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SEISMIC DISTRESS AND PROTECTION OF FLEXIBLE MEMBRANE LINERS OF SOLID WASTE LANDFILLS

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ABSTRACT

Seismic distress of solid waste landfills may result from any of the two consequences of a seismic event: (a) the transient ground deformation related to seismic wave propagation, (b) the permanent ground deformation caused by abrupt fault dislocation. Design provisions for solid waste landfills prohibit the construction of landfills in the vicinity of an active fault aiming to prevent the latter. Nonetheless, the impact of applied permanent deformation on the system components of landfills and on the waste mass has not been fully demonstrated yet. For this purpose, efficient finite-element analyses were performed, taking also into account the potential slip displacement development along the interfaces formulated on each side of the flexible membrane liner (FML). It is shown that base fault dislocation causes significant plastic strains at each one of the components of the waste landfill. Therefore, four hazard levels were identified considering the most critical aspects for the safe function of a landfill. Subsequently, the ability of several potential mitigation measures to reduce the permanent deformation was examined, by developing and analyzing elaborate finite element models. These measures were developed in accordance to the two basic components of typical composite liners, i.e., clay and geomembrane. Evidence is provided that the efficiency of the proposed measures on minimizing the impact of the applied fault displacements is significant, since the deformations of the FML were remarkably reduced. Hence, the results of this study justify the applicability and effectiveness of mitigation measures for the protection of FML against fault dislocation.

Keywords: waste landfills, geomembranes, fault rupture, permanent deformations, mitigation measures.

INTRODUCTION

Design of solid waste landfills is of great socio-economic and environmental importance, since a potential failure may result in contamination of the surrounding soil or water. Hence, public health and environmental concerns have led to the formulation of design guidelines for waste landfills in European Union (EC, 1999) and USA (EPA, 1993). Both regulations entail detailed provisions for the design and construction of the composite liner system and the leachate collection system. These two systems are expected to prevent leakages to the environment, and therefore provide a safe isolation of waste material from the surrounding soil. In particular, a typical composite liner system comprises of two parts, a clay layer of 0.6m thickness and a flexible membrane liner of thickness equal to 0.75mm or an HDPE geomembrane of 1.5mm thickness (EPA, 1993). Moreover, EU regulations are more demanding, since the minimum thickness of the clay layer is required to be equal to 1m. Nonetheless, seismic design provisions

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are included only in EPA (1993) guidelines and they focus mainly on the location of the waste landfill. More specifically, in order to prevent the impact of a fault rupture, it is recommended that a waste landfill should not be cited in a distance closer than 60m from a Holocene period fault. The difficulty in fulfilling this provision becomes even more pronounced as there is continuous urban development even in earthquake prone regions. Whenever the location of the landfill is selected to be closer than 60m from an active fault, then it is mandatory that the structure is properly designed to (a) withstand excessive peak ground accelerations (0.1g – 0.75g), (b) avoid any potential slope instabilities and (c) ensure the stability of the foundation soil (EPA, 1993). Even though it is advised to account for the excessive inertia distress taking place in the vicinity of the fault rupture, the induced permanent displacements seem not to be a concern of the suggested design process.

However, seismic distress may be imposed on engineering structures and infrastructures not only due to seismic wave propagation, but also due to fault movement. The vulnerability of engineering structures to permanent displacements resulting from fault movement has been observed after several earthquakes. Damages have been reported to pipelines, embankments and buildings (Bray & Kelson, 2006) as well as dams (Louderback, 1937), due to the strike-slip fault dislocation after San Francisco earthquake (1906, California). More recently, the Kocaeli and Duzce earthquakes (1999, Turkey) triggered by the north Anatolian fault have also revealed useful aspects on the performance of buildings and bridges when subjected to permanent deformation (Anastasopoulos & Gazetas, 2007; Bray, 2001). The rupture of the reverse fault of Chelungpu, has damaged several buildings located within a distance of 5-10m from the fault scrap (Kelson et al., 2001). These failures have been attributed to the significant ground deformations taking place either as slope inclination or as vertical displacements in the vicinity of the fault outcrop. A surface rupture associated with the same fault has caused the initiation of severe deformations at the toe of the fill slope of Wu Feng, a canyon type landfill in Taiwan (Anderson, 2000). Although the landfill was lined with an HDPE geomembrane, rupture of the liner was not reported and the case has not been investigated ever since.

Increased research interest has been observed during the past decades on seismic design of waste landfills. This has initiated after the observed damages of the 1994 Northridge earthquake (Matasovic et al., 1998). Several aspects of the seismic distress of waste landfills have been investigated, like the dynamic response of landfills in terms of acceleration levels (Yegian et al., 1998; Rathje & Bray, 2001; Psarropoulos et al., 2007), the slope stability assessment (Bray et al., 1995; Kramer and Smith, 1997; Matasovic et al., 1998b) or the deformation of the geomembrane liners (Thusyanthan et al., 2007; Zania et al., 2010). Nevertheless, all the aforementioned studies are addressing the various aspects of the design arising from the inertial loading, i.e., the effects of the transient displacements taking place during the strong ground motion.

It is evident that the impact of an abrupt fault dislocation on waste landfills has not yet been fully understood and moreover design provisions do not encounter appropriately this issue. Therefore, in the current study the distress developed after fault movement taking place at the foundation of a solid waste landfill is investigated. For this purpose, efficient finite element models were developed and the permanent deformations occurring not only along the composite liner, i.e., clay layer and geomembrane, but also within the waste mass were obtained. The results indicate that severe distress is expected, thus four characteristic hazard levels were specified. Aiming at reducing the detrimental impact of the fault rupture propagation, seven alternative mitigation configurations were implemented. These potential mitigation measures can be easily constructed at the foundation of a waste landfill to prevent damages at the FML after a fault movement. The efficiency of each one of the seven configurations, in terms of increasing the fault displacement which is required to damage the composite base liner, was estimated. Moreover, the analyses of the numerical models have revealed that the proposed mitigation measures are efficient in protecting the geomembrane, which remains intact up to moderate magnitude of fault dislocation.

DISTRESS OF THE WASTE LANDFILL

The assessment of fault rupture propagation through soil deposits has been performed in the past years utilizing experimental setups, small scale shear boxes (Cole and Lade, 1984; Lin et al. 2006; Johansson and Konagai, 2006), and centrifuge apparatus (Lee et al., 2004) as well as the finite element or finite difference method (Lin et al., 2006; Anastasopoulos et al., 2007; Loukidis et al., 2009; Athanasopoulos et al., 2007). The numerical studies have proven that the accuracy of the obtained results is strongly dependent on the discretization of the mesh, the constitutive model for the soil material behaviour and the boundary conditions. Hence in the current study special attention has been driven to these issues. The finite element models were developed in the commercial code ABAQUS. The cross section of the analysed above ground landfill was trapezoid and a composite liner system was considered along its base. The latter comprises of a 1m depth clay layer and a 1.5mm thick HDPE geomembrane (see Figure 1). The fault trace is assumed to be located at the bedrock foundation of the landfill along the axis of symmetry of the model. The applied displacements were considered constant along the hanging wall and representative of a normal fault with dip angle equal to 45^o. Hence the corresponding boundary conditions were included in the analyses.

Description of the numerical model

The finite element discretization of the model was performed utilising plane strain elements for soil and waste material and truss elements for the geomembrane, since only tensile stiffness can be provided by geosynthetics. The global element size was approximately equal to 0.25m, almost 1% of the total height. Moreover, quadrilateral elements were applied in the soil and waste material in vicinity of the fault, for a distance equal to 60m at each side of the fault trace, while near the corners triangular elements were used. A detail of the central part of the finite element mesh is also shown in Figure1. The influence of the element size on the numerical results was found to profoundly affect the fault rupture propagation through waste material and the resulting surface deformation, while the axial stresses in the geomembrane were not affected by the discretization (Zania, 2009).

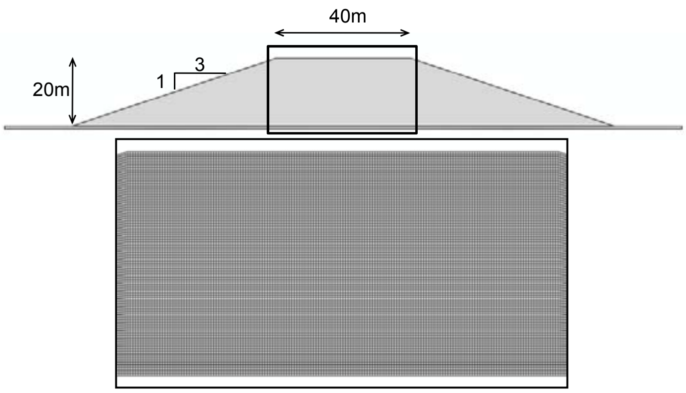


Figure 1. Geometry of the waste landfill analysed in the current study. A detail of the finite element mesh is also depicted.

In addition, the three basic parts of the model, i.e., waste material, geomembrane and clay layer, were considered to interact through a contact formulation. More specifically two couples of contact surfaces were developed: (a) the lower surface of waste material with the upper surface of the geomembrane (first interface), and (b) the upper surface of the clay layer with the lower surface of the geomembrane (second interface). The distribution of the normal stress, which is transmitted through the contact of the two surfaces, with respect to the vertical displacement was assumed to be rigid, thus, no over-closure was allowed between the two connected parts. Regarding the shear strength, it attains a rigid–plastic behaviour, with angles of friction for the first and second interface equal to 9° and 12°, respectively. A thorough literature review on the interface properties of geosynthetic interfaces has shown that the parameters affecting their shear strength are numerous (Zania, 2009). More specifically, for HDPE geomembranes in contact with clay or geotextile (which is always placed over the geomembrane for protection in a waste landfill) these factors are: the shear strength of the clay, the test conditions (drained or undrained), the polymer, the mass per unit area, the fibre and fabric typed as well as calendering of the geotextile, and the surface roughness of the geomembrane. Within the wide range of the proposed shear strength parameters, the aforementioned values used herein are considered appropriate. These values of angles of friction approach the lower range of the corresponding reported in the literature and they are aligned with the other assumptions of the model.

Moreover, the shear strength of waste material has been a subject of intense research during the past decades. Several test procedures have been employed, like direct shear tests and triaxial tests, in large and small scale experiments. However, in order to analyse the behaviour of the waste material on applied permanent deformation, the failure envelopes proposed after large scale direct shear tests were considered more appropriate (Houston et al., 1995; Zekkos, 2005; Singh, 2008). Hence, the variation of the cohesion intercept is within the range of 5-43kPa and of the angle of friction lies between 30° and 36°. In the current study the Mohr–Coulomb failure envelope applied to the waste material was characterized by cohesion equal to 15kPa and angle of friction equal to 36°. The undrained shear strength of clay material was assumed equal to 53kPa and it was modelled using the Mohr-Coulomb criterion as well. A sensitivity analysis of the impact of the clay stiffness to the fault rupture propagation has provided evidence that the increase of the stiffness of the clay material may not affect the permanent deformation within waste mass, but it increases the distress of the geomembrane. Finally an elasto–plastic stress–strain relationship was assigned to the geomembrane, assuming the Young's modulus equal to 300MPa and the yield stress equal to 16MPa. An ultimate stress was not specified since geomembranes can experience up to 300%-500% tensile strains without breaking (Koerner, 1994). The parametric study presented herein does not account for the phreatic levels, hence total stress analyses (drained) were performed.

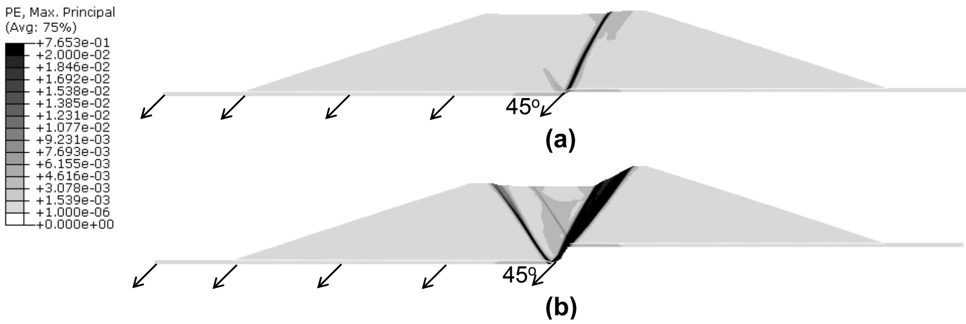


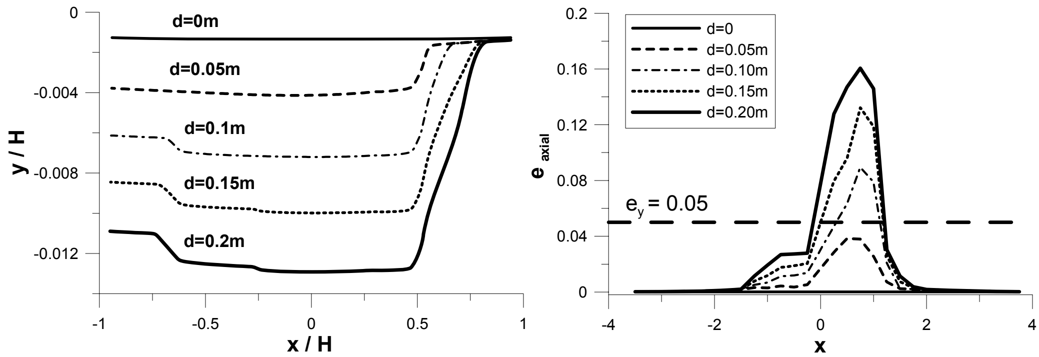
Figure 2. Plastic strain contours within the waste landfill. The development of the failure surfaces is shown for vertical component of the fault displacement equal to: (a) 4cm, and (b) 20cm.

Impact of fault rupture on waste landfills

In Figure 2 the plastic strain contours are plotted, in which the zones of high plastic strains represent the failure surfaces developed within the waste mass. Note that the deformation scale is exaggerated by a factor of 25, so that the deformation pattern of the landfill becomes evident. It was observed that only low magnitude of applied displacement is required for the fault rupture to reach the geomembrane (2.4cm), while this value increases slightly for the failure surface to reach the surface of the landfill (3.7cm).

For larger magnitude of applied displacement a secondary failure surface originates from the fault tip and a graben is developed in the surface of the waste landfill, similarly to the observations on propagation of normal shallow dip fault within cohesionless soils (Cole and Lade, 1984; Loukidis et al., 2009). In addition, a third failure surface can be observed in Figure 2b, which initiates in a vertical distance equal to 2m from the geomembrane and is almost parallel to the secondary failure surface. The primary failure surface propagates with an angle equal to 65^{o}, while the inclination of the secondary one is 55^{o}. The distribution of the surface deformation is shown in Figure 3a. It is evident that the fault outcrops in a distance equal to 0.5H from the fault tip, but the increase of the fault displacement extends further the region of significant deformation (large inclination of the surface) up to a distance equal to 0.85H. The slope crest is located at a distance equal to the height of the landfill away from the fault tip, thus, the permanent deformation do not affect the slope stability for the examined case.

Furthermore, the induced permanent deformations during the fault rupture cause the increase of the axial strains along the geomembrane (see Figure 3b). The yield stress is reached for a base fault dislocation (vertical component) equal to 6.4cm, while the maximum strain is observed almost at the projection of the fault. The part of the geomembrane, which experiences severe tensile strains, lies over the foot wall. In addition, the axial strains are reducing in a short distance from the fault tip, while they are almost equal to zero in a distance of 2m away from the fault tip. It should be also mentioned that along the lower interface of the geomembrane slip displacements take place. The maximum slippage is equal to 2cm and corresponds to vertical fault displacement equal to 20cm. It is expected that slip displacements along the lower interface reduce the distress of the geomembrane. However, due to the development of plastic deformations along the geomembrane and the moderate magnitude of the applied fault displacement the beneficial role of slip accumulation is not substantial.



(a) (b)

Figure 3. (a) Variation of the normalized vertical displacement to the height of the landfill (y/H) with respect to the normalised deformed horizontal coordinate (x/H); (b) Variation of the axial strain along the geomembrane (fault tip is located at x=0m). Results are shown for four levels of vertical fault displacement.

The analysis of the behaviour of waste landfills when subjected to permanent displacements has provided evidence of their vulnerability. Even though only one indicative case is presented, four characteristic hazard levels can be proposed for waste landfills founded in the vicinity of active faults, namely:

- Hazard level 1: failure of the clay layer because of excessive permanent deformation;
- Hazard level 2: failure of the waste mass resulting to surface exposure of the fault rupture;
- Hazard level 3: failure of the geomembrane, when the yield stress is reached;
- Hazard level 4: failure of the cover liner system caused by excessive surface deformation.

The design issues of geomembranes of the composite liner system of a landfill are usually carried out considering the yield stress obtained in a wide-width test. Therefore, even though HDPE geomembranes have the ability to deform beyond their yielding (without rupture) the yield stress is selected in this study as the criterion for the third hazard level. In order for the last hazard level to take place, the allowable deformations of the composite base liner are expected to be exceeded. Consequently, the last hazard level is not examined hereafter, and the next part of the study focuses on mitigation measures for the protection of waste landfills against the first three hazard levels.

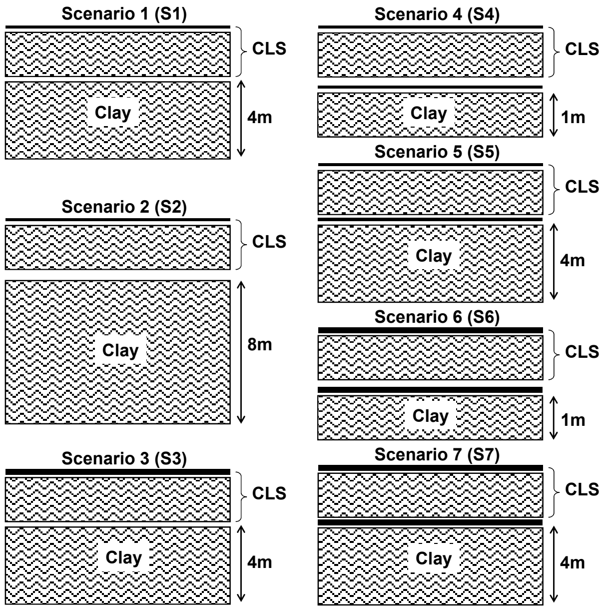


Figure 4. Alternative configurations of the examined mitigation measures against fault rupture in solid waste landfills.

MITIGATION MEASURES

In this section the efficiency of the proposed mitigation measures is investigated in reducing the distress of the examined landfill provided by fault dislocation at its base. The examined configurations, shown in Figure 4, were developed following the concept of strengthening the composite liner system. Moreover, geomembranes have been selected among the other types of geosynthetics, due to their ability to decouple the shear stresses transmitted by a fault movement, as it was reported from field observations (Bray, 2001). Initially, the potential increase of the clay layer thickness was investigated (Scenarios 1 & 2). Subsequently, the increase of the thickness of the existing geomembrane (3mm), besides the increase of the total clay thickness to 5m (Scenario 3), the application of an additional geomembrane and clay layer of thickness equal to 1m and 4m (Scenarios 4 & 5), and finally the increase of the thickness of the geomembranes (3mm) of the former scenarios (Scenarios 6 & 7), were considered. Each one of the aforementioned configurations was considered to be constructed at the foundation of the landfill depicted in Figure 1, and the corresponding finite element model was developed. The assumptions outlined regarding the numerical analyses were also adopted for the following parametric investigation.

Impact of the increase of the height of the clay layer

The first and second potential mitigation measures consider an increase of the thickness of the clay layer by 4m and 8m, respectively. The plastic strain contours for these two cases are shown in Figure 5 compared to the case where no mitigation measures are applied. The application of the first scenario does not alter the direction of the fault rupture propagation within waste material. However, for the second scenario the failure surface develops in a plane inclined with respect to the horizontal at 55^{o} within the clay layer and 65^{o} within the waste material. Therefore, in the latter case the fault rupture approaches the slope crest. The required vertical fault dislocation for the rupture to reach the geomembrane is equal to 3.7cm for both mitigation measures, thus only a slight increase is observed compared to the corresponding value for the case of no mitigation measures. Moreover, the increase of the thickness of the clay layer has resulted to an offset of the secondary failure surface. More specifically, the latter propagates in a distance approximately equal to 2m above the geomembrane, while the direction of propagation is the same as in the case of no mitigation measures (55^o). The permanent deformation at the surface of the landfill decreases when referring to the same magnitude of fault movement. This observation is attributed to the fact that the total height of the soil and waste, through which the fault propagates, increases. In addition, the increase of the thickness of the clay layer has reduced significantly the slip displacements along the two interfaces. Only small relative displacements were obtained and they occurred mainly along the upper interface due to the reduction of the permanent deformation directly applied to the geomembrane.

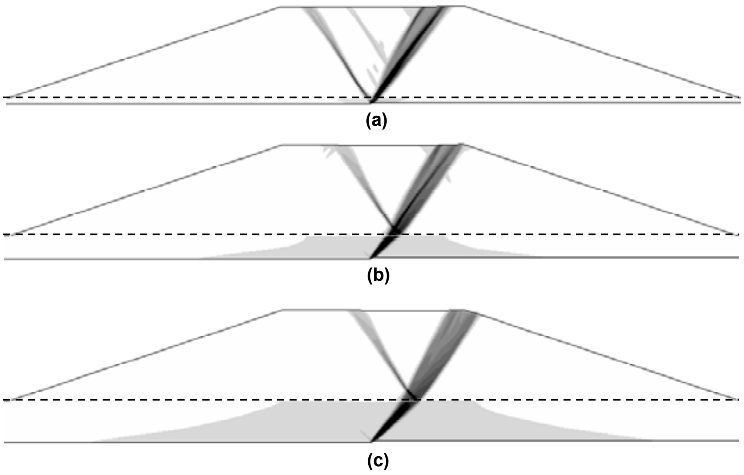


Figure 5. Plastic strain contours within the waste landfill corresponding to vertical base fault dislocation equal to 20cm. The cases of (a) no mitigation measures, (b) Scenario 1, and (c) Scenario 2 are shown.

This behaviour has direct implications to the distress of the geomembrane as well. The vertical component of the fault displacement, which is required to produce maximum axial stress equal to the yield stress to the geomembrane, increases to 14.2cm and 21.2cm for the first and second scenarios, respectively. Figure 6 illustrates the significant decrease of the axial strains along the geomembrane after the application of the two scenarios. In addition, it is evident that the region of maximum axial stresses has been offset by a distance of almost 4m and 8m for the first and second scenario, respectively. This means that the maximum axial strain develops close to the projection of the fault on the plane of the geomembrane. Though both scenarios have efficiently decreased the plastic strains developed along the geomembrane, the beneficial effect of the second scenario is more prominent. Nevertheless, for the second scenario the axial strains induced by the applied permanent deformation take place along a larger portion of the geomembrane.

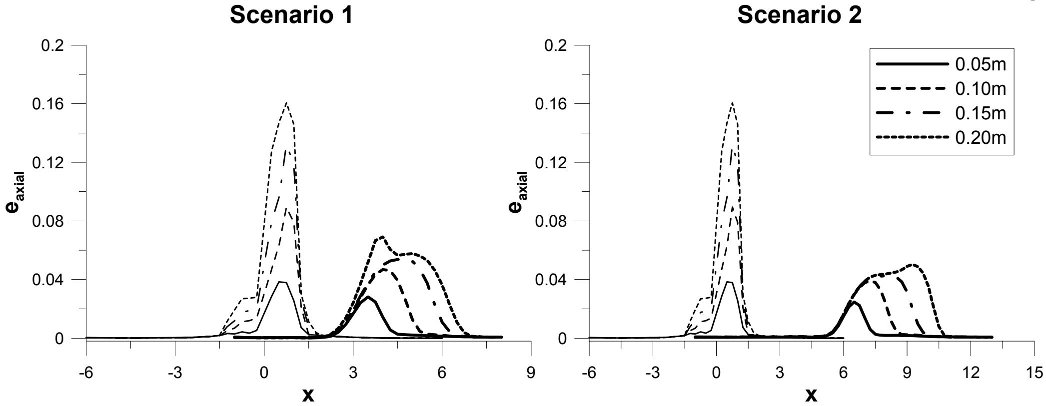


Figure 6. Effect of the increase of the thickness of the clay layer. Variation of the axial strain along the geomembrane (fault tip is located at x=0m). Results correspond to the case without mitigation measure and Scenarios 1 & 2 (bold lines) for four levels of vertical fault displacement.

Impact of increasing the thickness or the number of the geomebranes

Enhancing the role of the geomembranes in the mitigation of the consequences of the fault rupture propagation has been confronted by: (a) increasing the thickness of the geomembranes and (b) including additional geomembranes. The application of these modifications to the first scenario has led to the configurations of Scenarios 3 & 5. The fault rupture propagation is not altered comparing the three scenarios, meaning the inclination of the two failure surfaces as well as the required fault dislocation for the surface exposure of the fault is identical for these cases. This becomes evident by the variation of the normalised surface deformation shown in Figure 7a. Only minor increase on the permanent surface deformation is observed for the third scenario, which emerges as a higher inclination at the region of the primary failure surface and a slightly larger vertical displacement along the graben.

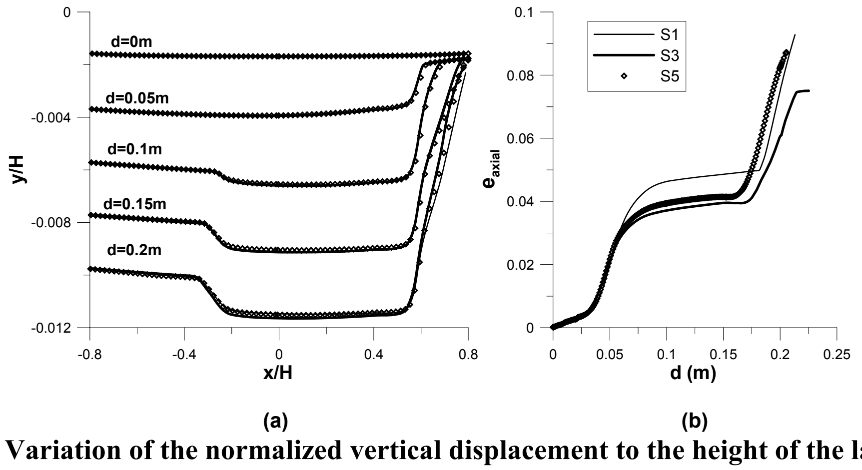


Figure 7. (a) Variation of the normalized vertical displacement to the height of the landfill (y/H) with respect to the normalised deformed horizontal coordinate (x/H); (b) Variation of the maximum axial strain with respect to the vertical component of the fault displacement. Results are shown for Scenarios 1, 3 & 5.

Additionally, it seems that the increase of the thickness of the geomembrane (Scenario 3) is more efficient in reducing the maximum strains of the geomembrane than the inclusion of an additional geomembrane (Scenario 5). The required vertical component of the fault movement for the geomembrane to yield is

19.5cm and 17.6cm for Scenarios 3 & 5, respectively. The beneficial role of the increase of the thickness of the geomembrane is also demonstrated in Figure 7b. The maximum axial strain along the geomembrane reduces also when an additional geomembrane is considered (S5), but only for base fault displacement lower than 17cm. Nonetheless, the increase of the thickness of both geomembranes of Scenario 5 generates the configuration of Scenario 7. In this case the vertical fault displacement for the geomembrane to yield increases to 20.5cm and the maximum axial strains of the upper geomembrane are substantially decreased (see Figure 8b). However, the increase of the thickness of the geomembranes has also resulted to the increase of the permanent deformation at the surface of the landfill (Figure 8a). Note that this trend was also observed when comparing scenarios 1 & 3.

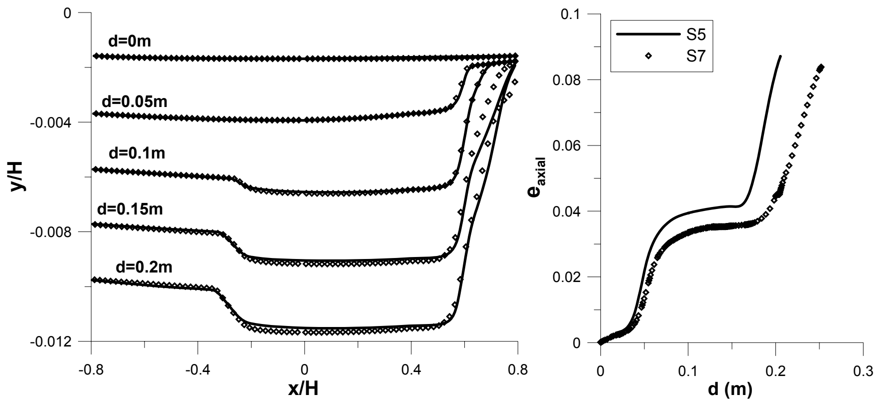


Figure 8. (a) Variation of the normalized vertical displacement to the height of the landfill (y/H) with respect to the normalised deformed horizontal coordinate (x/H); (b) Variation of the maximum axial strain with respect to the vertical component of the fault displacement. Results are shown for Scenarios 5 & 7.

The last two scenarios are representative of a double composite liner (Scenarios 4 & 6). Thus, the mitigation measure comprises of a clay layer of thickness equal to only 1m and a geomembrane. The fault rupture propagation for these cases is not modified with respect to the case of no mitigation measures. The vertical fault displacement required for the primary clay layer to be ruptured is slightly increased to 3cm, regardless of the thickness of the geomembrane. In accordance, the permanent deformation variation at the surface of the landfill (Figure 9a) remains almost unaffected, except from the fact that the increase of the thickness of the geomembranes has resulted to a minor increase of the vertical displacements at the surface. These two scenarios were also the only ones for which slip displacements took place. Figure 9b shows the influence of the applied mitigation measures on the decrease of the slippage which develops along the lower interface. In addition, the application of the two mitigation measures increase the value of vertical fault displacement for which the geomembrane yields, to 8.1cm and 14.8cm, respectively.

Figure 10a shows the distribution of the axial strains along the upper geomembrane for the two scenarios, while in Figure 10b the comparison of the maximum axial strains of the two mitigation measures with the case of no measures is depicted. It is evident that the application of Scenarios 4 & 6 has resulted to decrease of the maximum axial deformations of the geomembrane, especially for fault displacement greater than 5cm. The part of the geomembrane that experiences significant distress, does not exceed a distance of 4m from the fault tip. The maximum axial strain takes place on the projection of the fault for Scenario 4, while for Scenario 6 this position is slightly shifted towards the fault tip.

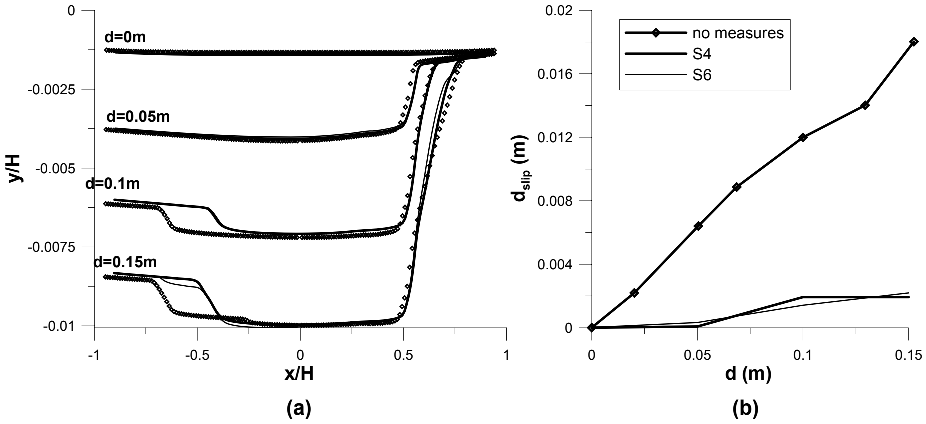


Figure 9. (a) Variation of the normalized vertical displacement to the height of the landfill (y/H) with respect to the normalised deformed horizontal coordinate (x/H); (b) Variation of the maximum slip displacement with respect to the vertical component of the fault displacement. Results are shown for the case of no mitigation measures and for Scenarios 4 & 6.

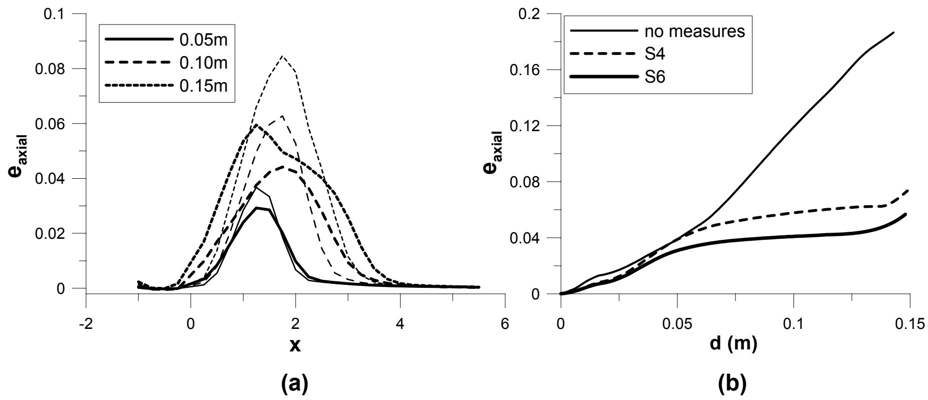


Figure 10. (a) Variation of the axial strain along the geomembrane (fault tip at x=0m) for Scenarios 4 & 6 (bold lines) for three levels of vertical fault displacement; (b) Variation of the maximum axial strain with respect to the vertical component of the fault displacement.

CONCLUSIONS

The current study investigates the impact of fault movement on solid waste landfills. Initially, the potential hazards associated with fault displacements were identified and afterwards mitigation measures were proposed and analysed. It has been proven that the increase of the thickness of the clay layer as well as the increase of the thickness of the geomembrane has substantially decreased the developed deformation of the geomembrane. The efficiency of the proposed mitigation measures has been assessed defined as the relative increase of the magnitude of the applied fault displacement for the development of each hazard level. The results shown in Table 1 demonstrate that the proposed mitigation measures are particularly efficient for the protection of the geomembrane (Hazard level 3). In detail the less effective scenario was the one of the double composite liner (Scenario 4). Even though the second scenario appears to be the most effective, since it attains the highest efficiency levels, the construction of a clay layer of thickness equal to 8m might not be feasible or economic sustainable. It is evident that the efficiency increases as the thickness of the clay layer increases when additional geomembrane is applied, and this becomes even more pronounced as the thickness of the geomembranes is also increased. The aforementioned trends should be critically evaluated with respect to cost estimates as well, so that the optimum mitigation measure is selected. Nonetheless, the results of the parametric numerical analyses are encouraging the application of such mitigation measures to protect the composite liner system of waste landfill against fault movements. Similar seismic mitigation approaches can be developed for the protection of other infrastructure and buildings as well.

Table 1. Efficiency of the proposed mitigation measures for the three hazard levels.

Mitigation Measures	Efficiency (%)		
	Hazard Level 1	Hazard Level 2	Hazard Level 3
Scenario 1	52.9	8.1	121.9
Scenario 2	57.0	18.9	231.3
Scenario 3	61.2	5.4	204.7
Scenario 4	24.0	5.4	26.6
Scenario 5	61.2	5.4	175.0
Scenario 6	32.2	2.7	131.3
Scenario 7	77.7	2.7	220.3

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