DYNAMIC BEHAVIOR OF GEOSYNTHETIC LINED WASTE IMPOUDMENTS

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ABSTRACT :

Over the last fifteen years increased research interest has been observed on the dynamic response and stability issues of landfills. Nevertheless, there are still important aspects that have not been yet fully resolved. Geosynthetic liners, constructed to isolate waste material from the environment, are undoubtedly one of the most important issues related to seismic design of landfills, since a potential failure is directly related to leakage of leachate to the environment. This study aims to highlight the contributing role of the base liner on the seismic behavior of landfills. As landfills are characterized by several uncertainties, related mainly to waste material characterization, the current investigation takes also into consideration the significant parameters addressed in the literature affecting the dynamic response of this type of geostructures. For this purpose, two-dimensional efficient dynamic finite-element analyses are performed. The tension of the geosynthetics resulting from the seismic loading is estimated along with the potentially induced seismic slip deformations taking place on the interfaces. Results indicate that the seismic strains on the geosynthetics should not be neglected. Conclusively, seismic design of landfills should take into account these phenomena and ensure the integrity of the lining systems as well as the stability of the waste impoundment.

KEYWORDS: waste landfills, dynamic response, geosynthetic liners, tensile strains

1. INTRODUCTION

Waste disposal is undoubtedly related to both environmental safety and public health issues. The design of waste containment facilities should be oriented in minimizing the detrimental impact on the aforementioned issues. Therefore, a crucial condition to be fulfilled, not only during but also after the operation of the facility, is the assurance of the stability of the landfill and the maintenance of the integrity of each part that comprises it. The objective of preventing leachate from releasing to the surrounding environment is accomplished through the construction of a composite base liner system (CLS) and a leachate collection system. The minimum requirements for waste disposal facilities are specified in both US (EPA, 1993) and EU (Council Directive, 1999) regulations. In the case of non-hazardous waste the mandated constituents are a protective filter (either sand or geotextile) over a high permeability drainage layer (either physical, i.e. granular soil material or synthetic, i.e. geonet) and a flexible geomembrane over a geological barrier. Furthermore, more complicated systems are obliged for hazardous waste, like the multilayer liner system constructed at the base of the hazardous waste Kettleman Hills landfill (Mitchell et al., 1990).

The static stability of waste landfills is strongly influenced by the low shear strength interfaces, which are most probably formed along the discrete boundaries of the composite base liner of the geostructure. Failure along the aforementioned interfaces has been demonstrated through documented case histories (Seed et al., 1990 and Koerner and Soong, 2000). Additionally, research interest has been focused on the investigation of the role of the lining system by evaluating the static stability through analytical (Bergado et al., 2006) or numerical procedures (Filz et al., 2001 and Reddy et al., 1996). Furthermore, it has been proven that one of the basic factors affecting the displacement development is the stiffness of the waste material.

Nevertheless, seismic loading induces large shear strains to earth structures, like landfills, causing a significant instability potential along geosynthetic interfaces. Several researchers have examined this issue mainly by utilizing analytical procedures. Kramer and Smith (1997), using the model proposed by Westermo and Udwadia (1983), provided an experimental verification and, in addition, they estimated the effect of damping and mass ratio to the seismic displacements. Moreover, a generalized single degree of freedom (SDOF) system with mass and elasticity distributed along its height (Rathje and Bray, 1999) and a non-linear lumped mass model (Rathje and Bray, 2000) have been developed, illustrating also the importance of parameters as the ratio of structure's eigenperiod to the period of the excitation and the ratio of the amplitude of the applied acceleration to the yield acceleration. The aforementioned studies examined the seismic stability of landfills ignoring the effect of slippage development on the tension of the geosynthetics. The tension in geomembranes resulting from earthquake loading has been examined in a geotechnical centrifuge experimental study conducted by Thusyanthan et al. (2006). They have measured an increase of 25-40% at the maximum measured tension and a 15-25% increase in permanent tension that can be attributed to seismic loading.

The current study aims to provide a comprehensive insight into the dynamic behavior of the composite base liner system by determining the critical failure scenarios. A simple analytical model based on the Newmark's sliding block model (1965) is implemented for the evaluation of slip development along several interfaces and the influence of the main parameters is determined. Subsequently, efficient two-dimensional finite element analyses are performed by considering not only the interaction between base sliding and response of a typical above-ground landfill, but also the tension on geosynthetics. A parametric study is conducted and the effect of the eigenperiod of the geostructure and of the period of the excitation is investigated on the examined characteristics. Results are interpreted in terms of permanent displacements and stress distribution along the geosynthetic layers. Therefore, a valuable insight in this complicated problem is provided in the potential instability of the landfill and the resulting distress of the geosynthetics.

2. EVALUATION OF DYNAMIC BEHAVIOR OF CLS

It is essential to demonstrate the ability of the composite liner system (CLS) to provide seismic displacements at any or even at all the existing interfaces during dynamic loading. In the rigid sliding block model proposed by Newmark (1965) the limiting acceleration, i.e. the critical acceleration for sliding to occur is $a_{crit} = g \cdot \tan\varphi$. Moreover, it is important to investigate whether slip displacements are feasible to develop along more than one interface, since the composite base liner consists of several parts. For this purpose a simple Newmark - type model was developed, considering that two discrete interfaces are formed, dividing thus the waste mass and the base liner into two parts. The major assumption of this model is that the two parts (blocks) are considered to be rigid. It is evident that, when the angle of friction corresponding to the lower interface is lower than the one of the upper interface, slip displacements are not possible to develop along both interfaces, since the shear strength of the upper interface will not be exceeded. On the contrary, when the upper interface is characterised by the lowest angle of friction, it is feasible to observe the development of seismic displacements along both interfaces. The critical acceleration of the upper interface is $a_{crit1} = g \cdot \tan\varphi_1$. Considering now equilibrium of the rigid block between the two interfaces, the following condition determines the critical acceleration along the lower interface, regarding that sliding has already initiated along the upper interface:

$$a_{crit2} = (m_1/m_2)\,(\tan\varphi_2 \pm \tan\varphi_1)\,g + g\tan\varphi_2 \qquad (2.1)$$

where m_1,m_2 are the masses of the upper and lower block respectively and φ_1,φ_2 are the angles of friction of upper and lower interface respectively. The two signs in the term of the frictional force of the upper rigid block represent the two possible directions towards which displacement along the upper interface may develop. Figure 1 shows the variation of the critical acceleration of the lower interface, as slip displacements have been accumulating along the upper interface.

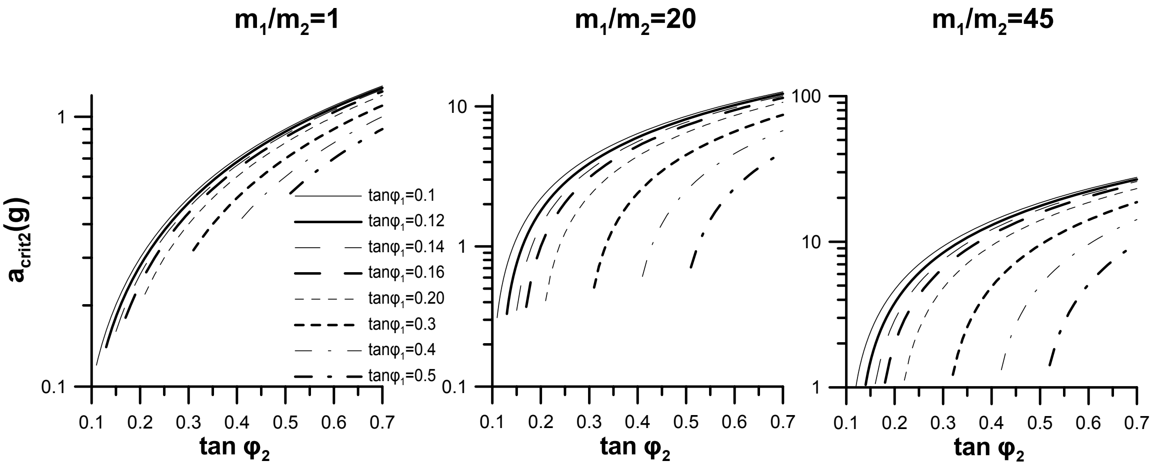

Figure 1 Variation of critical acceleration of lower interface (a_{crit2}) for ratio of mass of upper (m_1) to lower (m_2) block equal to 1, 20 and 45.

The critical acceleration of the lower interface increases as the shear strength of the lower interface increases. In contrast, the parameter is receiving lower values for higher shear strength of the upper interface, referring to the same shear strength of the lower interface. It is also evident that the mass ratio of the two rigid blocks determines the value of the critical acceleration of the lower interface. More specifically, when the mass ratio is equal to 1.0, 20 and 45 the minimum critical acceleration is equal to 0.13g, 0.3g and 1.2g, respectively. Considering that in solid waste landfills the waste mass is significantly larger than the mass of the composite liner system ($m_1/m_2 > 45$), the case of slip displacement development along two interfaces is unrealistic. Concluding, it is evident that seismic displacements may potentially develop along a single interface, the one with the lowest interface strength. Furthermore, if the critical interface is located beneath any of the geosynthetic layers of the composite liner system, then additional distress may be applied at these regions. Consequently, this is considered to be the most critical scenario and will be further investigated in the sequence.

3. TWO-DIMENSIONAL NUMERICAL ANALYSES

As aforementioned, the current study examines the dynamic behavior of a typical above-ground landfill, taking into account the slip displacements that may develop along the most critical interface. Figure 2 shows the geometry of the examined model. The selected cross-section may also represent any kind of embankment, since a “reinforcement” layer is commonly placed at the base of embankments to avoid a potential soil failure. The structure was modelled utilizing the finite element code ABAQUS (2004). The composite base liner was modelled as a single geosynthetic layer with only axial stiffness using rod elements or the discretization. Additionally, a low shear strength interface at the base of the geosynthetic layer was considered, providing thus the potential for slip displacement development. Furthermore, the shear strength of the interface was assumed to exhibit rigid-plastic behavior and the interpenetration of the two surfaces was not allowed. As the seismically induced displacements may be excessive, the residual angle of friction was considered accurate enough to represent the shear strength of the interface, while elastic slip was not taken into account. The model was discretized using triangular plane strain finite elements, the size of which was tailored to the wavelengths of interest, resulting thus to a finer mesh from rock to soil. A finer mesh was also developed at the base of the structure; consequently, a better estimation of the contact properties, which are related to the vertical stress of the interface, was accomplished.

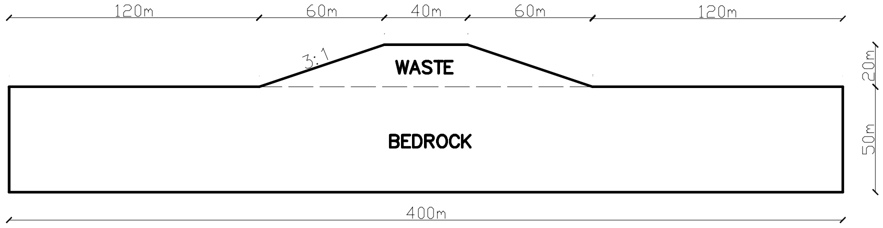

Figure 2 Geometry of the model examined. Note that the geosynthetic layer at the foundation of the waste landfill is shown with dashed line.

The simplest configuration of a composite base liner should have at least the following interfaces: (a) compacted clay liner to geomembrane, (b) geotextile to geomembrane, (c) geonet to geotextile, and (d) sand (gravel) to geotextile. The determination of the most critical interface and its shear strength is quite complex, mainly due to the uncertainties and the parameters affecting not only the soil to geosynthetic interface but also the geosynthetic to geosynthetic interface. After an extended literature review, the main parameters, as well as the range of the shear strength of the aforementioned interfaces are summarized in Table 3.1.

Table 3.1 Parameters affecting the shear strength of interfaces that are present at a typical composite base liner and characteristic range of values.

Interface	Parameters		Shear strength	References
	Material 1	Material 2		
Clay - geomembrane	shear strength, test procedure (drained/undrained)	material type, texturing and surface roughness	c= 0-48kPa φ= 10-40°	Fishman & Pal (1994).
Geotextile - Geomembrane	mass per unit ratio, fiber type, fabric style, material and calendering.	material type, texturing and surface roughness	φ= 6-37°	Martin et al (1984), Hillman & Stark (2001), Jones & Dixon (1998), and De & Zimmie (1998).
Geonet - Geotextile	material type, orientation, normal stress	mass per unit ratio, normal stress	φ= 9-24°	Bergado et al (2006), De & Zimmie (1998).
Sand (gravel) - Geotextile	shear strength, normal stress	normal stress	φ= 19-42°	Bergado et al (2006), Martin et al (1984).

Therefore, it is evident that the shear strength of the interfaces that are present on a base liner system should be obtained on a case-by-case basis. This conclusion has been also depicted by several researchers (Bergado et al., 2006 and Hillman and Stark 2001), who propose that shear strength of interfaces is project specific, and product dependent, i.e. directly related to site specific conditions and candidate geosynthetics and soil materials used in the project. The selection of the interface properties was in accordance to the reported dynamic friction properties of geosynthetic interfaces. The selected dynamic friction angle in this study is 11.3 degrees, which is rather small in order to allow sliding to occur more frequently. The basic dynamic property of waste material, i.e. the shear wave velocity (V_S), was selected to be consistent with values reported in the literature. For example, Matasovic and Kavazanjian (1998) as a part of pre-design studies for closure of OII landfill, used site characterization studies which included field investigations and evaluated V_S values ranging between 120 to 390 m/sec. In the current study five values of V_S were selected: 400m/sec, 325 m/sec, 250 m/sec, 188 m/sec and 125m/sec. The landfill was considered to be founded on elastic rigid bedrock where the damping was set equal to 1%, while for waste material the corresponding value was 5%. For a better understanding and interpretation of the results the excitations used for the analyses are sinusoidal pulses characterized by frequency 17.4Hz, 7Hz, 3.5Hz and 0.7Hz all scaled to maximum acceleration equal to 0.4g.

Apart from the aforementioned factors related to seismic slip development, i.e. angle of friction of interface, tuning ratio and amplitude of applied motion, the stress state obtained after the static equilibrium is also of great importance. Figure 3 shows the normal and shear stress distribution along the foundation of the landfill, calculated numerically. It is evident that the shear strength ($\sigma_v \cdot \tan\varphi$) varies symmetrically, while on the contrary, shear stresses vary anti-symmetrically with respect to the axis of symmetry of the model. To address the effect of the static shear stress on the phenomena under investigation, results on the interface will be initially presented in five characteristic locations: (a) the lower left corner of the model (x= -80m), (b) the minimum shear stress point (x= -40m), (c) the axis of symmetry point (x= 0m), (d) the maximum shear stress point (x= 40m), and (e) the lower right corner of the model (x= 80m).

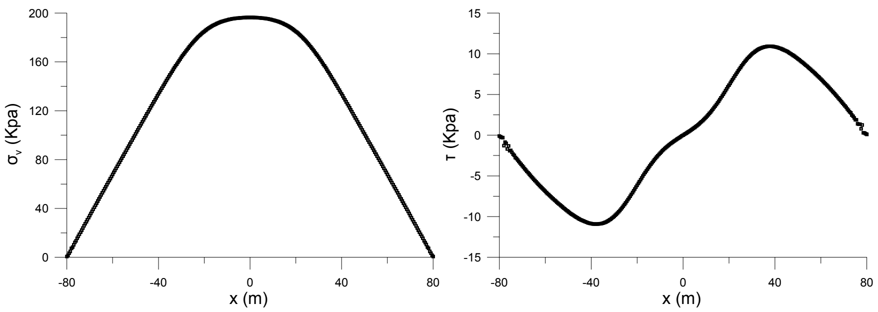

Figure 3 Shear (τ) and normal stress (σ_v) distribution along the foundation of the landfill under static conditions.

At first, the results of the analysis corresponding to tuning ratio equal to 0.63 will be presented. In Figure 4 the relative displacement (slip) time history is shown for the five characteristic locations along the interface. The corresponding velocity time histories and the base velocity time history are also presented. It is evident that at the end of each slip cycle an amount of relative displacement accumulates. Usually, each slip cycle consists of two subsequent stick-slip phases at the end of which the velocity of the examined point becomes equal to the base velocity. The value of the additional permanent displacement per slip cycle decreases, but on the other hand, the end of the four-cycle applied motion results to significant slippage along the base. This phenomenon is inconsistent with the rigid block analysis, which yields zero permanent displacement per slip cycle. This accumulation of displacements may be attributed to: (a) the different durations of the two slip phases taking place within a slip cycle, and (b) the non-symmetric variation of the velocity time history during two subsequent slip phases (see Figure 4b).

Examining, for instance, the first slip cycle of the point corresponding to the minimum shear stress it is evident that the two slip phases of the cycle are characterized by different duration. The duration of a slip phase is related to the critical acceleration, i.e. the value of the acceleration for which shear strength is overcome and displacements develop (critical acceleration during the slip phase is equal to the derivative of the velocity of the sliding point). Apart from the shear strength, the factors affecting the critical acceleration are certainly the static shear stress and the inertia response. Regarding the static shear stress, as it is negative, it reduces the total shear strength and thus the critical acceleration of the first slip event, but on the other hand, it increases the critical acceleration of the second one where the direction of the dynamic shear stresses is reversed. Considering the inertia forces, it is evident that the velocity time history is not characterized by a constant inclination as is the case of the rigid-block approach. In particular, the variation of the velocity time history results to an increase of the duration of the first slip phase. Moreover, the accumulated displacements are related to both the duration of the slip phases and the variation of the critical acceleration during the slip phase. The velocity time history indicates that the magnitude of the slip displacement, which is provided by integrating the relative velocity between the point of interest and the base during the first slip phase, is larger than the corresponding one of the second slip phase.

The aforementioned trends are also evident at the point corresponding to the maximum shear stress (x=40m). In this case the positive static shear stress reduces the duration of the first slip phase and increases the duration of the second one. In addition, lower accumulated displacement is related to the higher critical acceleration of the first slip phase which resulted from the static shear stress. Inertia forces in both points of maximum and minimum shear stress have a similar effect and the shear strength is identical. Therefore, the difference between the slip displacements of the two points indicates the significant role of the static stress state. In contrast, the contribution of the inertia forces on the slip displacement development is evident, when observing the results at the point of the axis of symmetry. These trends are also valid for the subsequent cycles. However, since the results depend also in the initial conditions at the beginning of each cycle, it is rather complicated to provide a more comprehensive description. Summarizing the results related to sliding, the static shear stress variation along the interface (in combination with the inertia forces developed) was found to provide non-symmetrical sliding development at each point of the interface, resulting thus to permanent slip displacement. Furthermore, both parameters do not have a constant influence along the interface, due to the two-dimensional geometry of the examined model. More specifically, the shear stress exhibits an anti-symmetric variation, while the inertia forces and the shear strength exhibit a symmetric one leading to a complicated interaction of these factors and a non-uniform variation of slip displacements along the base of the earth structure.

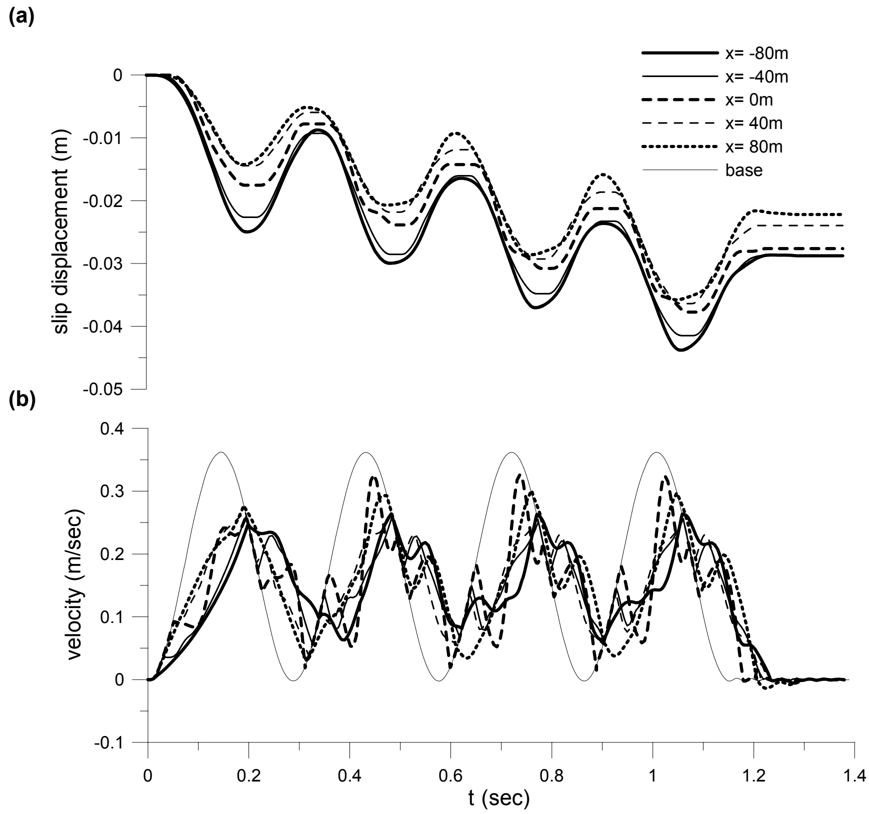

Figure 4 Accumulated seismic displacements and velocity time histories at five characteristic points along the geosynthetic.

In accordance, the effect of the differential slip (along the base of the landfill) on the axial stress of the geosynthetic layer is investigated. As the landfill is assumed to be founded on a rigid rock formation, axial stress is developed along the geosynthetic, mainly due to relative slip displacement between two subsequent nodes. Figure 5 shows the development of axial stress at five characteristic locations, where substantial magnitude was observed for the examined case, during the first slip cycle. The higher magnitude of axial stress is observed after the end of the first stick-slip phase, while in most locations the axial stress decreases during the second stick-slip phase. Additionally, the highest tension stress is observed at x= -20m, whilst among the examined cases only at x= 40m compression stress is developed.

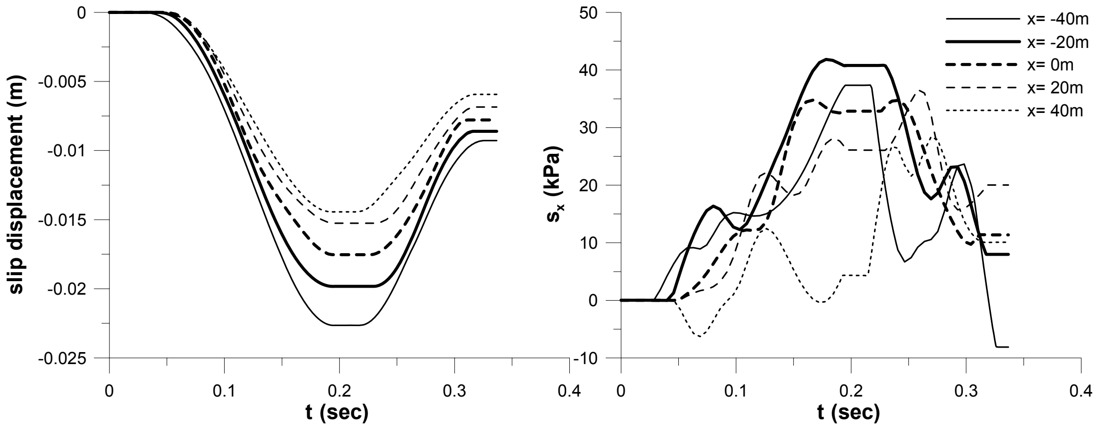

Figure 5 Accumulated seismic displacements and stress time histories at five characteristic points along the geosynthetic for the first cycle of the sinusoidal pulse.

In order to determine the influence of the tuning ratio on the aforementioned aspects of the interaction of the dynamic response and slip displacement development of a landfill, an extended parametric study was performed. Figure 6 presents the distribution of the permanent slip displacement and of the axial stress of the geosynthetic layer along the foundation of the geostructure. Results are calculated for several tuning ratios, regarding that only the structure's eigenperiod is varying. It is evident that for tuning ratios lower than unity, the permanent displacements are increasing relatively to the tuning ratio. On the contrary, for tuning ratios higher than unity, the increase of the tuning ratio results to lower absolute displacement. On the other hand, it is related also to more non uniform distribution of the displacements along the base. The significant variation of the displacement development along the base seems to be related to the stress of the geosynthetic layer. Therefore, the maximum tensile stress is increasing as the tuning ratio increases.

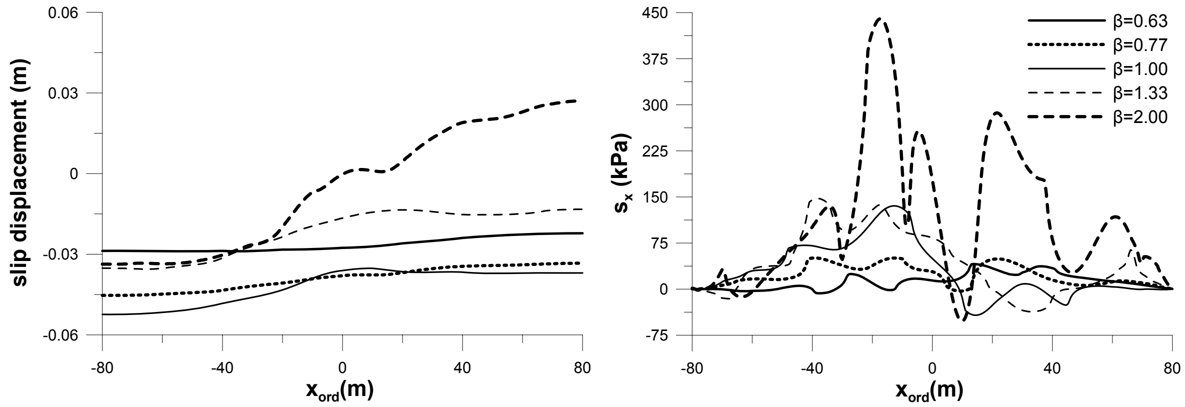

Figure 6 Effect of structure's eigenperiod: accumulated seismic displacements along the interface and stress distribution of the geosynthetic layer are presented.

4. CONCLUSIONS

The current study examined the seismic behavior of a waste landfill considering also the effect of the composite base liner. According to a simple Newmark - type model it is rather impossible that slip displacements could develop along two interfaces. The critical scenario, which was furthermore analyzed, was that the lowest shear strength interface located at the base of one of the geosynthetic layers of the composite liner. Efficient dynamic two-dimensional finite element analyses have provided a valuable insight into both the slip displacement and the stress development, which are considered to be the most important design parameters. The highest level of permanent displacement was observed for tuning ratio equal to unity, related to an overall instability potential generated from the rather uniform distribution of slippage. The highest level of tension along the geosynthetic was obtained for tuning ratio close to two, where to the most non-uniform distribution of slippage and therefore to critical stability of the slopes was observed.

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