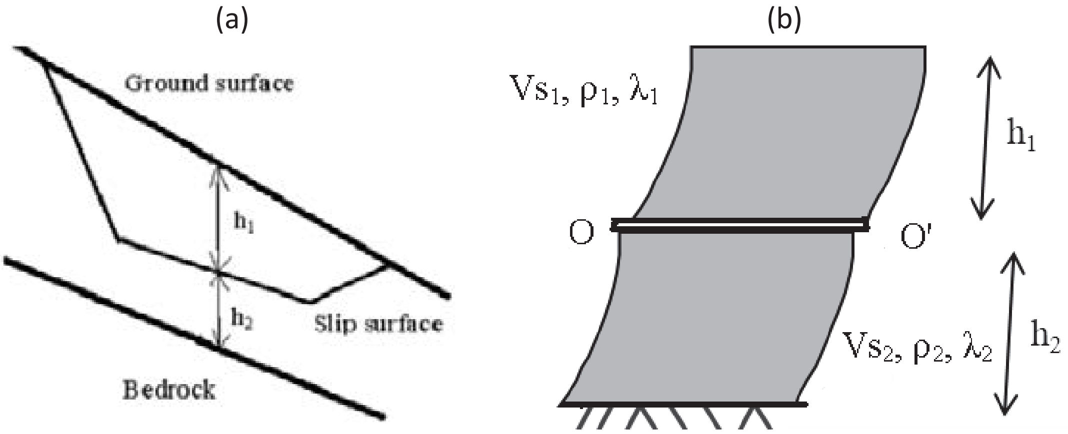

Figure 3: The Katsenis et al, (2020) model: (a) field configuration of a slope with a slip surface where seismic displacement may accumulate as a result of a horizontal shear wave, (b) simulation of (a) with a 1-D dynamic system of 2 continuous bodies separated by a horizontal slip element. In the dynamic system (b) slippage may occur along AA'.

2.4 Results of the Katsenis et al. [11] model

Katsenis et al. [11] define

$$Ts1=4\ h_1/V_{s-1} \quad (3a)$$

$$Ts\text{-}ave = 4\ (h_1/V_{s-1}+ h_2/V_{s-2}) \quad (3b)$$

and Fig. 4 presents a typical computed permanent seismic displacement (u_f) response of their model. In particular, the computed displacement (u_f) for the Aegion 1995 seismic motion with ac=0.5m/s2, h_1+h_2=30m, $\rho_1=\rho_2$=2 Mg/m3 and $\lambda_1=\lambda_2$=0.15 (a) versus Ts1/Tm for $V_{s-2}=V_{s-1}$, h_2=1m, 15m, 25m, (b) versus Ts1/Tm for h_2=15m and (c) versus Ts-ave/Tm for the cases (a) and (b) is presented.

It can be observed that the effect of the soil profile both above and below the slip surface on the seismic displacement is considerable and that if u_f is plotted in terms of the ratio Ts-ave/Tm, the scatter in results for different V_{s-2} and h_2 values decreases considerably. It is inferred that the dynamic effect on u_f can partly be interpreted by relating u_f to Ts-ave. In particular, similarly to the response of Figs. 1 and 2, but replacing Ts with Ts-ave, it can be observed that the dynamic response (a) does not exist for Ts-ave=0, (b) as Ts-ave increases, the dynamic effect increases and it produces maximum response approximately when Ts-ave=Tm and (c) as Ts-ave further increases beyond Tm, it decreases the final seismic displacement along the slip surface (u_f) towards zero.

Furthermore, Katsenis et al. [11] illustrate that the dynamic response play an important role for small seismic displacement, but a smaller role for large seismic displacement (>0.5 m). Typical results are given in Fig. 5, where the ratio of the rigid and dynamic u_f value tends to zero as ac decreases. Indeed, as identified by previous researchers also [14], large seismic displacement corresponds to low critical acceleration value, which limits the seismic actions transmitted across the slip surface, and thus the dynamic effect.

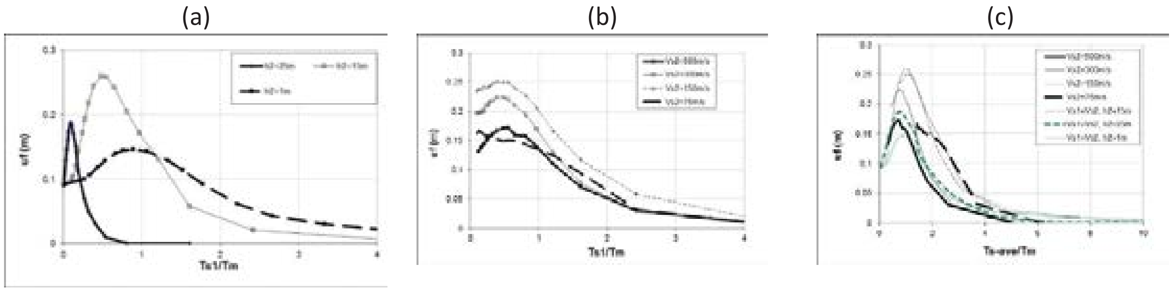

Figure 4: The computed permanent seismic displacement (u_f) for the Aegion 1995 seismic motion with a_c=0.5m/s2, h_1+h_2=30m, $\rho_1=\rho_2$=2 Mg/m3 and $\lambda_1=\lambda_2$=0.15 (a) versus Ts1/Tm for $V_{s-2}=V_{s-1}$, h_2=1m, 15m, 25m, (b) versus Ts1/Tm for h_2=15m and V_{s-2}=75, 150, 300, 500m/s and (c) versus Ts-ave/Tm for the cases (a) and (b) [11].

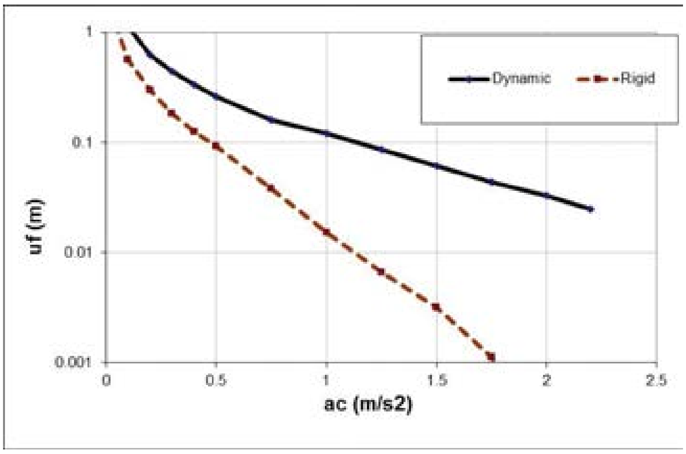

Figure 5: Computed permanent seismic displacement (u_f) by [11] for the elastic and rigid analyses in terms of of a_c for the Aegion 1995 seismic motion, $h_1=h_2$=15m, $V_{s-1}=V_{s-2}$= 200m/s, ρ1=ρ2=2Mg/m3, $\lambda_1=\lambda_2$=0.15.

2.5 Previous empirical equation

Different empirical expressions have been proposed predicting the seismic displacement of the conventional sliding-block model (u_{f-bl}) in terms of a_c and characteristics of the seismic motion such as a_{max}, Arias intensity, earthquake magnitude etc. [2-6]. In addition, some of these expressions are region-specific [7]. Katsenis et al. [9] in order, to separate the dynamic effect from the seismic displacement accumulating along the slip surface for rigid blocks, propose to relate u_f on the conventional sliding-block model ($u_{f\text{-}bl}$) seismic displacement for the same applied seismic motion and critical acceleration value, as

$$u_f = R\, u_{f\text{-}bl} \tag{4}$$

where the factor R simulates the dynamic effect and depends on various factors such as $u_{f\text{-}bl}$,the soil profile type and the depth of the slip surface.

3 PROPOSED EQUATION PREDICTING THE DYNAMIC EFFECT ON THE SEISMIC DISPLACEMENT OF SLOPES

The problem considered is that of Fig. 3a where a seismic horizontal motion is applied at the bedrock underlying a soil profile where a potential slip surface exists at some depth, which is simulated with the system of Fig. 3b.

In order, to separate the dynamic effect from the seismic displacement accumulating along the slip surface for the same seismic motion, which has been predicted by previously proposed empirical equations, similarly to [9], we relate u_f on the conventional sliding-block model seismic displacement for the same applied seismic motion and critical acceleration value ($u_{f\text{-}bl}$). More specifically, we propose the following equation to predict u_f:

$$u_f = u_{f\text{-}bl}\, Kdyn \tag{5a}$$

At this point it should be noted that $u_{f\text{-}bl}$ equals to u_f in the case of a very stiff or of a very shallow soil profile, where Ts-ave tends to 0.

As described above, (i) the dynamic response can be simulated in terms of the critical period by an equation of the form of equation (1), (ii) the dynamic response of the problem considered depends on the value of Ts-ave, given by equation (3b), (iii) the response of Figs. 4 illustrate that the dynamic response (a) does not exist for Ts-ave=0, (b) as Ts-ave increases, the dynamic effect increases and it produces maximum response approximately when Ts-ave=Tm and (c) as Ts-ave further increases beyond Tm, it decreases the final seismic displacement along the slip surface (u_f) towards zero and (iv) the dynamic effect is affected by the magnitude of the sliding seismic displacement. Thus, we apply equation (1) by assuming that Ta=Tb and replacing and Ts with Ts-ave and we obtain

$$Ts-ave \ \le\ Ta \qquad \text{Kdyn(Ts-ave)=1+ A Ts-ave/Ta} \tag{5b}$$

$$Ts-ave\ >\ Ta \qquad \text{Kdyn(Ts-ave)=1+(1+A) (Ta /T-ave)}^{B}$$

where Ta is the Ts-ave value where Kdyn is maximum and the parameters A, B determine the peak value and the post-peak rate of decrease of the dynamic effect, as illustrated in Fig. 6. Section 2.4 above, described that the dynamic effect diminishes as the seismic displacement increases, or, equivalently, as the critical acceleration value for relative motion increases. Indeed, at the time intervals where seismic displacement accumulates, the body above the slip surface is separated from and moves independently from the body below the slip surface, and thus the relationship between the dynamic effect and the factor Ts-ave ceases to exist.

We define as (Rt) the ratio of the sum of times where the seismic displacement accumulates (ts) by the total duration time of the applied seismic motion:

$$Rt = ts /tt \tag{6a}$$

Based on the discussion above, it is inferred that as (Rt) increases towards 1, the dynamic effect diminishes. Thus, as Rt increases, the factors A and B of equation (5b) decrease, and in particular for large values of Rt, A and B tend to zero.

Yet, the factors tt, ts are not usually used or specified on earthquake engineering. On the other hand, the intensity of a seismic motion is best defined by the Arias Intensity measure (Ia) [5, 6] and the corresponding magnitude of the relative slip which occurs can be identified by $u_{f\text{-}bl}$. Thus, we approximate the factor Rt of equation (6a) with the factor R't defined by commonly used and well defined parameters Ia and $u_{f\text{-}bl}$ as

$$R't=(u_{f\text{-}bl}/ Ia) \tag{6b}$$

As R't increases, the factors A and B of equation (5b) decrease towards zero and thus we can write

$$A= a1\ (Ia/ u_{f\text{-}bl})^{a2} \tag{5c}$$

$$B= b1\ (Ia/ u_{f\text{-}bl})^{b2} \tag{5d}$$

where a1, a2, b1, b2 are model parameters.

It can be noted that equations (5b) and (5d) predict that, similarly to the response described in section 2.4, (a) A and B decrease, and the dynamic response decreases, as Ar decreases and u_f increases and (b) A and B tend to zero and the dynamic response diminishes as Ar tends to zero and as u_f becomes very large.

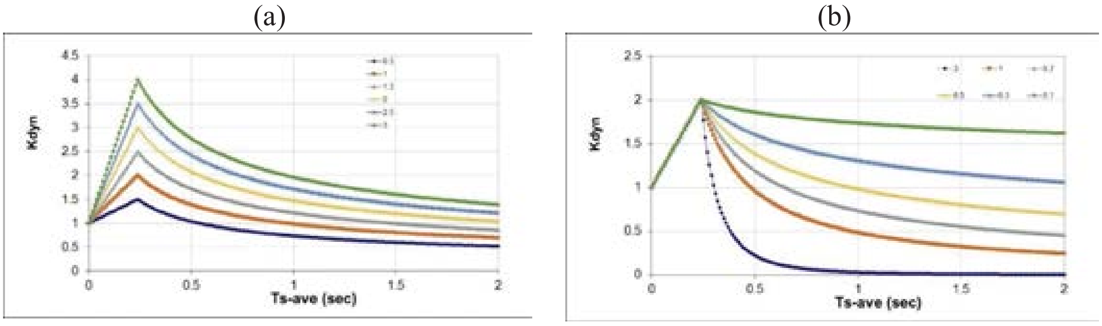

Figure 6: The function Kdyn in terms of (a) A and (b) B. In (a) B=0.5 and in (b) A=1.

4 DATA BASE AND PARAMETRIC ANALYSES

A data base of seismic motions was obtained using the ESM site (the Engineering Strong-Motion Database), which contains waveforms with magnitude ≥ 4.0, mainly recorded in the European-Mediterranean regions and the Middle-East and provides a set of facilities to search, select, download and analyze ground-motion data. It is obtained by selecting the Northern and Eastern components of seismic motions with the following restrictions: Soil type according to EC8 : A (Rock), max(PGA) >100 cm^2/s, M >5. The reason of the selection described above is that (a) the Katsenis et al. [9, 11] model input motions must correspond to seismic motions at rock sites without the amplification and modification phenomena that seismic motions exhibit as they pass thru soil layers and (b) seismic motions with max(PGA) <100 cm^2/s and M<5 typically do not cause intolerable seismic displacement along slip surfaces.

The data base included 56 cases, sorted in descending PGA order, given in Appendix A. For the present application four seismic motions were selected. In particular, as the seismic displacement greatly depends on PGA, the seismic motions were selected staring from the first and taking the next after passing 12. In this way, the seismic motions No1, 13, 25, 37 were selected, having a variety of PGA values, ranging from large to small PGA. Table 1 gives the main characteristics of these applied seismic motions.

Coupled linear dynamic parametric analyses were performed using the Katsenis et al. [9, 11] model, and more specifically the corresponding numerical code DIAS [11]. All the seismic motions described above were applied at the base of soil column with $h_l=h_2=15m$. The shear wave velocities of the two bodies considered are given in table 2. In each seismic motion, at the slip surface three a_c values were assumed, selected in such a way that $u_{f\text{-}bl}$ equals 0.01, 0.1, 1m, which cover the range of typical values of typical field problems of instability interest. In addition ,$\lambda_1=\lambda_2=0.05$, $\rho_1=\rho_2=2t/m^3$ were assumed.

No	Region	Date	ML	Epicentral Distance	PGA (cm/s^2)	Ia (cm/s)	Tcr (s)
1	Turkey, Düzce	11/12/1999	6.6	27.4	-1010	1331.53	0.25
2	Montenegro	15/04/1979	6.8	62.9	211	73.32	0.25
3	Turkey, Düzce	12/11/1999	6.6	30.3	-157	44.30	0.25
4	Italy, Umbria	30/10/2016	6.1	46.6	121	19.68	0.13

Table 1: The main characteristics of the applied seismic motions.

$V_{s\text{-}1}$ (m/s)	50	100	130	180	270	370	470	580	700	1000	2000
$V_{s\text{-}2}$ (m/s)	75	1500	300	500	750	5000					

Table 2: Shear wave velocities applied in the parametric analyses

5 EVALUATION OF MODEL PARAMETERS

Fig. 7 gives the obtained results of the parametric analyses: The ratio $u_f/u_{f\text{-}bl}$ in terms of Ts-ave in terms of applied seismic motion and $u_{f\text{-}bl}$ is given for all seismic motions. Similarly to the theory described above, it can be observed that plotting the results for each case of seismic motion and $u_{f\text{-}bl}$ values in terms of Tave has small scatter and this is true especially for small

$u_{f\text{-}bl}$ values. It is also worth noting that in the results presented in Fig. 7, $u_f/u_{f\text{-}bl}$ was plotted in terms of Ts1 instead of Ts-ave also, and it was observed that the scatter was much larger.

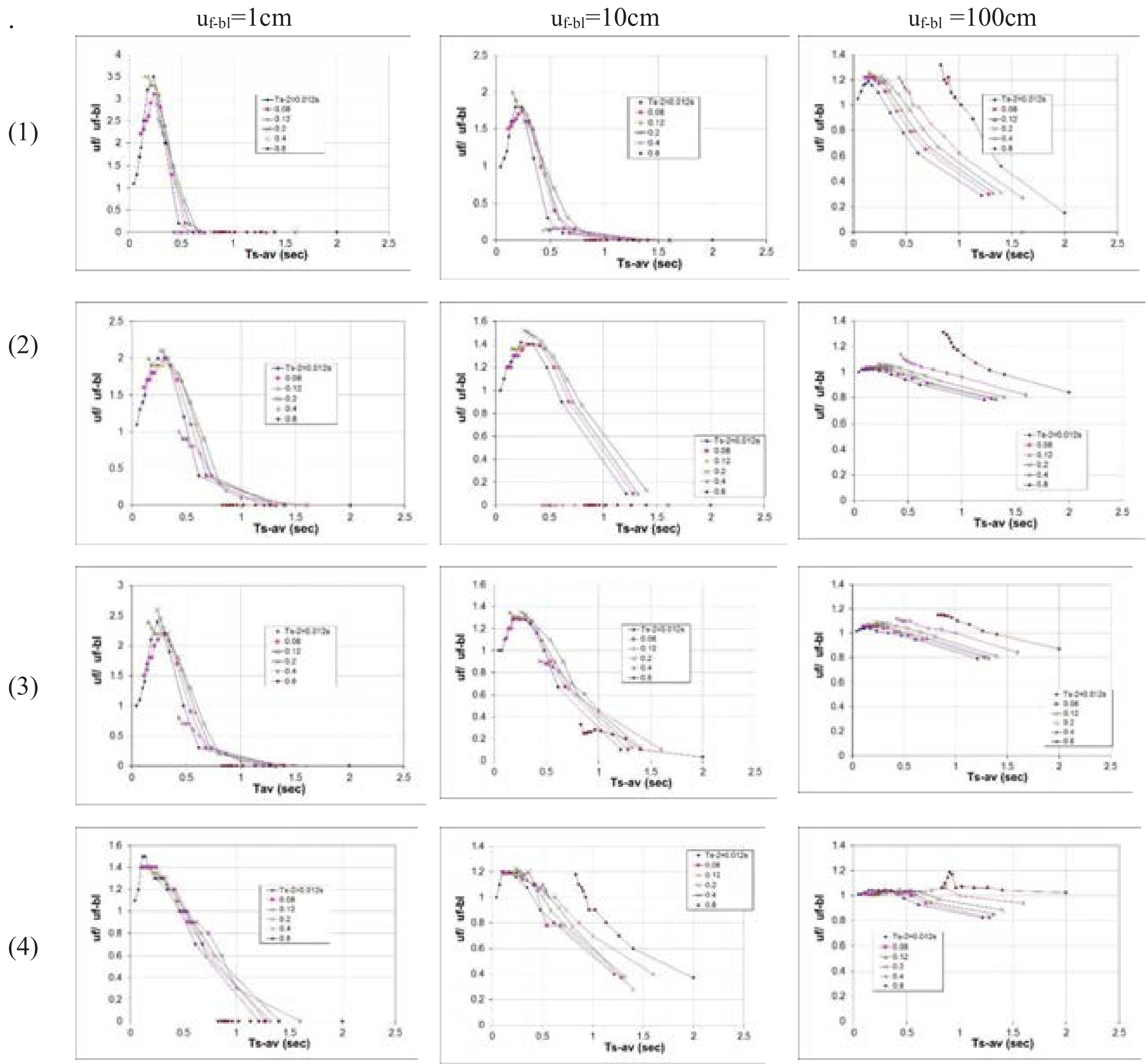

Figure 7: The function Kdyn for the seismic motions (1)-(4) in terms of $u_{f\text{-}bl}$.

For each case of seismic motion and $u_{f\text{-}bl}$ value, the model parameters simulating the dynamic response according to equation (5) were obtained. In all cases, the seismic response was simulated well when

$$Ta=0.3s \tag{5.e}$$

It can be noted that this value is consistent with section 2.1 statement that in rock sites Tm does not exceed 0.4s. With Ta=0.3s, table 3 gives the obtained factors A and B. Fig. 8 presents the parameters of table 3: The factors A and B in terms of (a) ($1/u_{f\text{-}bl}$), (b) Ia, (c) ($Ia/u_{f\text{-}bl}$) are given.

Strong correlations are observed in all cases and as illustrated in Fig 8c, the best-fit correlations of the relations (5c) and (5d), according to equation (5b), occur when,

a1=0.17, a2=0.39 (5.f)

b1=0.20, b2=0.35 (5.g)

As illustrated in Fig. 8c, the coefficient of determination is larger than 0.85 in all cases and as the coefficient of determination is close to unity, it is inferred that the proposed equation describes well the computed response

(a) Factor A

Ia (cm/s):	$u_{f\text{-}bl}$*(cm): 1331.5*	*73.3*	*44.3*	*19.7*
1	2.5	1.2	1.2	0.5
10	1.2	0.4	0.3	0.2
100	0.2	0.2	0.1	0.1

(b) Factor B

Ia (cm/s):	$u_{f\text{-}bl}$*(cm): 1331.5*	*73.3*	*44.3*	*19.7*
1	1.8	0.8	0.8	0.7
10	1	0.55	0.55	0.43
100	0.55	0.1	0.1	0.1

Table 3: The model parameters A and B simulating the dynamic response according to equations (5) , for each case of the $u_{f\text{-}bl}$ (cm) and Ia(cm/s) of the seismic motion

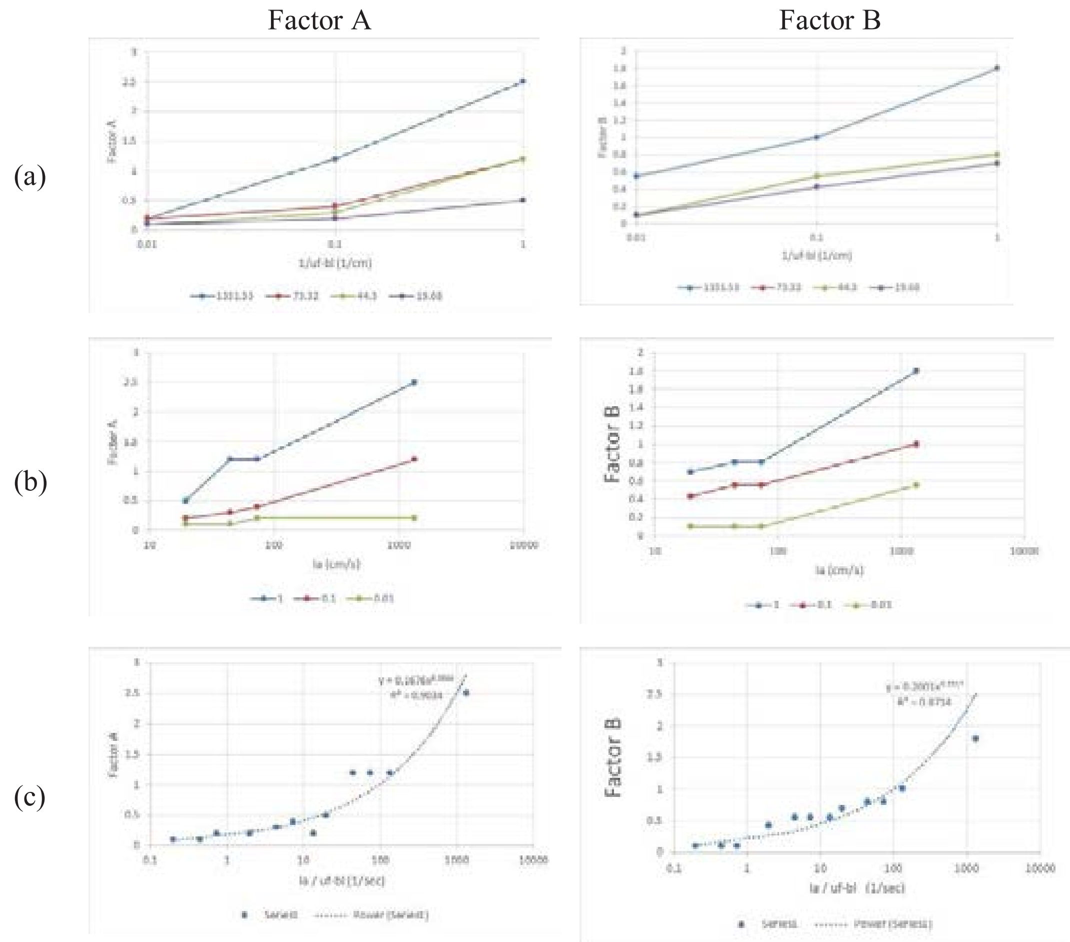

Figure 8: Analysis of the results of the table 3: The factors A and B in terms of (a)1/ $u_{f\text{-}bl}$, (b) Ia, (c) Ia/ $u_{f\text{-}bl}$.

6 DISCUSSION

6.1 Validation and Application

Partial validation of the proposed equation (5) is the fact that the coefficient of determination (R^2) of the fitting parameters a1, a2 and b1, b2 of the proposed equation is near unity and certainly larger than 0.8. However, it is desirable to perform additional analyses to validate equation (5), especially as only four seismic motions were used to derive it. For this purpose, more parametric analysis to validate the proposed equation and analyze its error may be performed by applying all the seismic motions of table A1, as well as different soil profiles.

*Furthermore, b*ecause deterministic methods obtaining empirical expressions predicting the seismic displacement of slopes do not rationally take into account the uncertainty of these expressions, researchers have recently turned to the probabilistic approach: (a) Creating probability curves of an annual exceedance of a specific value [15], or (b) fragility curves which give the possibility of exceeding a certain seismic displacement value in the design time depending on the properties of the seismic excitation and of the slope [16]. Thus, it is desirable to extend and modify as necessary the proposed equation (5) by applying probabilistic methods.

6.2 Effect of non-linearity

Soil behaves linearly only at very small shear strains, well below the typical shear strains exerted in soil profiles near severe earthquakes [11]. It is inferred that for accurate predictions, the linear methods described above must be extended with constitutive equations simulating the non-linear soil response. Under dry conditions the degradation of the shear modulus with shear strain must be simulated. The Katsenis et al [11] model simulates this degradation in terms of the Plasticity Index of the Soil (PI), as proposed by the state-of-the-art model of Vucevic and Dobry [17], shown in Fig. 9a. Typical results of numerical simulations illustrating the profound effect of soil non-linearities on the seismic response are given in Fig. 9b. The case of the Aegion 1995 seismic motion with ac=0.5m/s2, $V_{s-2}=V_{s-1}$, $h_1=h_2=15$m, $\rho_1=\rho_2=2$Mg/m3, $\lambda_1=\lambda_2=0.15$, $PI_1=PI_2=0$ is considered.

Katsenis et al. [11] observed that the effect of soil non-linearities can be simulated in linear analyses by reducing the shear wave velocity to the average value one during the non-linear dynamic simulation. Thus, it is inferred that equation (5) may potentially be extended to predict the non-linear soil response by proposing methods which adequately reduce the V_{s-1} and V_{s-2} values in terms of the intensity of the applied seismic motion and the soil stiffness.

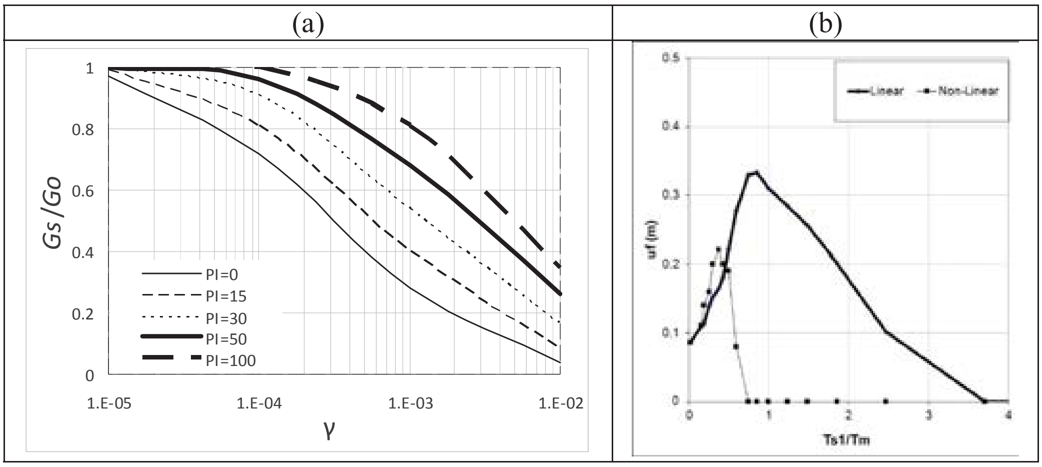

Figure 9: (a) Shear modulus degradation versus shear strain in terms of PI, as proposed by Vucevic and Dobry [17], (b) The computed displacement (u_f) by Katsenis et al. [11] for the linear and nonlinear dynamic analyses versus Ts1/Tm for a specific case, described in the text.

7 CONCLUSIONS

- Expressions have been proposed predicting the seismic displacement of slopes in terms of characteristics of the applied seismic motion and the critical horizontal acceleration for sliding and only the dynamic characteristics of the sliding mass [7]. Only Katsenis et al. [9] proposed empirical expressions in terms of the soil profile both above and below the slip surface. Yet, their expressions are in terms of the soil profile type of the slope according to Eurocode 8 and not related to the dominant profile period.
- The present work proposes equation (5) simulating the effect of the dynamic response on the seismic displacement of slopes in terms of the dominant period of the soil profile both above and below the slip surface.
- This equation is based on state-of-the-art descriptions of the dynamic response, results of previous dynamic seismic sliding displacement analyses and numerical predictions of the model of Fig. 3b.
- It is desirable to perform more parametric analysis to validate the proposed equation and analyze its error.
- The proposed equation may be extended to predict the non-linear soil response.

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Appendix

Table A1. Seismic motions collected and their magnitude and distance.

No	Name	Date	M (Mw)	Epic. Distance (km)
1	Turkey, Düzce	12/11/1999	6.6	27.4
2	Turkey, Düzce	12/11/1999	6.6	27.2
3	Italy, Umbria	30/10/2016	6.1	12
4	Italy, Abruzzo	07/04/2009	5.4	3.6
5	Italy, Umbria	30/10/2016	6.1	18.6
6	Turkey , Kocaeli	13/09/1999	5.8	13.8
7	Turkey, Düzce	12/11/1999	6.6	25.9
8	Greece, Ioannina	15/10/2016	5.6	55.9
9	Greece, Ioannina	16/10/2016	4.8	53.3
10	Italy, Umbria	10/30/2016	6.1	10.5
11	Turkey, Düzce	12/11/1999	6.6	32.3
12	Montenegro	15/04/1979	6.8	62.9
13	Italy, Lazio	24/08/2016	6	32.9
14	Italy, Marche	26/10/2016	5.4	11.5
15	Turkey, Kocaeli	17/08/1999	7.25	3.4
16	Italy, Marche	26/10/2016	5.4	16.7
17	Montenegro	15/04/1979	6.8	19.7
18	Italy, Marche	26/10/2016	5.4	15.2
19	Italy, Umbria	06/10/1997	5.4	20.8
20	Italy, Umbria	09/26/1997	5.8	21.6
21	Italy, Calabria	25/10/2012	5	2.4
22	Italy, Umbria	14/10/1997	5.5	8.7
23	Italy, Calabria	09/09/1998	5.5	18
24	Italy, Abruzzo	18/01/2017	5.4	19.2
25	Turkey, Düzce	12/11/1999	6.6	30.3
26	Italy, Umbria	26/09/1997	5.6	24.2
27	Turkey, Düzce	12/11/1999	6.6	27.4
28	Bosnia and Herzegovina	1990-04-03	4.8	22
29	Italy, Abruzzo	18/01/2017	5.1	37.9
30	Italy, Abruzzo	07/04/2009	5.4	15.6
31	Italy, Umbria	30/10/2016	6.1	26
32	Italy, Campania	29/12/2013	5	8.5
33	Turkey, Düzce	12/11/1999	6.6	34.7
34	Greece, Ioannina	16/10/2016	4.5	62.4
35	Italy, Marche	26/10/2016	5.9	31.6
36	Italy, Calabria	25/10/2012	5	10.7
37	Italy, Umbria	30/10/2016	6.1	46.6
38	Croatia, zupanija	27/11/1990	5.6	56.9
39	Greece, Athens	07/09/1999	5.8	19.7
40	Italy, Marche	26/10/2016	5.4	22.8
41	Italy, Marche	26/10/2016	5.9	17.4
42	Greece, Peloponeze	13/10/1997	5.8	51.4
43	Italy, Abruzzo	18/01/2017	5.4	31.4
44	Italy, Calabria	25/10/2012	5	9.4
45	Greece, Rodos	24/01/2019	5.2	86.3
46	Italy, Umbria	07/05/1984	5.9	10.1
47	Italy, Abruzzo	18/01/2017	5.4	20.7
48	Turkey, Düzce	12/11/1999	6.6	15.6
49	Italy, Catania	13/12/1990	5.6	36.9
50	Italy, Abruzzo	18/01/2017	5.3	34.5
51	Italy, Marche	26/10/2016	5.9	60.2
52	Italy, Abruzzo	18/01/2017	5.4	17

Table A2. Characteristics of the seismic motions of table A1.

	PGA (cm/s^2)		Ia (cm/s)		Tcr (s)	
No	E	N	E	N	E	N
1	-743	-1010	649.35	1331.53	0.26	0.25
2	489	-888	198.95	979.16	0.32	0.4
3	779	-850	555.65	608.67	0.17	0.15
4	652	304	89.77	49.83	0.19	0.2
5	426	385	201.09	192.23	0.25	0.16
6	317	-74	30.49	3.76	0.23	0.22
7	277	298	156.33	185.24	0.37	0.2
8	287	241	64.36	84.47	0.36	0.32
9	284	194	23.12	22.85	0.3	0.34
10	274	273	80.30	70.73	0.65	0.22
11	-254	116	100.62	19.58	0.28	0.32
12	-249	211	45.88	73.32	0.29	0.25
13	242	186	30.33	12.33	0.4	0.12
14	-194	239	23.44	19.74	0.13	0.16
15	229	164	97.78	73.72	0.29	0.28
16	-218	-130	31.84	17.65	0.12	0.12
17	210	173	72.89	61.59	0.7	0.17
18	177	-192	9.88	8.89	0.26	0.13
19	-101	-184	6.57	13.84	0.28	0.22
20	184	164	23.49	27.93	0.32	0.19
21	182	-130	10.69	8.99	0.19	0.28
22	94	-176	5.07	11.43	0.24	0.24
23	-152	-162	10.26	15.68	0.11	0.5
24	82	-161	3.45	9.71	0.13	0.28
25	121	-157	41.07	44.30	0.36	0.25
26	111	152	5.79	11.30	0.25	0.22
27	-133	-148	27.54	37.35	0.19	0.24
28	109	-139	8.00	12.37	0.05	0.08
29	-83	-138	2.47	4.92	0.06	0.1
30	88	131	2.47	4.58	0.1	0.32
31	-131	114	16.15	11.65	0.2	0.22
32	130	-77	9.45	8.56	0.12	0.1
33	-129	98	24.36	22.52	0.32	0.32
34	127	-114	6.37	9.41	0.2	0.3
35	-117	-125	7.22	9.25	0.08	0.13
36	-117	-124	5.38	5.63	0.12	0.19
37	-90	121	9.33	19.68	0.09	0.13
38	-121	121	19.87	18.62	0.35	0.16
39	-119	-108	9.48	6.54	0.1	0.25
40	-119	100	5.88	5.80	0.2	0.2
41	-119	-84	8.59	8.63	0.16	0.2
42	-116	117	28.17	19.12	0.3	0.22
43	109	-116	7.90	10.43	0.1	0.1
44	96	-114	3.20	3.45	0.09	0.1
45	43	112	3.34	11.19	0.35	0.4
46	110	98	5.29	6.23	0.25	0.11
47	95	108	5.97	8.78	0.12	0.29
48	106	74	11.02	6.42	0.1	0.26
49	105	61	5.53	4.71	0.08	0.22
50	-68	103	3.83	6.41	0.1	0.1
51	71	103	4.49	4.29	0.19	0.1
52	-76	-102	3.46	5.78	0.17	0.17