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DOUBLE SLIDING PHENOMENA AND SEISMIC RESPONSE OF EARTH STRUCTURES

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ABSTRACT

Strong earthquake excitation usually induces large shear strains to earth structures resulting to the generation of low shear-strength surfaces, and subsequently, to sliding along these surfaces. The generation of permanent deformations is a phenomenon commonly examined through the well-known procedure of sliding block proposed by Newmark. Nevertheless, many types of earth structures include pre-existing potentially-sliding surfaces, like base liners on waste landfills or geosynthetic layers on soil embankments. These structures when subjected to dynamic loading may develop two sliding surfaces, a phenomenon that can be referred as double sliding. Finally, in some cases sliding phenomena are even desired in the seismic design, as they are considered to act like isolators that could alter the induced acceleration levels, protecting thus the earth structure. In the current study, a series of finite-element analyses of a typical landfill/embankment is conducted. Initially, the effect of base sliding on the dynamic response is evaluated, and since that response is proven to be considerable, a simple analytical model (based on the principles of the sliding block approach) is developed. The characteristics of double sliding are investigated and the main aspects related to this phenomenon are determined. Parameters such as the properties of interface, the angle of sliding plane, and the mass of sliding blocks are examined. The effect of the aforementioned parameters on the permanent deformations is evaluated. The results of this investigation present a clear indication of the complicated role of double sliding on the response of earth structures, and consequently, the necessity of incorporating properly this phenomenon on the seismic design of such structures.

Keywords: sliding block, double sliding, geo-structures, dynamic response, permanent deformations.

INTRODUCTION

The seismic stability of geo-structures like earth dams, soil embankments, and waste landfills is commonly assessed by estimating the developed permanent deformations along well-defined surfaces of low-shear strength. The simplified procedure proposed by Newmark (1965), known as *sliding block model*, is widely utilized for the calculation of the seismic developed displacements. The method simulates the seismic developed deformations along a slip surface of a geo-structure with the sliding of a block resting on an inclined plane, subjected to horizontal seismic excitation. Furthermore, permanent displacements are developed when the inertia forces of the block exceed the shear resistance of the interface, and they are calculated through double integration of the relative acceleration. The major assumptions associated with the method are: a) the sliding block is rigid, b) sliding resistance is rigid-plastic, and c) uphill resistance is infinitely large. Several researchers have

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used the sliding block model, to investigate the validity of these basic assumptions and their relevant effect to the calculated seismic displacements.

Since earth structures are flexible structures characterized by relatively high eigenperiods, the most basic of the aforementioned assumptions is expected to be the rigidity of the sliding mass. Makdisi and Seed (1978) proposed a procedure, which consists of two steps: a) determination of the dynamic response of the earth structure in terms of equivalent acceleration time-history of the sliding mass, and b) the displacements are calculated utilizing the sliding block method. This procedure ignores the effect of sliding on the response of the sliding mass, thus the limitations included in this decoupling assumption were further investigated by various researchers. Lin and Whitman (1983), utilizing three lumped-mass systems, conducted permanent-displacement analyses, and concluded that the decoupled assumption provides conservative estimates of permanent displacements. Furthermore, Westermo and Udwadia (1983) proposed a simple model and examined the interaction between the response of a single-degree-of-freedom (SDOF) system and the sliding displacement at its base, for harmonic excitations. Kramer and Smith (1997), using the same model, provided an experimental verification, and they additionally estimated the discrepancy between the coupled and the decoupled procedure. Bray and Rathje (1999) considered that the aforementioned model was not appropriate to capture the soil response sufficiently. Therefore the model proposed by Chopra and Zhang (1991), a generalized SDOF system with mass and elasticity distributed along its height, was modified to represent the response of a one-dimensional soil layer. A nonlinear lumped mass model was developed by Bray and Rathje (2000) to overcome the limitation of the linear dynamic behavior of the soil mass. In general the results of the aforementioned studies agree that the decoupled procedure may be over-conservative in the case that the ratio between the structure's eigenperiod and the excitation's period (T_{str}/T_m) is less than one, while for greater values of this ratio the decoupled procedure may be either conservative or not.

Though the level of the developed accelerations was not the main concern of any of these studies, some important issues have also been described. Westermo and Udwadia (1983) concluded that the response of a SDOF sliding system may not always be less than the corresponding non-sliding system. According to Rathje and Bray (2000) the acceleration above the sliding plane is not limited to the value of yield acceleration, but on the other hand, the slip event may reduce the acceleration levels. Furthermore, the increase of the developed displacements results to a decrease of the acceleration level. Concerning the frequency characteristics of the sliding structure, they proposed that the system has a modified frequency which is double than the corresponding frequency of the non-sliding system.

The current study initially provides an insight into the response characteristics of a specific geo-structure (that may represent either an embankment or a landfill) with a predefined slip surface at its base, such as a geosynthetic interface. For this purpose two-dimensional finite-element models were developed, and coupled dynamic analyses were conducted. The effect of parameters (like the material properties of the soil or the waste, and the characteristics of the excitation) on the response of the sliding structure was examined. The potential of large shear strains developing within the soil or waste mass (due to high levels of acceleration) would result to the generation of a second slip surface, a phenomenon, which will be referred from now on as double sliding. Finally, in order to examine the characteristics of double sliding, a simple model based on Newmark's sliding-block concept was developed, and the influence of the basic parameters (interface properties, angle of sliding plane and mass of sliding blocks) were examined.

NUMERICAL ANALYSES

As mentioned before firstly, the dynamic response of an earth structure with a sliding surface at its base is examined numerically. The earth structure may be either an embankment or an above-ground landfill, while the sliding surface at its base may be a geosynthetic base liner. A typical cross-section of the structure is shown in Figure 1. Two-dimensional coupled finite-element analyses were performed utilizing the finite-element code ABAQUS (2003), which is capable of simulating the contact-related phenomena of deformable surfaces. The geosynthetic interface was modeled as a contact characterized by standard Coulomb-type friction. It was assumed that the shear strength of the interface exhibits a rigid-plastic behavior, elastic slip does not take place during the stick phase, and additionally the interpenetration of the two surfaces was not allowed. The model was discretized using triangular plane-strain finite elements, the size of which was tailored to the wavelength of interest, resulting to a finer mesh from rock to soil/waste. The soil/waste material was considered linear viscoelastic with damping 5%. The dynamic properties of the material were selected to cover a sufficient range of shear-wave velocity. The dynamic analyses were conducted for three shear-wave velocity values, namely 160m/sec (Type A), 250 (Type B), and 400m/sec (Type C). The interface properties were selected to be consistent with the reported dynamic friction properties of geosynthetic interfaces. De and Zimmie (1998) performing cyclic direct-shear tests and shaking-table tests, estimated a range of 10-24 degrees for the dynamic friction angle of eight different geosynthetic interfaces. In order to ensure that sliding will certainly take place, the dynamic friction of the model's interface was selected to be characterized by an angle of friction equal to 11 degrees (friction coefficient 0.2). Two excitations were used: a Ricker pulse with central frequency equal to 2Hz, and the Shin-Kobe record of 1995 Hyogoken-Nanbu (Kobe) earthquake (Figure 2). Both excitations were scaled to peak ground acceleration (PGA) equal to 0.36g. The mean period T_m of an excitation can be estimated following Rathje et al. (1998). T_m is equal to 0.34sec for the Ricker pulse and 0.66sec for the Shin-Kobe record.

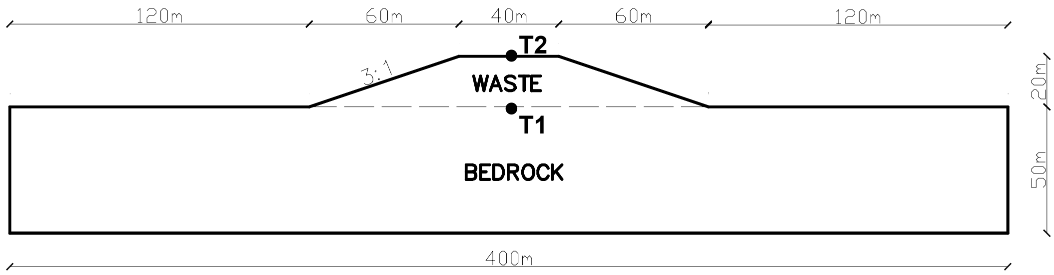

Figure 1. Geometry of the model examined. Note that the geosynthetic interface is shown with dashed line, while T1 and T2 are the points of interest

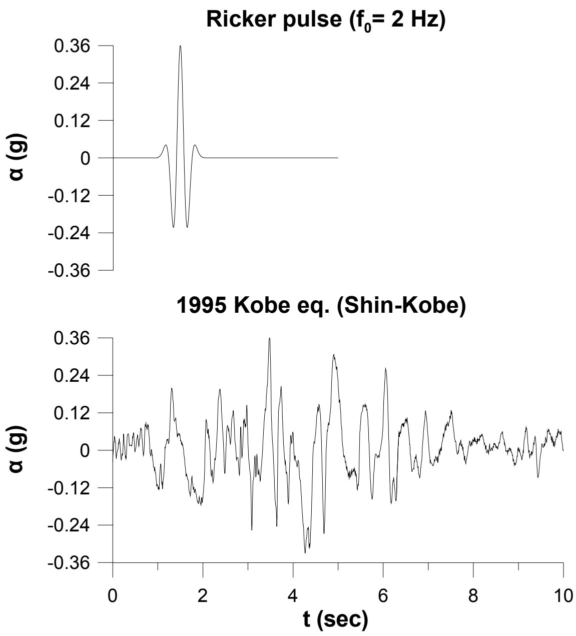

Figure 2. Acceleration time–histories of the excitations used in the analyses; all scaled to PGA equal to 0.36g

Equivalent-linear finite-element analyses of the aforementioned examined cases were conducted utilizing the code QUAD4M (Hudson et al., 1994). Material nonlinearity was taken into account by an iterative procedure, in which the curves proposed by Singh and Murphy (1990) were selected the shear-modulus reduction and the damping variation. Finally, ABAQUS was also used to perform frequency analyses. The first eigenperiods of the model were estimated to be 0.46, 0.29, and 0.18 sec for material Type A, B, and C, respectively.

In order to examine the response of the geo-structure, the determination of the developed slip displacements along the interface is considered important, as the two phenomena (i.e. response and sliding) take place simultaneously. The permanent displacement (d_{per}), as well as the maximum displacement (d_{max}), developed at the base of the model (point T1) are shown in Table 1. As observed in previous studies, the level of the d_{per} depends strongly on the ratio of T_{str}/T_m. It is noticeable that during a seismic event displacements higher than the permanent displacement levels may take place.

Table 1. Calculated displacements along the geosynthetic interface for the examined cases.

	Ricker pulse (f_0=2Hz)			Kobe earthquake		
	Type A	Type B	Type C	Type A	Type B	Type C
T_{str} / T_m	1.35	0.85	0.54	0.70	0.44	0.28
d_{per} (mm)	11	14	11	68	9	9
d_{max} (mm)	18	18	15	68	41	27

The dynamic response characteristics of the sliding structure are examined by presenting the Transfer Function (TF) at point T2 of the geo-structure for the three examined material types. Transfer function is defined as the ratio of the Fast Fourier Transform (FFT) of the response of the point of interest to the corresponding FFT of the base excitation. In Figure 3 the cases of linear, equivalent linear, and coupled linear (sliding) response of the geo-structure are examined. Coupled linear is the response evaluated when linear response and sliding of the geo-structure take place simultaneously. In the coupled linear case the amplification levels observed in the TF for Type A material appear reduced, compared to linear response, at a frequency range between 2.0 and 4.5Hz. Furthermore, in Type B material, and for a more wide range of frequencies the corresponding values appear even lower.

This is also evident in Figure 4, where the distributions of the maximum normalized horizontal acceleration along the height of the model at the cross-section T1-T2 are shown. The effect of sliding on response appears more significant in material Type B than in Type A. The substantial effect of the sliding on response of Type B material can be attributed to the higher values of developed permanent displacements observed in this case. On the contrary, the response of material Type C seems to be less affected by sliding than any other case. In that case there exists a frequency range (5-6 Hz) close to resonance, where sliding response is higher than the linear case. Note, also that for Type A a second significant frequency (almost 2.5 times higher than the first one) appears, while for Type B the second significant frequency is observed to be almost 2 times higher than the first one. Material nonlinearity generally seems to be more critical on dynamic response than sliding, but this effect is relevant to the selected modulus-reduction and damping-variation curves. Therefore, the comparison between the effect of material nonlinearity and geometrical nonlinearity (sliding) on the response is related to the selected dynamic material properties.

The effect of sliding on response is related to: a) the level of the developed permanent displacements, b) the characteristics of the structure, and c) the frequency content of the excitation. It is evident though that for base displacements that are regarded as acceptable in the seismic design of such structures the developed accelerations may remain significant. Therefore the dynamic shear strains within the soil/waste mass may receive high values, and slope instability may be finally the case.

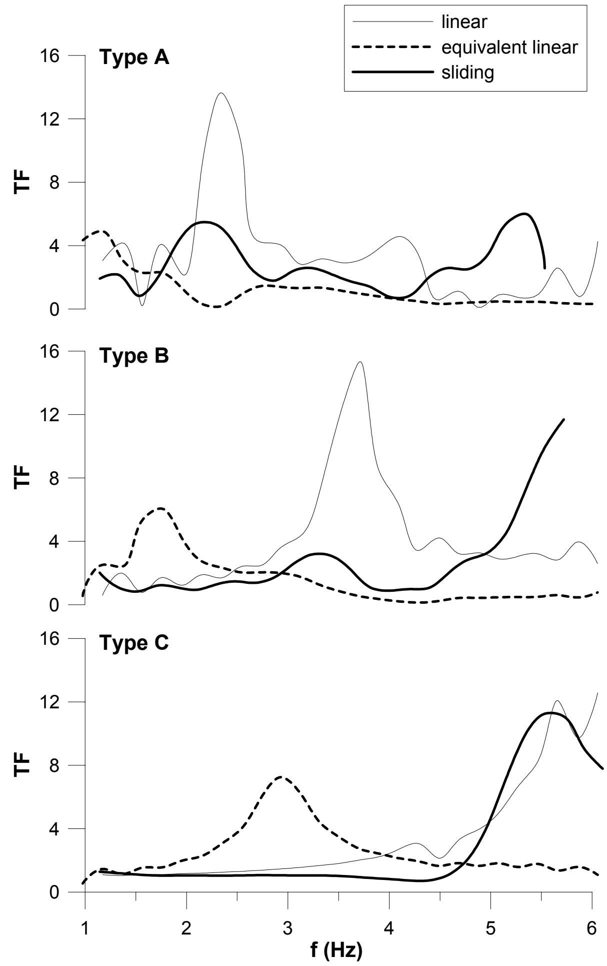

Figure 3. Transfer Functions (TF) of the dynamic response at point T2 for the Ricker pulse excitation (PGA=0.36g) are presented

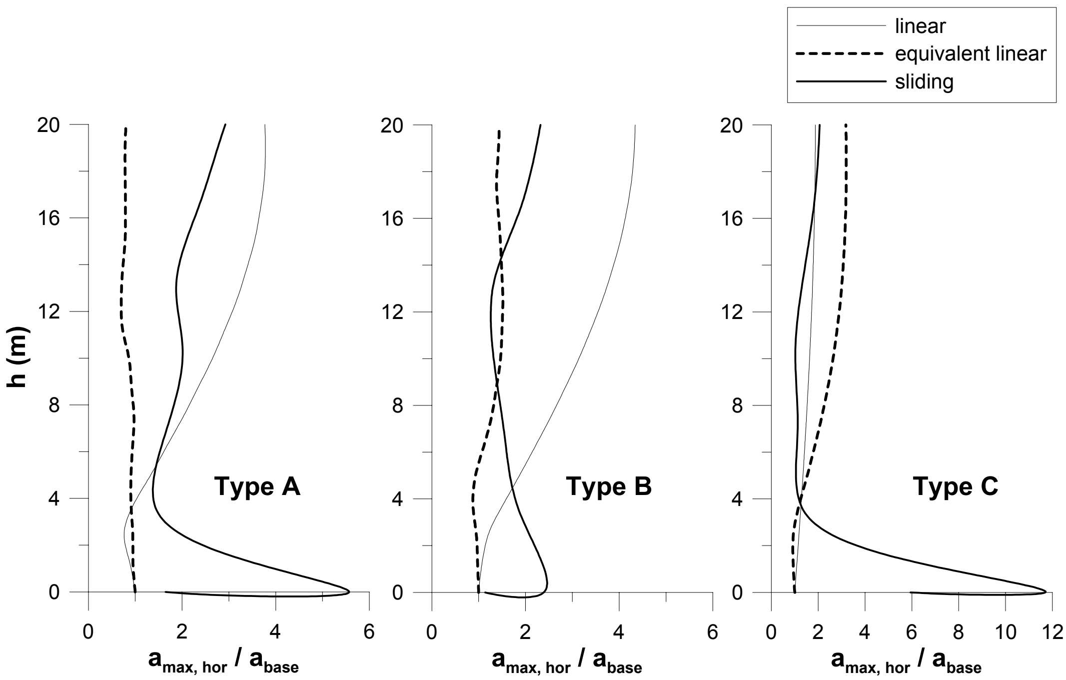

Figure 4. Maximum normalized horizontal acceleration at cross-section T1-T2 for Ricker pulse excitation (PGA=0.36g) are presented

DOUBLE SLIDING MODEL

The numerical results indicated that the generation of two well-defined surfaces, along which sliding occurs, is possible in a geo-structure, like an embankment or a solid-waste landfill. Therefore it is considered, important to provide an insight into the double sliding phenomenon, and to understand the mechanism of its development, as well as the role of the basic parameters influencing its generation and progress. For this purpose, a simple analytical model was developed according to the Newmark's sliding block model. Consequently, the basic principles used in the formulation of the model, as well as the observed behaviour of double sliding phenomenon are presented hereafter.

Description of the double sliding model

The developed model, shown in Figure 5, is based on Newmark's sliding block method, extended to two rigid blocks with two possible sliding interfaces. The basic assumptions maintained in this model are the rigidity of the sliding blocks and the rigid-plastic behaviour of shear resistance of the interfaces. Upslope movement is taken into account in the formulation of the analytical expressions. The upper block, with mass m_1, lies on the inclined plane of angle α, which is the upper surface of the lower block, with mass m_2. The upper and lower interfaces are characterized by angles of friction φ_1 and φ_2, respectively.

The procedure followed for the calculation of the developed displacements consists of two cases: a) when sliding occurs only along the lower interface, and b) when sliding occurs along the upper interface, and possibly along the lower as well. In the first case the system responds as the single rigid block of Newmark's model, while the displacement is provided by double integration of the relative acceleration, which is defined as the difference between inertia acceleration and the ratio of the friction force developed along the lower interface to the total mass of the system. Since the inertia forces overcome the upper block's shear resistance the second case takes place, where the displacements of the upper block result from double integration of the ratio of the difference between destabilizing forces and resistant forces to the mass of the block. During the estimation of the displacements of the lower block, the forces transmitted from the upper block (namely the contact pressure and the friction force) are also taken into account.

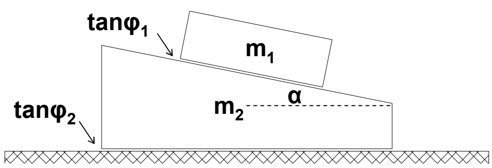

Figure 5. The simple model developed to simulate the double sliding phenomena

Basic aspects of double sliding

The main characteristics of double sliding are described by observing the progressive occurrence of the phenomenon in a representative case study, in which mass ratio of the two blocks (m_1/m_2) is equal to 0.1, angle of inclined plane is equal to 15^o, and angle of friction of the upper and lower interface are equal to 23^o and 16^o, respectively. The results of the displacement analysis are presented in Figure 6. Specifically, the acceleration, velocity and displacement time histories of the base, of the lower block and of the upper block are shown for the case of a Ricker pulse of central frequency 2Hz and PGA equal to 0.5g. In the sliding event starting at 0.44sec, sliding of the upper block occurs at first, while the lower block's sliding initiates slightly later. This is attributed to the difference between the yield acceleration of the upper and lower blocks. Though the angle of friction of the upper interface is higher than the lower, the opposite condition characterizes the yield acceleration, as a result of two combined situations: a) the upper interface is inclined, and b) during the upper block's sliding the contact forces transmitted to the lower block are contributing to the increase of the yield acceleration.

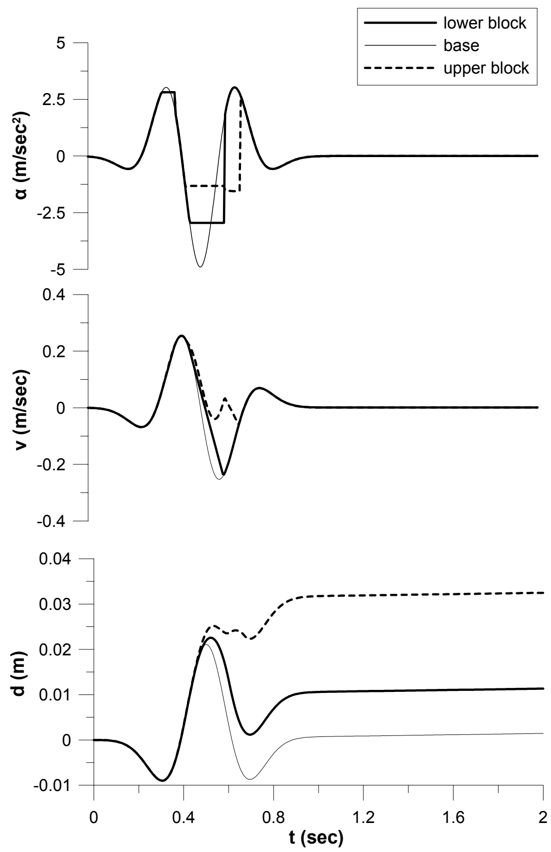

Figure 6. Ricker pulse (PGA=0.5g) m_1/m_2=0.1, α=15^o φ$_2$=16^o and φ$_1$=23^o: acceleration, velocity and displacement time histories of the base excitation, the lower block and the upper block.

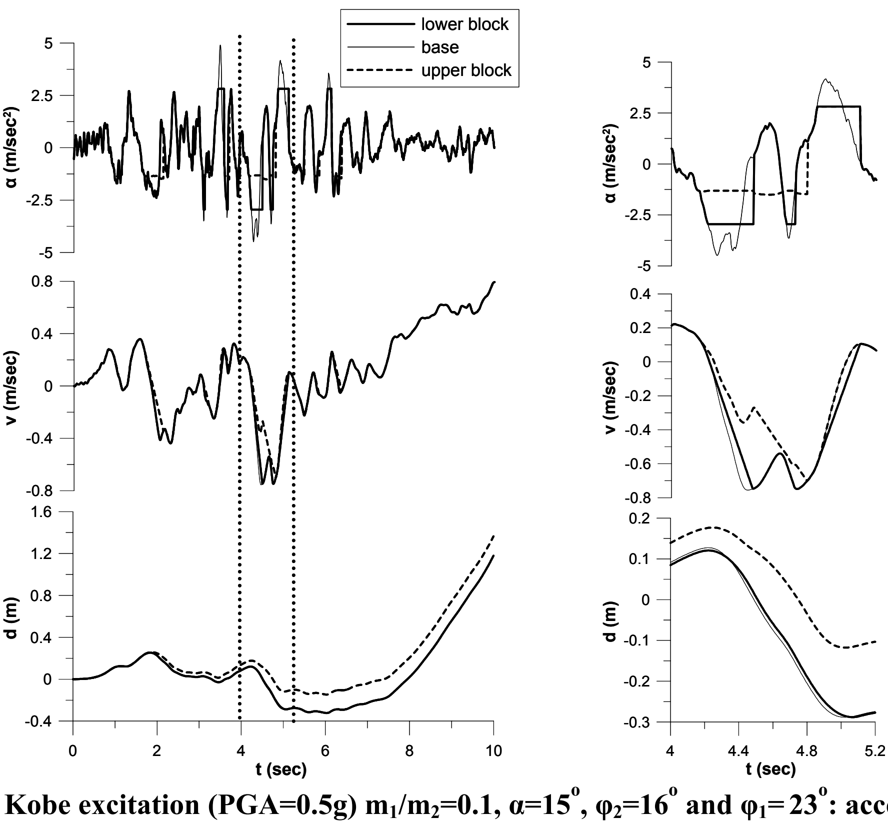

Figure 7. Kobe excitation (PGA=0.5g) m_1/m_2=0.1, α=15^o, φ$_2$=16^o and φ$_1$= 23^o: acceleration, velocity and displacement time histories of the base excitation, the lower block and the upper block. A double sliding event that takes place between 4 and 5 sec is shown in detail on the right-hand side

The latter indicates that the characteristics of the upper block's sliding affect through an interactive process the sliding of the lower block. Thus, the effect of the mass of the upper block and the angle of friction of the upper interface are also related to the sliding of the lower block. The same case of double sliding was also examined for a real earthquake excitation. The Shin-Kobe record was used for this purpose, scaled to PGA equal to 0.5g. In addition to the three complete time histories ($\alpha(t)$, $v(t)$, $d(t)$) of the base excitation, and of the lower and upper block, a detail of the sliding occurrence is also presented in Figure 7. As long as the inertia acceleration causes destabilisation of the upper block, double sliding takes place, characterised by the trends aforementioned in the Ricker pulse case. The acceleration reversal causes the sliding of the lower block, but no upslope sliding of the upper block is possible to take place due to the high levels of induced acceleration required to overcome the yield acceleration in that direction.

From the above results, it is evident that the initiation of sliding and the whole progress of the phenomenon depend on the relation between the two angles of friction and the angle of the inclined plane, as well as on the ratio of the masses of the two blocks. Therefore, these parameters and their effect on the phenomenon are extensively examined hereafter.

Parametric study

The effect of the parameters influencing the double sliding phenomenon was examined by a parametric study. The parameters examined were the ratio of the two masses (m_1/ m_2), the angles of friction of the two interfaces, and the angle of the sliding plane. The values of the examined parameters were selected to be representative of the case of an embankment/landfill with a geosynthetic layer along its base. Therefore, the angle of friction of the lower interface (φ_2) received values in the range of 10-24 degrees, which are representative of the dynamic angle of friction of geosynthetic interfaces (De & Zimmie 1998). The angle of friction of the upper interface (φ_1) ranged between 20 and 34 degrees, values that are characteristic of the angle of friction of soil or waste materials. The angle of the sliding plane was between 10-25 degrees, while the mass ratio was considered to range between 0.05 and 0.3, in order to take into account the effect of the size of the upper sliding mass. In this parametric study the displacement analyses were conducted for a Ricker pulse of central frequency equal to 2Hz, scaled to a PGA equal to 0.5g.

Angle of sliding plane

The role of the angle of the sliding plane seems to be very important as it is related to the yield acceleration of the upper block, and thus to the initiation of double sliding. In Figure 8, the ratio of upper block's displacement to the corresponding of the lower (d_1/ d_2) is shown in variation with the ratio $\tan\varphi_1/\tan\varphi_2$. The cases of angle of inclined plane equal to 10, 15 and 20 degrees are presented for mass ratio equal to 0.3. The double sliding initiates for a lower value of $\tan\varphi_1/ \tan\varphi_2$ in the case of angle of plane equal to 10^o ($\tan\varphi_1/\tan\varphi_2 \approx 2$), while for 15^o this value is increasing ($\tan\varphi_1/\tan\varphi_2 \approx 2.5$), and for 20^o it reaches its highest value ($\tan\varphi_1/\tan\varphi_2 \approx 3.5$). Additionally, the ratio of the developed displacements increases significantly as the angle of the inclined plane increases, referring to the same values of angle of friction and mass ratio. This may be attributed to: a) an increase of the displacement of the upper block due to significant decrease of its critical acceleration, and b) to a decrease of the displacements of the lower block, which results from the increased upper block displacements. Especially in the case of the 20^o inclined plane, these phenomena become extremely intense, as the angle of the upper plane (20^o) exceeds even the highest value of friction of the lower interface (18^o).

Angles of friction

In Figure 8 the influence of the friction angle of the interfaces is also evident. The ratio of the upper block's to lower block's displacement increase as the ratio $\tan\varphi_1/ \tan\varphi_2$ decreases; this may be attributed to the decrease of the difference between the shear strength of the two interfaces, and consequently of the frictional forces. Additionally, observing the curves in Figure 8 (each referring to a value of φ_2) the reduction of angle of friction of the upper interface (φ_1) results to an increase of the displacement of the upper block, as it was expected. The increase of angle of friction of the lower interface (φ_2) also results to an increase of the ratio of displacements d_1/d_2, and furthermore to a rise of the rate of increase as the ratio $\tan\varphi_1/\tan\varphi_2$ decreases. Also, it can be seen that the shape of the curves changes, most probably due to the sliding of the lower block. The displacements of the upper block maintain a constant rate of increase for each value of φ_2, as φ_1 decreases. The same is not valid for the lower block, where the displacements decrease as the upper block starts to slide. This decrease of displacement of lower block may be attributed to the increase of φ_1, as the shear strength transmitted from upper block during sliding, and furthermore the yield acceleration of the lower block increases.

Ratio of masses

In Figure 9 the ratio d_1/ d_2 is presented in variation with the ratio $\tan\varphi_1/\tan\varphi_2$ for the two extreme cases of the ratio of masses (0.05 and 0.30). The results presented here correspond to an angle of plane equal to 15^o. However, the results are similar to the results of the rest cases of inclination examined. The ratio d_1/d_2 increases as the mass ratio increases. The shape of the curves is strongly influenced by the mass ratio. The rate of decrease of the lower block displacement (occurring when the displacement of the upper block increases), appears to be more increased for greater mass ratios.

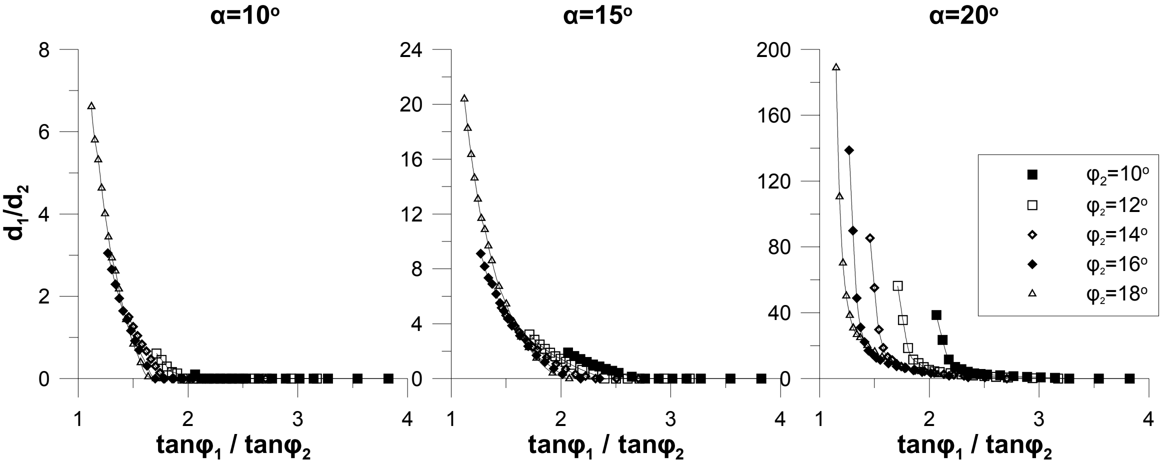

Figure 8. Effect of angle of sliding plane on the ratio of upper block's to lower block's displacement (d_1/d_2) for Ricker excitation (PGA=0.5g). The case of m_1/m_2=0.3 is only presented. Note that vertical axes are in different scales

CONCLUSIONS

The initial aim of the present study was to investigate the possibility of slope instability taking place in a geo-structure, like a soil embankment or a waste landfill, in which a plane of weakness (geosynthetic interface) already exists. The response of the examined sliding geo-structure was found to be affected, not only by the characteristics of the structure and of the excitation, but of the developed displacements as well. These phenomena appear to be interrelated, as the level of the accumulated displacements is also affected by the response characteristics of the embankment.

Furthermore, a simple analytical model was developed and the double sliding concept was investigated. It was found that the progress of double sliding, and thus the developed displacements of the upper and lower sliding blocks, is affected by: a) the frictional characteristics of the interfaces, b) the angle of the failure plane and c) the mass ratio of the two sliding blocks. More specifically, the angle of the sliding plane has a predominant role in the initiation and development of double sliding. The effect of the angles of friction of the interfaces is also important. It is characteristic that the displacements of the lower block decrease, while the corresponding of the upper block increase, when the angle of friction of the upper interface increases. Finally, the rate of the decrease of the displacements of the lower block is more increased for higher mass ratios of the two blocks.

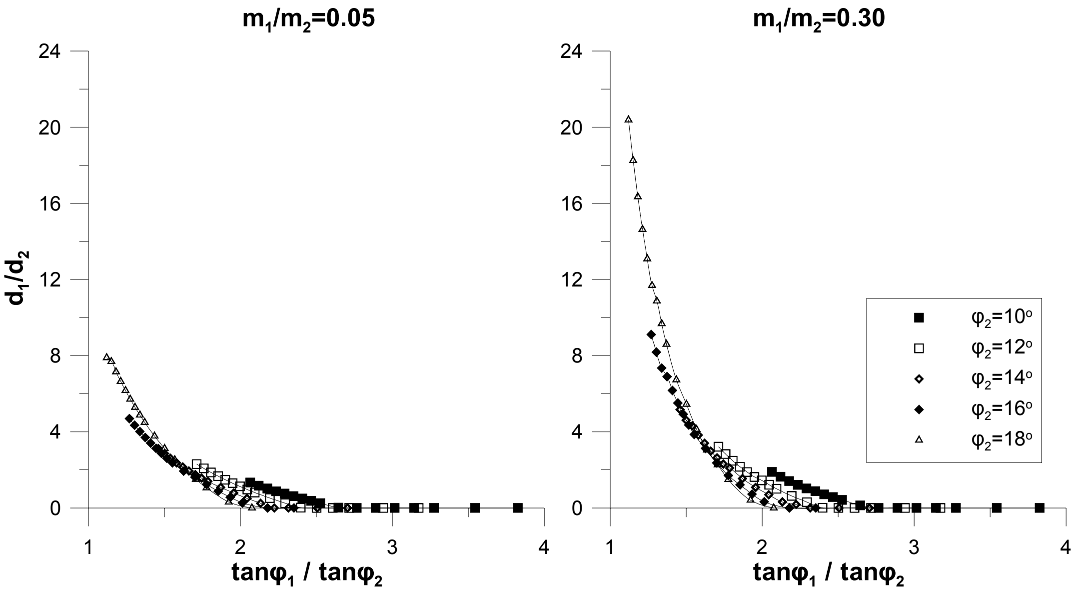

Figure 9. Effect of mass ratio (m_1/m_2) on the ratio of upper block's to lower block's displacement (d_1/d_2) for Ricker excitation (PGA=0.5g). The case of angle of sliding plane equal to 15^o is only presented.

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