A comparison of analytical approaches for the assessment of seismic displacements of geosynthetically reinforced geostructures

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SUMMARY:
Aim of the current study is to assess the dynamic response of reinforced soil structures and the potential of the geosynthetics to prevent the seismic induced instabilities taking advantage of their reinforcing effect. For this purpose, representative models of reinforced soil slopes are developed based on a modified procedure of the well – known Newmark's model. The dynamic response of the sliding soil mass and the development of the seismic accumulated slippage are taken into account simultaneously, while reinforcement is introduced by a spring element which models its stiffness. Parametric finite element analyses were performed and the impact of the flexibility of the sliding system, the mechanical properties of soil and geosynthetic material, and the frequency content of the excitation were investigated. Permanent displacements are shown to decrease with the increase of the stiffness of the reinforcement, while the decoupling approximation appears to be conservative for the majority of the examined cases.

Keywords: seismic slope stability, geosynthetics, soil reinforcement, sliding, finite-element analyses

1. INTRODUCTION

Geosynthetics have been widely used over the last decades in various fields of engineering practice, such as geotechnical, transportation, hydraulic, and geoenvironmental, mainly due to the numerous functions that they can be efficiently serve which are reinforcement, drainage, filtration, containment, and separation. Slope stabilization has been one of the major applications of reinforced soil, since steeper configurations are constructed without compromising their stability (Abramson et al., 2002). The static design of geosynthetically reinforced slopes is based on modified versions of classic limit equilibrium slope stability methods. Kinematically, the potential failure surface in a reinforced homogenous slope is assumed to be defined by the same idealized geometry (but not the location) as in the unreinforced case, e.g., circular, log spiral, bilinear wedge (Paulsen, 2002).

The assessment of seismic slope stability of geosynthetically reinforced soil structures has also been performed with the application limit-equilibrium methods, following the same approach as for the case of unreinforced slopes (Abramson et al., 2002). Usually the pseudostatic method is adopted, where the dynamic earth pressures are calculated using the Mononobe - Okabe method or a modified two-part wedge method (Richards and Elms, 1979, and Ausilio et al., 2009). However, the seismic response of reinforced slopes is often related to the development of permanent deformation. Newmark (1965) proposed a relatively simple analytical model, where the displacement of a soil mass above a slip surface is modeled as a rigid block of soil sliding on a plane surface. When the acceleration of the block exceeds the yield acceleration, a_y, the block begins to slip along the plane. Any acceleration that exceeds yield acceleration causes block sliding and imparts a velocity to the block relative to the velocity of the underlying mass. This stick-slip pattern of motion continues until the acceleration falls below the yield acceleration and the velocity drops to zero. The computation of the permanent displacement is achieved by double integrating the relative acceleration.

One of the basic assumptions to calculate seismic displacements according to Newmark (1965) is to consider the sliding mass as totally rigid. This means, that the dynamic response of the slope of which the seismic stability is estimated, is not taken into account in the calculation of seismic displacements. Soil slopes are flexible systems characterized by relatively large fundamental period. In order to take this fact into account for the estimation of seismic displacements of slopes, a decoupled method was proposed by Makdisi and Seed (1978), which consisted of two steps. The first step is focused on the evaluation of the dynamic response of sliding soil mass in terms of an equivalent time history of acceleration after the calculation of the response of the earth structure . The time history of equivalent horizontal and vertical acceleration is defined as the integral of horizontal and vertical stresses respectively, along the slip surface divided by the weight of sliding mass. In the second step, the permanent seismic displacement is calculated by double integration of the relative acceleration. Note that the relative acceleration is defined as the difference between the applied acceleration and the critical acceleration. A decoupled sliding block analysis does not accurately model the forces at the sliding interface, because sliding is ignored, when calculating the dynamic response, leading to an overprediction of the system response.

Several researchers have proposed and analyzed simple non-rigid systems where the dynamic response of the sliding mass and the slip displacement accumulation are performed simultaneously. This method is known as coupled. Initially, Westermo and Udwadia (1983) and Mostaghel et al. (1983) examined the dynamic behavior of a system that consisted of an SDOF system. At the base of the SDOF system a rigid mass was applied, and by limiting the shear strength along the lower surface allows for slip displacement accumulation. Many investigations have been performed thereafter in order to examine the difference between decoupled and coupled analysis. Chopra and Zhang (1991) investigated the influence of base sliding on the seismic behavior of concrete gravity dams. The authors developed a modal based solution in which only the fundamental vibration mode shape was taken into account in order to calculate the response of the dam. Then the results of the proposed coupled method were compared with the corresponding ones of an equivalent approximate decoupled procedure. Although approximate, this method showed that the permanent displacements were overestimated. Furthermore, Lin and Whitman (1983) have examined the dynamic response and the corresponding slip displacements using the decoupled and the coupled method for three lumped- mass systems. The results of this study show that the decoupling assumption is related to over- conservative estimates of the sliding displacements, especially for resonance conditions. Results from several investigations indicate that the difference between coupled and decoupled approaches depends mainly on two factors: (a) the ratio of critical to maximum acceleration and (b) the tuning ratio (denoted as β), which represents the ratio of the eigenperiod of the structure to the period of excitation (Kramer and Smith (1997), Bray and Rathje (1998),and Rathje and Bray (2000)). The outcome of the aforementioned studies is that decoupled analysis is significantly conservative for tuning ratios lower than one in comparison to coupled analysis. In contrast, the decoupled approach can provide acceptable accuracy for higher values of yield acceleration.

The main aim of the current study is to assess the seismic stability of deep seated reinforced and unreinforced soil masses, taking into account the most important aspects of the problem. For this purpose, flexible SDOF models were developed with a sliding plane along their base, while the effect reinforcement was also considered. The dynamic response of these models to harmonic excitations was calculated following both coupled and decoupled procedures. The permanent slip displacements of the coupled analysis are then compared with the corresponding ones of the decoupled analysis.

2. DESCRIPTION OF THE COUPLED SDOF MODEL

The prototype model that has been used as reference for this work was initially proposed by Westermo and Udwadia (1983), who developed a model procedure to calculate, coupled sliding displacements for slopes using the discrete mass model shown in Figure 1.

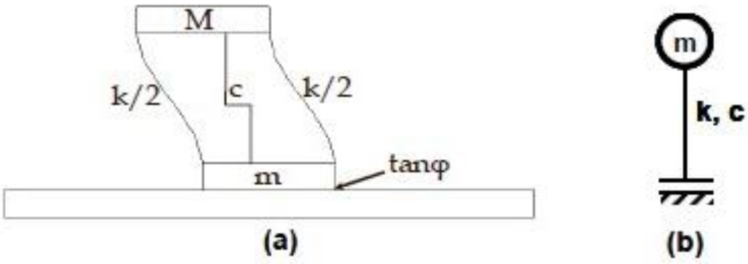

Figure 1. Single-degree-of-freedom (SDOF) system on sliding support. Two cases are shown: (a) with mass at the base, and (b) without mass at the base.

In the current study, two lumped mass SDOF shear beam models have been developed, which are shown in Figures 2a and 2b. As it can be observed, the first model represents the reinforced soil structure which consists of five discrete parts, which are: (a) a concentrated mass (M), (b) a dashpot (coefficient c), (c) beam element with stiffness (K), (d) a spring (with stiffness k) placed at the base to represent the reinforcement, and (e) a gap element between the SDOF and the ground. The properties of the soil and the reinforcement were regarded constant, defined by the density, ρ, the shear modulus, G, Young modulus, E, and Poisson's ratio, v.The second model represents the unreinforced soil structure, which constitutes of all the parts which were mentioned above apart from the reinforcement spring (k).

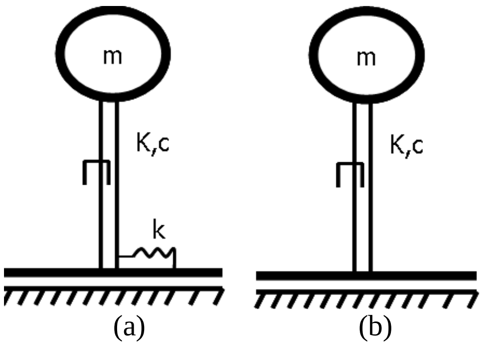

Figure 2. (a) Reinforced SDOF model, and (b) unreinforced SDOF model.

Based on the aforementioned models, the SDOF systems shown in Figures 2a and 2b were analyzed numerically utilizing the finite element software ABAQUS (2010). A harmonic motion with period T equal to 0.288 sec was used as base applied motion in the coupled and decoupled nonlinear time history analyses of the deformable sliding block. Four cycles of sinusoidal motion were applied as imposed acceleration. The results of harmonic excitations provide a better insight to basic response characteristics and are often used in dynamic analyses, especially in analytical calculations. Moreover two cases of hysteretic damping for elastic dynamic response were considered by setting the damping ratio ξequal to 5% and 10%.

In the current study the seismic stability of reinforced and unreinforced soil structures is assessed in order to highlight the most important aspects of the problem and to compare the results of the coupled analysis with the results of the decoupled analysis. Parametric analyses were performed and the reinforced model (see Figure 2a) was analyzed assuming the geosynthetics stiffness equal to 150kN/m/m. The numerical configuration of this study replicated as closely as possible, the physical model developed in the geotechnical centrifuge by Nova-Roessig and Sitar (1999), providing thus a realistic basis for the parameters of the coupled SDOF model. However, a more comprehensive comparison would require the modelling of the cyclic nonlinear soil response and of the two-dimensional seismic wave propagation which is beyond the scope of this preliminary investigation.

Parametric analyses were performed, taking into account the factors that influence the flexibility of the system since one of the most important of all the assumptions inherent in the sliding-block model is the rigidity of the sliding mass.. The permanent seismic displacement of the unreinforced model has been shown to be efficiently normalized when referring to constant: (a) ratio of critical to maximum acceleration ($\tan\varphi * g/a_{max}$), and (b) tuning ratio (denoted as $\beta = T_{str}/T$), the latter representing the ratio of the eigenperiod (T_{str}) of the structure to the period (T) of the excitation (Zania et al., 2010). This illustrates the significance of the aforementioned ratios in the dynamic response of the examined systems, which is in accordance with results of previous investigations (Kramer and Smith (1997), Bray and Rathje (1998, 2000)). For this purpose, the dynamic response has been assessed for several models with different flexibility, by calculating different values for the tuning ratio (β) equal to 0.4, 0.6, 0.8, 1.0, 1.5 and 2.0, while for the ratio of critical to maximum acceleration ($\tan\varphi * g/a_{max}$) the values of 1.0 and 0.5 were considered.

3. RESULTS OF THE PARAMETRIC STUDY

The present formulation allows the calculation of the sliding and permanent displacement for both reinforced and unreinforced models. The sliding displacement (denoted as d in the vertical axis of the subsequent plots), is defined as the difference between the displacement at the base of the deformable sliding mass and the ground displacement. The base of the models to be analysed, i.e. the sliding plane of the deformable mass, was assumed horizontal, implying that only symmetrical sliding may take place. This condition is representative of a deep seated failure plane. A detailed parametric analysis was performed and the effect of the most significant parameters that control the seismic slip displacements was thoroughly investigated. The results in the following figures are plotted for the examined values of tuning ratio (β). More specifically, Figures 3, 4, 5 and 6 present the ratio of decoupled permanent displacements to the coupled permanent displacements of the two SDOF models for tuning ratios equal to 0.4, 0.6, 0.8, 1.0, 1.5 and 2.0, ratio $\tan\varphi * g/a_{max}$ equal to 0.5 and 1.0 and spring stiffness (k) equal to 150 kN/m/m.

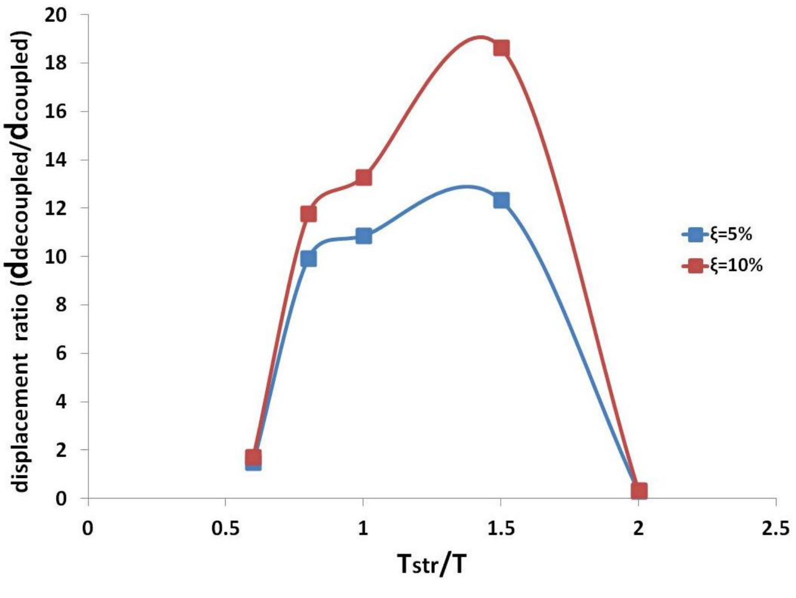

Figure 3. Ratio of decoupled displacements to coupled displacements of a sliding unreinforced SDOF system for various values of the tuning ratio $\beta = T_{str}/T$. Damping ratio (ξ) is equal to 5% and 10% and yield acceleration ratio ($\tan\varphi * g/a_{max}$) equal to 0.5.

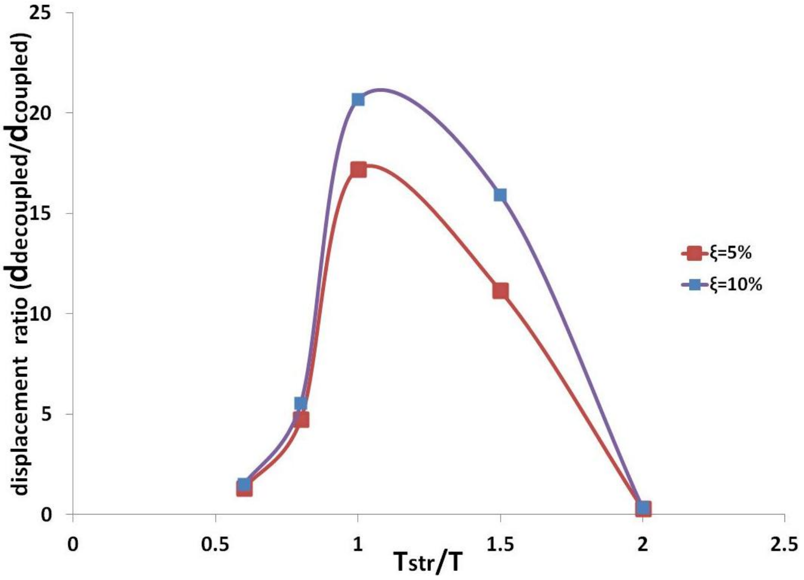

Figure 4. Ratio of decoupled displacements to coupled displacements of a sliding reinforced SDOF system for various values of the tuning ratio $\beta = T_{str}/T$. Damping ratio (ξ) is equal to 5% and 10% and yield acceleration ratio ($\tan\varphi * g/a_{max}$) equal to 0.5.

By observing Figures 3 and 4 it is evident that as the tuning ratio values increase (when $\beta < 1.5$), higher permanent displacements occur for both coupled and decoupled approaches, while the opposite trend appears for ratios larger than 1.5. In almost all the examined cases the decoupled approach led to the overestimation of the permanent seismic displacements, i.e., ratio of displacements ($d_{decoupled}/d_{coupled}$) larger than unity. As it can be seen in both figures, when the tuning ratio is quite large, i.e., it is equal to 2.0, the two methods give the same results, since the system above the sliding element will respond as a rigid block. Comparing Figures 3 and 4 it can be observed that, the inclusion of reinforcement in geostructures is beneficial. The permanent slip displacements in the reinforced model are lower compared to the unreinforced model. With respect to the impact of the decoupling approximation, the reinforced model follows the same trends as for the unreinforced case. Only in the resonance case the ratio of displacements in the reinforced model are greater than the unreinforced. This illustrates probably the reduction of the absolute magnitude of permanent displacements.

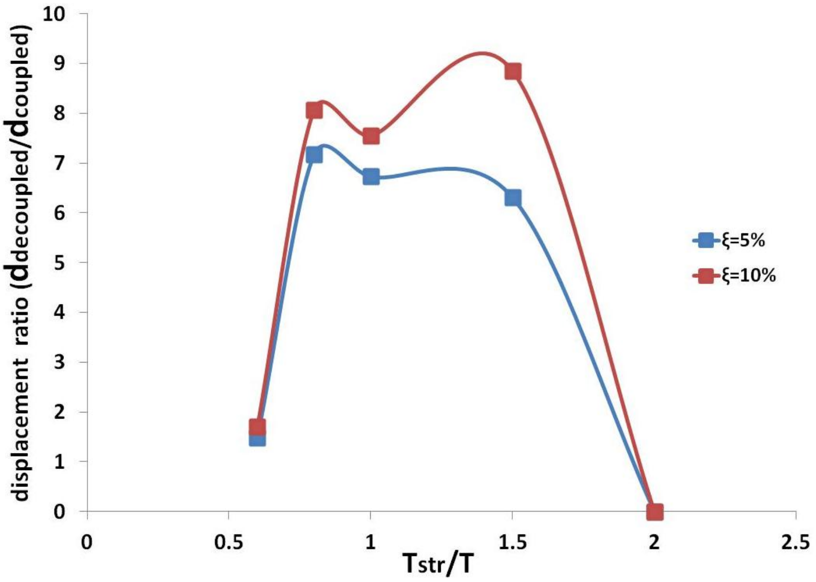

Figure 5. Ratio of decoupled displacements to coupled displacements of a sliding unreinforced SDOF system for various values of the tuning ratio $\beta = T_{str}/T$. Damping ratio (ξ) is equal to 5% and 10% and yield acceleration ratio ($\tan\varphi * g/a_{max}$) equal to 1.0.

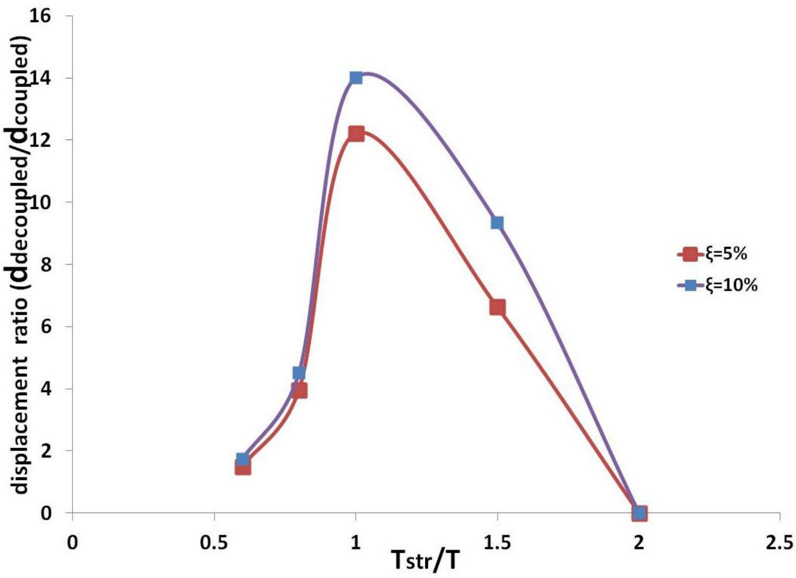

Figure 6. Ratio of decoupled displacements to coupled displacements of a sliding reinforced SDOF system for various values of the tuning ratio $\beta = T_{str}/T$. Damping ratio (ξ) is equal to 5% and 10% and yield acceleration ratio ($\tan\varphi * g/a_{max}$) equal to 1.0.

Additionally, the impact of the yield acceleration ratio on the ratio of displacements was investigated, by increasing the ratio $\tan\varphi * g/a_{max}$ from 0.5 to 1.0 in the case of unreinforced model and when the geosynthetic reinforcement's stiffness is equal to k= 150 kN/m/m. The corresponding results are illustrated in Figures 5 and 6, respectively. The increase of the yield acceleration ratio, for both reinforced and unreinforced models, resulted to a decrease of the permanent displacements. Hence, the ratio of the permanent displacements as obtained from the decoupled and the coupled methods is also decreased. However, the decoupling approximation still overestimates the permanent displacements. In addition, the increase of the damping ratio leads to an increase of the displacement ratio consistently for all the performed analyses. Finally, it is noticed that a decoupled sliding block analysis does not accurately model the forces at the sliding interface, because sliding is ignored, when establishing the dynamic equilibrium of the system. The forces at the sliding interface are allowed to exceed the strength of the interface, leading thus to an over-estimation of the system response.

4. CONCLUSIONS

In the current study the seismic response of soil slopes with and without geosynthetics was investigated, focusing on their potential permanent displacement using two approaches a coupled and a decoupled one. For this purpose, a SDOF model was formulated, which was subsequently used to calculate the magnitude of slip displacements. Parametric analyses were performed to take into account the effect of the flexibility of the sliding system, the mechanical properties of the soil (represented in the model by the angle of friction of the sliding plane) and of the geosynthetic material, and the frequency content of the excitation. It was observed that permanent slip displacements depend on the $\tan\varphi * g/a_{max}$ ratio and the so-called tuning ratio (β) of the eigenperiod of the structure to the period of the excitation (T_{str}/T). During the evaluation of the dynamic response of the sliding mass and the development of the seismic accumulated slippage a horizontal sliding plane was assumed leading to a symmetric pattern of slip displacement accumulation.

The ongoing development of this study is to modify the inclination of the sliding plane to capture the inclined region of plastic deformations (and progressive failure) that occur in reinforced slopes, as it has been observed in situ in slope failures as well as in experimental and numerical studies (Nova-Roessig and Sitar (1999), Tzavara et al., (2009)). Moreover, multiple degree of freedom (MDOF) models will be developed to simulate more realistically the typical configuration of soil slope reinforcement consisting of several geosynthetic layers.

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