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Original Research Article

PERFORMANCE OF SOLID WASTE LANDFILLS UNDER EARTHQUAKE-INDUCED VIBRATIONS

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Abstract

The stability inside the waste, internal stability, and co-stability between the elements of the insulation system and the landfill bed should be considered in the landfill design. The stresses and the resulting deformations in both mineral and geosynthetic materials of the insulation system must be controlled in the design, so that an unpredictable flow path is not created. Besides, long-term durability in the insulation system should be considered. An evaluation of the durability of the system requires knowledge of the interaction between the components and the waste as a settling object. The numerical modeling methods can be used to evaluate the local instability. In this study, a landfill constructed in the UK has been modeled in ABAQUS finite element platform and was verified with the results of obtained data from precision instruments at the landfill site. Then, by applying the earthquake excitations, the seismic behavior of the solid waste landfill under Far-Field and Near-Field earthquakes and their effect on the durability of the landfill wall system were investigated. The outputs include maximum displacement, maximum stress, the most critical state, and investigation of yield stress and rupture of the geomembrane layer. The results indicated that in the landfill wall, the maximum displacement occurs in the waste section. It occurs especially between the boundary of natural soil and waste. It

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was also observed that the geomembrane layer under the earthquake loadings had experienced some ruptures.

Keywords: landfill, numerical modeling, earthquake force, landfill wall stability, geosynthetics, FEM, ABAQUS, rupture

1. INTRODUCTION

Every year, countries deal with millions of tons of waste. Municipal solid waste includes household waste and some industrial waste. Landfill is the most common and cheapest way to dispose of wastes, so understanding the behavior of solid waste landfills under seismic loading that causes rupture and environmental, groundwater, soil pollution, and problems for humans, is of great importance. The seismic behavior of landfills is studied by the use of experimental and mathematical methods. Landfill design principles against earthquakes are similar to the design of earthen dams and embankments. Mathematical methods of landfill analysis are based on stability methods and dynamic evaluation methods. In the stability method, the design is conducted based on the quasi-static method and deformation analysis-based methods. Determining the dynamic properties is the first step in analyzing the municipal solid wastes under seismic conditions. In the reports, the most observed damage in the landfills has been in the surface cracking of the soil surface, especially the border between natural soil and waste. In a landfill, the waste represents the main structural and controlling elements of both the landfill stability and the integrity of its coating system [1-5].

The municipal solid landfills are often composed of multilayer insulation systems made of synthetic and mineral materials. Over the last 20 years, extensive research has been conducted on the interaction of materials and the performance of geosynthetic materials in terms of durability. In the recent decade, geosynthetic materials have been widely used in construction. In particular, they have been used as a suitable insulator against conventional waste (household and municipal solids) and in landfill design. Multiple usages and easy installation have led to their acceptance by designers and contractors. The results of this research have led to many advances in the field of design, especially the design of insulation systems. Studying the durability and stability of insulation systems with an emphasis on common engineering problems related to geosynthetics in the landfill environment. The researchers' studies include phased fabrication, softening strain, progressive failure, tensile stress in materials, re-presentation of waste properties and behavior, weathering, and waste decomposition. By considering this point, the use of numerical analysis methods will be of great importance. Measuring the behavior of materials on a real scale, at the project site, and under the operating conditions can provide valuable information on the performance of the Landfill insulation system as well as providing a better understanding of the behavior of the composite insulation layer systems. Despite the large number of numerical modeling programs to evaluate the stability of the insulation system, there is limited data to validate these modelings. Common analytical methods are the boundary element method (BEM), the finite element method (FEM), and the finite difference method (FDM) [6-8].

Feng et al. (2019) used a landfill with geomembrane and geosynthetic clay liner (GCL) underneath. A numerical model has been used to analyze the deformation and state of the linear system (GCL and geomembrane) under earthquake effect due to the dynamic interaction of the landfill with its embankment. This model has been validated with the experimental results of a centrifuge test. A series of finite element two-dimensional dynamic analyzes have been performed on a landfill In the presence of a linear system to determine its deformation mechanism. The results showed that the GM (geomembrane) tension is mainly affected by non-uniform frictions between the upper and lower surfaces, while the GCL shear strain is strongly related to the external landslide slip, and the strength of the hybrid linear system plays an important role in the force distribution. The roughness and coarseness of the GM are more favorable for controlling landfill deformation, but it should be noted that the GM tensile and shear strain of the GCL should reach a high level at the same time [9].

In 2018, Pavanelloa et al. evaluated the shear strength of the dynamic joint surface between geosynthetics, using the results of both sloping plates and shocking tests. In the second experiment, a tool was provided for analyzing the joint surface behavior under seismic recorded conditions. For this purpose, two common levels of geosynthetics were tested with dynamic loading behavior that has different displays. Contact with different types of nonwoven polypropylene geotextiles Experimental results show that the dynamic friction in a seismic event created according to the same law as by the free sliding tests and vibration tests performed with sinusoidal base movements depends on relative velocity. In addition, for two different types of joint surfaces studied, the dynamic friction may be greater than, or equal to the static friction [10].

In 2018, Pain et al. discussed landfill behavior, under ground motion acceleration, considering damping properties in MSW. The purpose of the study was to provide an integrated methodology for seismic acceleration characteristics in the landfill, as well as the safety factor and yield acceleration values for a sample with a normal geometric position located on a hillside. Traction-dependent dynamic properties (shear modulus and damping ratio) of MSW are used as a seismic safety factor to amplify the landfills through an iterative scheme to calculate the shear modulus and damping ratio. The maximum shear displacement created in the landfill for significantly lower input frequencies is significantly greater, since, at lower frequencies, seismic inertial forces were presented at all depths, whereas, at higher frequencies, they were out of phase. The calculated safety factor values by the use of the present method were higher than the conventional quasi-static method [11].

Zamara et al. (2012) used readings of instrumentation installed at the landfill site for three years and compared the measured values with the numerical modeling results of the landfill wall insulation system during the construction period in FLAC software. The results presented in this study indicated the important effect of temperature on the displacement of geosynthetic materials. They used precision instruments to investigate the performance of insulation and drainage systems in the landfill wall to report the stress-strain due to the residual weight generated in the insulation system, which included geomembrane, geotextile, and dense clay. Many deformations were observed in the part of the landfill wall that was exposed to sunlight due to the performance of part of the geotextile [12].

Nowadays, the use of the finite element methods (FEM) (due to the complex and nonlinear nature of soil) is very important for studying the interaction of soil with various reinforcements and also for predicting the shear behavior of soil. It has also become common to use a nonlinear finite element analysis program such as ABAQUS for such simulations [13-20]. In this research, a three-dimensional simulation of the wall insulation system of a landfill is conducted (Milligate Landfill in Yorkshire, England) with accurate scaling and modeling verification with the recorded results of on-site instrumentation. In a later stage, the foundation was modeled by considering the wall and dry soil conditions. Then by applying the earthquake loadings, the seismic behavior of the landfill was studied under near- and far-faults conditions, and its effect on the durability of the landfill wall system, which includes evaluation of the maximum displacement, maximum stress, the most critical condition, yield stress and rupture of the geomembrane layer.

2. THEORETICAL BACKGROUND

2.1. Scientific Waste Landfill and the Main Components

A Sanitary landfill is the discharge of waste into a trench, compacting and covering it with soil in a completely systematic way so that the waste is wholly enclosed inside the capsule and leachate and gas infusion are not allowed to penetrate to the surrounding cells. Leachate and gas collection systems as well as leachate treatment, are included in a landfill. A sanitary landfill includes a waste disposal site, surface control system, biogas observation and control system, biogas collection facility, surface runoff structure and control structure, sediment pit, layered systems, structural management system, and an area with a radius of 90 meters in the UK has been selected for this investigation. Figure 1 shows the outline of a landfill on which different components are shown [21].

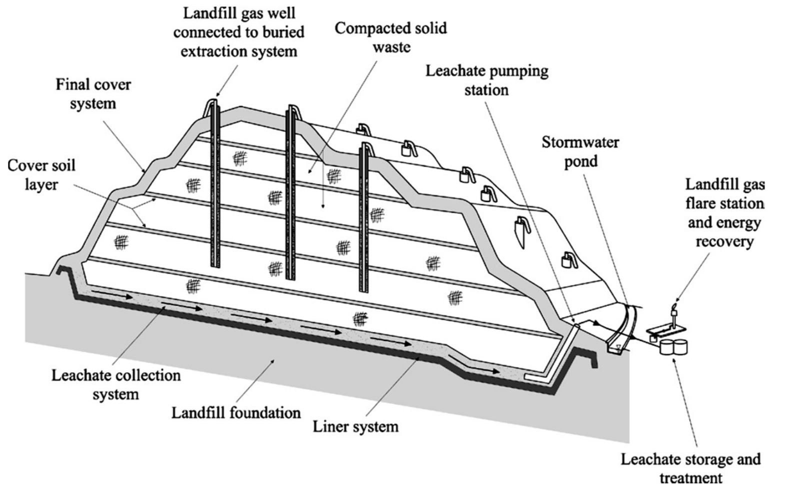

Fig. 1. Main components of a landfill [21]

<u>Impermeable layers (liners):</u> Impermeable or insulating layers act as the first barrier against leachate flow; therefore, they play a crucial role in the performance of landfills. The most important feature of these layers is their very low impermeability to pass the minimum amount of leachate. Usually, the permeability coefficient of landfills' insulation layers should be less than 10^9.

<u>Drainage layers:</u> Generally, these layers are made of sand and coarse grains, and because of this, they are highly permeable layers so that they can pass the leachate in some way. The leachate enters the drainage pipe after passing through the soil layers and is directed out of the landfill by a pump. Geosynthetic materials (such as geonet and geotextile) can also be used for drainage.

<u>Protective or separating layers:</u> These coatings are used to protect insulating layers such as geomembrane, and they are also used to separate different layers in the floor and wall.

<u>Leachate collection system:</u> The produced leachate in the landfill should be collected with a suitable system. This is done by installing a suitable slope on the floor of the landfill and by using the permeable layers that quickly pass moisture

and leachate to lead them toward the drainage pipes. Depending on the dimensions of the burial, a network of secondary and main drainage pipes is used, and the leachate produced in the burial is directed to a pond located at the end of the drainage pipe network. If the landfill is built in a dry climate and the amount of leachate from waste moisture, chemical, and biological interactions is low, the height or limit of leachate collected in the pond may not be high during the life of the landfill. In this case, the leachate remains on the floor of the landfill, and its pollution will decrease over time. If the collected volume is significant, it should be pumped out of the landfill and treated in various ways.

Biogas collection system: Anaerobic reactions produce gas inside the landfill, and approximately 98% of the produced gas is carbon dioxide (CO_2) and methane (CH_4). (CO_2) is heavier than air, so it moves downward and comes out with the leachate. (CH_4) is lighter than air and moves upwards. Until the top of the landfill is not covered, this will not cause a problem. However, a proper system should be considered for collecting and discharging the gas from the landfill. In some cases, (CH_4) gas is used to burn energy. Otherwise, the collected gases will enter the atmosphere through a suitable chimney. For this purpose, some wells are drilled vertically or horizontally at the landfill, so after reaching the final landfill, the gases can be transferred to gas treatment chambers. After the purification process, the energy produced from these gases can be used for various purposes, such as generating electricity and heavy machinery's fuel.

Landfill's final cover: When the landfill is filled, its exploitation ends. Solid waste should be covered with a layer consisting of several layers, and a green space should be created on it. The end of a landfill operation does not mean the end of its life. Landfill lifetime continues for decades after the final cover is created. During this time, the landfill acts as a biological reactor, and the chemical and biological interactions will continue aerobically and anaerobically inside it.

Surface water collection system in the final coverage: Surface water must be collected in and around the landfill and directed out of the workshop in order to reduce leachate production. As landfills are not always built next to natural springs, low-cost ways should be considered to lead the surface water. Calculating the discharge of collected water is very important in designing a system. Also, the design should be done in such a way as to prevent soil erosion and leaching.

2.2. Landfill Wall Covering System

Generally, the performance of the landfill wall covering system is discussed in two ways. First, the slope of the excavated trenches in the landfill wall must be stable against the external forces, and it should maintain its external or general stability due to the pressure of the residual body weight, as well as the hydrostatic forces due to the possible presence of leachate or surface and subsurface water behind the landfill wall. This multilayer insulation system must maintain its durability against applied stresses and remain flawless and impenetrable throughout its service life. Because in case of a defect in the wall insulation system, leachate will leak, and as a result, contamination of the surrounding soil and gradually contamination of the surrounding aquifer or surface water will occur, and the performance of the landfill will be affected. Therefore, in the designs, two general stability issues are always considered for the slope of the wall and the waste placed on it, as well as the durability of the insulation layers against applied stresses and its control by the bearing stresses of the materials. Based on Figure 2, the wall covering of the scientific landfill has various components. The sand materials that are used for drainage are sand and gravel. Sand is often used as drainage material and gravel as filter material. Geosynthetics, including a drainage core and a geotextile filter, can also be used instead of soil materials for the drainage layer. Geotextile filter should be used as a combination of filter and separator [21].

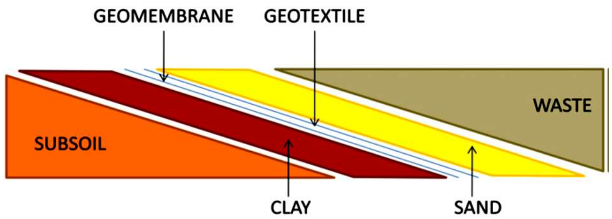

Fig. 2. Components of landfill wall covering against waste [12]

The typical method for assessing landfill stability during the waste disposal process is to use the finite balance analysis technique. However, it has been reported by several researchers that if the finite equilibrium method is used to determine the slope stability, the softening strain between the materials must be used. The main issue among the researchers is that the use of maximum resistance (Peak) along the entire length of the slope is uncertain, and also the use of residual resistance is not cost-effective. Software such as SLOPE-W has been used to evaluate the stability of landfill gutters with different geometries. The obtained results from these analyses were compared with the results obtained from numerical analysis. In addition, to evaluate the relationship between the methods for determining global stability, some information will be provided on the potential for local failure due to the loss of the protective layer of the geomembrane. The development of continuous failure levels and the local failure will be related to the development of local discontinuous surfaces. Fracture analysis compares non-curved rupture levels during the interaction between the floor and the sloping wall. The Morgenstern method was used to obtain the rupture reliability coefficient using several combinations of interface shear strength parameters. The following three combinations of interface shear strength parameters were used:

- Maximum shear strength in the floor and gable wall
- Residual shear strength in the floor and gable wall
- Maximum shear strength in the floor and the rest in the gable wall

The discussed example here is for geomembrane/geotextile layers both on the floor and on the landfill wall. This system is commonly used in executive activities in England. Laboratory tests give the results of the following interface shear parameters for the corresponding vertical stresses [21].

$$\delta_p=24.5^\circ \quad \& \quad \alpha_p=3.2 \text{ kPa} \qquad (1)$$
$$\delta_r=12.8^\circ \quad \& \quad \alpha_r=2.5 \text{ kPa}$$

Where δ represents the friction angle, α represents the apparent adhesion, and p and r represent the maximum and residual values, respectively. A summary of slope angle and residual height values is given in Table 1. In all cases, the landfill floor is horizontal and 100 m long, and the outer wall slope angle is 1 to 3.

Table 1. Different geometric characteristics and reliability coefficients obtained in each case [21]

Mode Number	**Wall slope angle**	**Waste height (meters)**	**Obtained Reliability coefficients**		
			Maximum floor, maximum wall	**Residual floor, residual wall**	**Maximum wall, residual wall**
Mode 1	1:3	30	3.3	1.7	2.6
Mode 2	1:3	60	2.0	1.0	1.4
Mode 3	1:2	30	3.0	1.5	2.5
Mode 4	1:2	30	2.9	1.5	2.6

Table 1 shows that the three combinations of maximum and minimum (residual) interface properties and values in the floor and the wall against the four modes of wall slope angle and different heights of the residue gives nine different reliability

coefficients, among which the highest coefficient to the result is related to mode 1 with maximum values both in the floor and in the wall of the landfill.
For all four geometric states in Table 1, the finite equilibrium analysis of the values of the failure of the progressive surfaces of the interface along its entire length is obtained. All reliability coefficients were calculated using the values of the maximum shear strength of the interface, which were significantly larger than the unit values. Reliability values between 1 and 1.7 have been obtained using the values of minimum shear strength in both floor and wall, and the lowest values of reliability are related to the geometric state with a height of 60 meters (mode 2). However, the floor interface may not have minimum values along its entire length, so it may be best to use the maximum values for the floor and the values remaining for the wall to consider the effect of residual settling. This method calculates the numerical reliability coefficient between 1.4 and 2.6 and is clearly an acceptable hypothesis that has increased its application by designers.
The stability of the insulation system and the durability of materials against applied stresses have been studied in this research. For insulation systems with geosynthetic materials, both stability and durability are affected by the shear strength of different interfaces (geosynthetics/geosynthetics and geosynthetics/soil). Shear stresses generally start to increase with displacement from the origin to their maximum point, after which the shear stresses decrease to a constant or residual value.
The used material properties in the numerical analysis of the example are given in Table 2. It should be noted that an elasto-plastic model and the Mohr-Columb rupture criteria for waste will be used for numerical simulation.
The effects of changes in residual properties of wall slope angle and landfill height on the shear strength of the interface have been studied. The amount of interface in dry conditions with zero pore water pressure was considered. Excess pore water pressure at the interface of geosynthetic materials will not be generated as long as the settling rate due to waste decomposition is slow (e.g., it will continue for more than thirty years) and the drainage layers (usually sand on the cover layers) ensure a short drainage path and a small amount of leachate pass through the insulation layer.
The shear strength of the interface was modeled using the conventional parameters of friction angle δ and adhesion α. These parameters are obtained in the dry state and in the long run. In FE platforms, it is possible to specify both δ and α by displacement, which is possible by entering the angle of friction and adhesion against interface displacement. The results of laboratory tests determined the shear strength against the displacement behavior of common interfaces and thus the input parameters in numerical analysis. The modified Columbus relation can be written as Eq. 2:

$$\tau_f = \alpha + \sigma_n tan\delta \quad (2)$$

This can be converted to Eq. 3 to obtain the friction angle

$$\delta = arvtan\left\{\frac{\tau_f - \alpha}{\sigma_n}\right\} \quad (3)$$

Table 2. Input data for numerical modeling [21]

Material	Material properties	Values
Material geometry	Size	(40, 17)
	Waste slope	1 in 3
	Wall slope	1 in 3
	Landfill height	30 m
Waste	Young module	500 KPa
	Bolson coefficient	0.3
	Downside	0.3
	Friction angle	25
	Cohesion	5KPa
Interface in the material of floor and walls	Interface shear stiffness	3000 KPa
	Interface normal stiffness	30,000 KPA
	Maximum friction angle	24.5
	Maximum Cohesion	3.2 KPa
	Residual friction angle	12.8
	Residual Cohesion	2.5 KPa

The values of σ, τ are known in each experiment. However, the values of cohesion must be estimated. A simple distribution of α with displacement is assumed to consist of the value of α equal to zero versus zero displacements to the value of maximum αp versus displacement created at maximum shear strength. Then, these values will increase by a large length (high strain) to the remaining value. This residual value will occur if the displacement is more than half of the displacement required to reach the maximum shear stress value.

The shear stress produced at the interface is controlled by the shear stiffness before the shear strength reaches the maximum value. Therefore, the results of direct laboratory shear tests can be used to determine the shear stiffness. The equilibrium value is obtained from the section before the values of maximum shear stress twice the strain. These results provide the recommended values for the shear stiffness of the interface between most geomembranes/geotextiles between 2400 and 3800 kPa. In the current research, the common value of 3000 kPa has been used in the analysis.

It is generally accepted that the waste material needs to undergo significant deformation to reach its resistance value. The results of the direct shear test by Jones et al. in 1998 showed that a strain of %10 cannot reach the waste resistance value. Recommended design values of c′ = 5kPa and φ′ = 25° were presented instead. These values have been used in the current study.

Young's modulus value (E) and Poisson's ratio (υ) were used for residuals to generate sediments related to the long-term subsidence values experienced by urban solid landfills (which is a combination of pressure and decomposition components). The final 20% of the initial thickness of the waste was considered as a common value in the England's landfills, and 15-20% of the recommended values were considered by the London Waste Research Center [12].

Numerical modeling shows that the residual sedimentation can cause the insulation components to slip on top of each other in the landfill wall. However, the amount of reliability is sufficient for the overall stability. Excessive displacement of geotextile on the geomembrane can lead to loss of protection of this layer and, as a result, lead to local defects and instability in that layer. For such evaluations, numerical modeling techniques should be used, which can model the residual/insulation interaction and the softening strain of the interface. However, this method cannot model all situations of local instability. Numerical modeling analyses that can model multiple geosynthetic and mineral layers and that these layers are numerically stable under large deformation conditions also need to evaluate the probability of shear rupture of its members.

3. MODELING PROCEDURE

Figure 3 illustrates the schematic model of the wall slope of the investigated landfill. This is the Mill-Gate landfill in Yorkshire, England. This landfill was constructed by trench method and extracting sand materials. Municipal solid waste; includes construction, agricultural, commercial and industrial waste, will be deposited in this landfill. The wall and floor of the landfill are assumed to be impermeable, and the vertical displacement of the bed is assumed to be zero. It should also be noted that in this study, only the immediate deposition of waste is considered, and the deposit due to chemical decomposition has not been discussed due to the unavailability of their behavioral model. The dimensions of the following landfill were reported by [12]. The slope of the trench is 31.2 m long and 12 m high, and its slope angle is 21.8°.

The bed soil characteristics are not known in this study and are considered as a bed with zero displacement. A layer of high density and low permeability clay with a thickness of 1 meter is placed on the bed. On the clay layer, a double-woven geomembrane sealing membrane made of high-density polyethylene with a specific gravity of 0.949 g/cm and a thickness of 2 mm is placed. To protect the insulation layer of geomembrane, a non-woven needle layer geotextile with a thickness of 7.8 mm with a specific gravity of 1400 g/cm^2 has been used. Then, a

50 cm thick layer of sand was used for drainage before the waste was placed. Sand materials are generally used for the drainage layer.

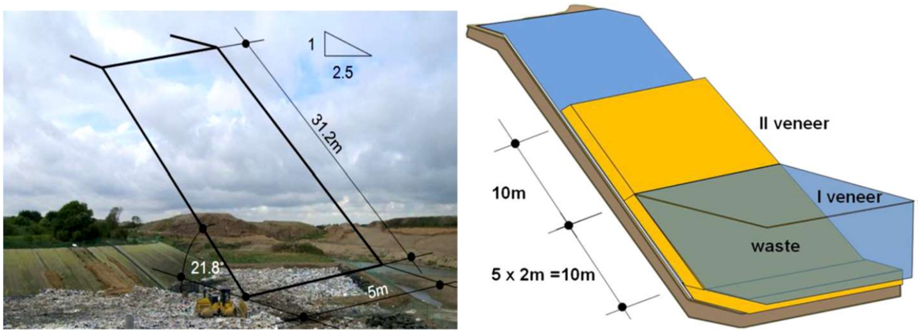

Fig. 3. Geometry of the studied Landfill wall slope [12]

In the FE modeling procedure, first, the geometry of the landfill wall was modeled layer-by-layer. The layers then overlapped. And each layer was assigned the mechanical properties mentioned in Table 3.

Table 3. Mechanical properties of the modeled materials

Materials	**Behavior model**	**Density (Mg/m^3)**	**φ′ (°)**	**C' MPa**	**Poisson coefficient**	**Young modulus**
Waste	Mohr-Coulomb	1.0	25	5.0	5.0	0.3
Sand layer	Mohr-Coulomb	1.7	35	70	0	0.4
Clay layer	Mohr-Coulomb	1.7	23	150	0.4	0.3

The FE modeling has been conducted in 16 sections. First, the clay layer was modeled, and then geomembrane and geotextile layers were placed on it. Before pouring the waste, the sand layer was applied in the direction of the slope and the floor, and then the waste was poured in a layer-by-layer thickness of 1 meter, and all four layers of waste were covered with a 50 cm layer of sand until the height reached 11.6 meters. Figure 4 shows the Landfill wall model in ABAQUS FE platform.

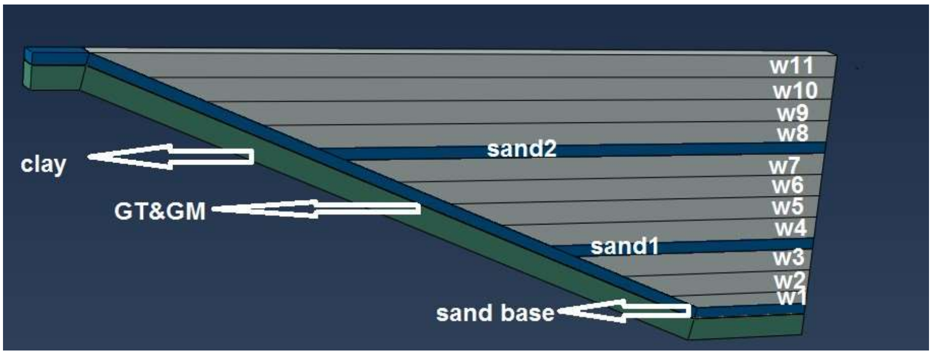

Fig. 4. 3D landfill wall FE model in this study

In the design stage, it is assumed that the leachate was working properly and that there was no leachate from inside the landfill behind the wall. Also, in this modeling, it was assumed that the wall thickness of the drilled trench is a layer of several tens of centimeters, and external instability will not be an issue. However, the internal stability and durability of insulation materials are considered.

For the interaction between the materials, in the software, the interface was modeled as a layer with the characteristics given in Table 4, which was presented from the results of the direct shear test by Zamara et al. in 2012 [12]. For each material combination, five tests were performed with five different normal forces (10-25-50-100-200 KPa). Also, the experiment of determining the properties of the material interface was used in both dry and wet modes. Each experiment was repeated at least three times, and each time new materials were used. Laboratory tests were not used for soil/waste interface, and conventional interface values between grain drainage and waste were used. The key point of this modeling is to apply the interface softening strain behavioral model.

According to the geometry of the scientific landfill, the natural ground floor movements are applied in the horizontal and vertical directions (x and y). Also, in the perpendicular direction to the slope of the wall (z) and the crown (highest level of landfill), the degrees of freedom were considered as zero.

Table 4. Material interface properties

Interface	δ(°)/ Maximum residual	α (KPa) / maximum residual	Normal Hardness (KPa/m)	Shear Hardness (KPa/m)
Sand/waste	20	5	10,000	5000
Geotextile / Sand Dry mode /Wet mode	29.9/29.6 29.6/29.9	6.3/1.8 3.2/1.3	10,000	4500
Geomembrance/geotextile Dry mode /Wet Mode	19.9/13.3 20.8/14.7	2.3/1.4 4.0/2.9	10,000	4500
Clay/geomembrane Drainage mode/Non-drainage mode	22,0/22.0 31.1/25.1	8.0/8.0 7.6/3.2	10,000	5500

All loading steps were defined in Dynamic Implicit mode. At the beginning of the loading force, the weight of aggregate and waste materials was defined, and finally, the seismic force was added to the model at the end of the landfill wall. The mesh is used in two types of hexagonal cubic and wedge, and due to the large number of loops and heterogeneity of the results, a mesh with dimensions of 1 meter was used. To increase the accuracy of the results, 30 cm mesh size were applied to the geosynthetics.

4. MODEL VERIFICATION AND SEISMIC PERFORMANCE EVALUATION

To verify the modeling accuracy, the FE results have been compared with the results of the study conducted by Zamara et al. in 2012 [12]. In reference modeling, the stiffness of sand and clay materials (E) was reduced to one-third, in order to apply the displacement obtained from the site in the second iteration of the analysis. In fact, the stiffness of clay decreased from 105 MPa to 50 MPa and the stiffness of sand reduced from 70 MPa to 20 MPa. In the present study, at the same time as reducing the above hardness values, the surface hardness of the contact surface (c and φ interfaces) was also reduced to one-third.

The vertical compressive stresses on the calculated coating in the software were in the range of values obtained from the pressure cells in place. It can be concluded that the stresses applied to the landfill wall by the weight of the waste and the sand cover can be reproduced by numerical modeling. The time factor was not directly included in this modeling, but the construction steps were specified separately.

The values of on-site stresses were plotted against time based on the time of landfill cell formation and filling. Figures 5 and 6 illustrate the compressive stress recorded by the compression cells and the results obtained from the two numerical modeling during the fabrication process.

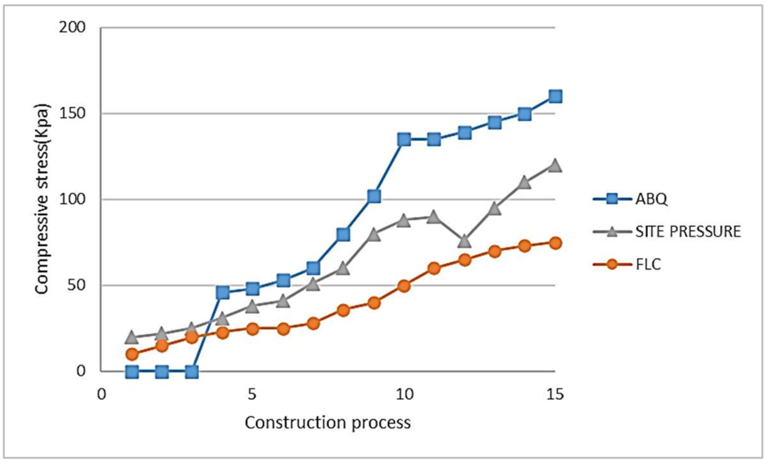

Fig. 5. Vertical compressive stresses at 13 m below the crest of the landfill wall (On the clay layer)

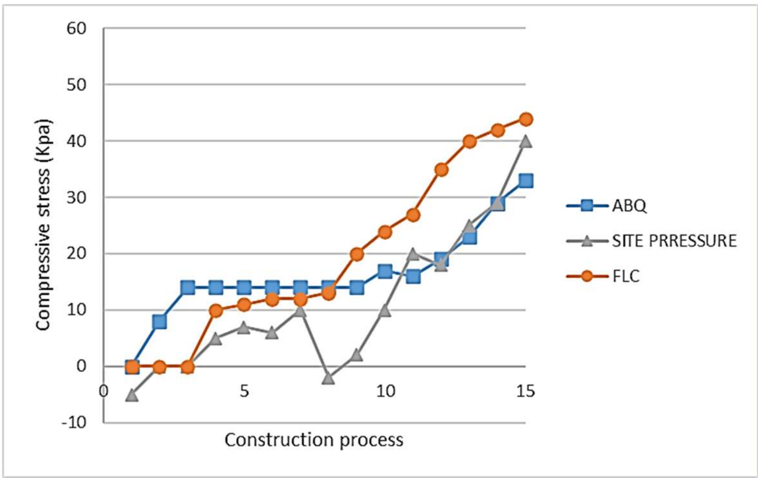

Fig. 6. Obtained vertical compressive stresses at 30 m below the crest of the landfill wall (On the clay layer)

Figures 7 and 8 illustrate the geotextile and geomembrane displacements recorded by extensometers, as well as the results of numerical modeling of reference research (FLAC software) by Zamara et al. 2012 [12], and present research (ABAQUS software). The results of the extensometers installed on the GM and GT were recorded during the three years of construction and filling of the landfill with waste.

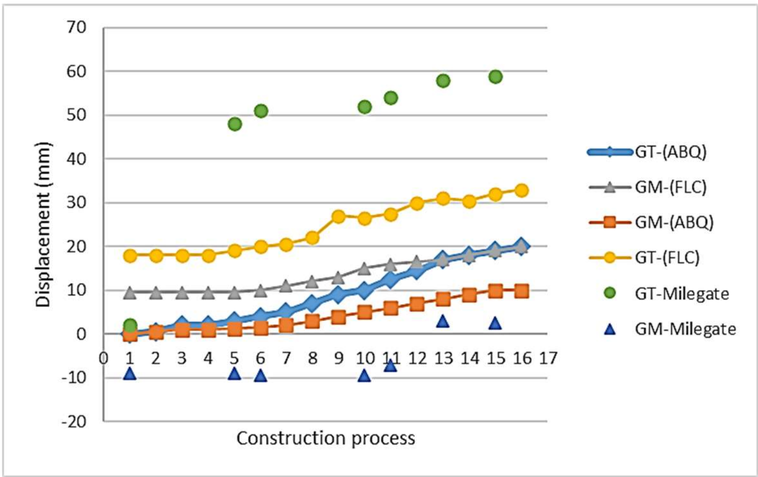

Fig. 7. Displacement in geomembrane and geotextile layers at the height of 24.6 m below the landfill crest

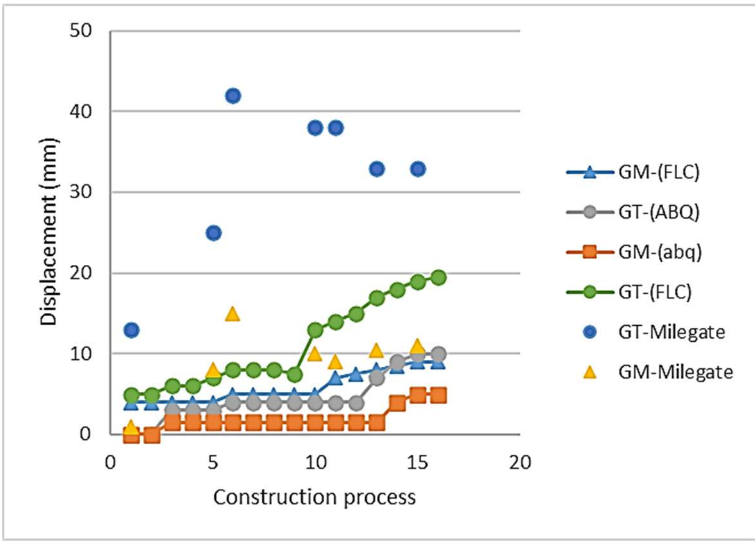

Fig. 8. Displacement in geomembrane and geotextile layers at the height of 8.4 m below the landfill crest

Significant displacements for the GT layer were recorded by instrumentation. The extensometers in the middle and at the top of the slope recorded a downward displacement of up to 80 mm. These displacements were due to delays in project implementation and non-implementation of the second and third sand cover, resulting in GT exposure to sunlight. In this study, the results of GT displacement were consistent with the numerical modeling values of the reference research at the interface softening strain.

The recorded displacements in the geomembrane showed a gradual increase during the cell filling process along the entire slope. However, the displacements due to the placement of the sand cover were small. The extensometers recorded the highest displacement of 25.9 mm. However, the displacement range recorded in the GM panels was between 10 and 10 mm, which was recorded by the instrumentation and no significant relationship was found between the displacement enhancement in the geomembrane and the geotextile in the slope direction. As it can be seen from the results, the modeling results of the current study have good compatibility with the results obtained in the reference study.

To determine the effect of seismic loading on the landfill wall, an array of strong ground motions from FEMA P695 [22] were applied to the model, 5 of which are far-fault earthquakes and the other 5 are near-fault earthquakes. The characteristics of these earthquakes are given in Tables 5 and 6. According to the Iranian Seismic Design Guideline (2800 standard), at a potential seismic hazard level with the probability of occurrence of 50% over 50 years, Earthquake records have been scaled in the time domain with appropriate scaling factors and a damping ratio of 5%. In the next stage, the earthquake loadings were applied to the lower part of the landfill wall to simulate a near realistic behaviour.

Table 5. The characteristics of the selected earthquakes far from faults in this study [22]

NGA Record Number	PGA_{max} (g)	Earthquake Name	Station Name	Direction/Type
68	0.21	San Fernando	LA-Hollywood Store FF	1/FF
174	0.38	Imperial Valley - 06	El Centro Arrey #11	2/FF
953	0.52	Northridge - 01	Beverly Hills-Mulhol	2/FF
752	0.53	Loma Prieta	Capitola	1/FF
848	0.51	Landers	Cool water	2/FF

Table 6. The characteristics of the selected earthquakes near the faults in this study [22]

NGA Record Number	PGA_{max} (g)	Earthquake Name	Station Name	Direction/Type
879	0.79	Landers	Lucerne	1/NFP
828	0.63	Cape Mendocino	Petrolia	1/NFP
1063	0.87	Northridge - 01	Rinaldi Receiving Sta	2/NFP
802	0.82	Loma Pericta	Saratoga-Aloha Ava	1/NFP
181	0.44	Imperial Valley - 06	El Centro Arrey 06	1/NFP

The maximum displacement of the landfill wall in earthquakes near and far from the faults showed that the range of maximum displacement of the landfill in near-field earthquakes is 0.43-0.50 m, whilst under far-field earthquakes, the values are in the range of 0.38-3.47 m. The Loma Prieta earthquake, which is far from the fault, and Cape Mendocino near-fault earthquake have caused the most critical responses, respectively. The maximum displacements in near- and far-field earthquakes were detected within the boundary between natural soil and waste (Figure 9).

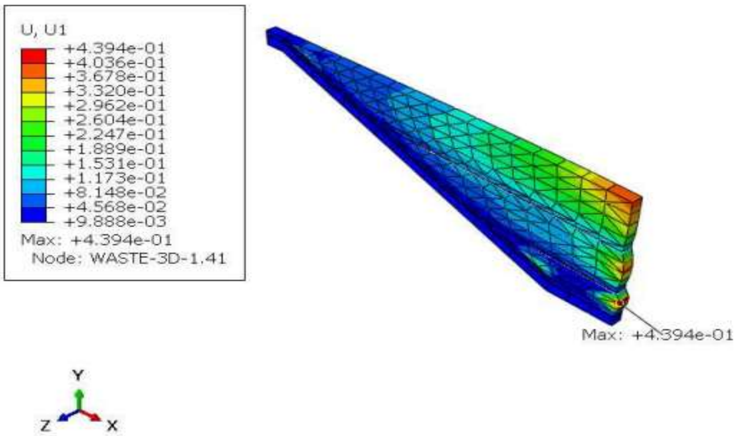

Fig. 9. Maximum displacement created in the landfill wall under earthquake force

According to Figure 10, the maximum principal stresses of the landfill wall under earthquake loadings have been about 5.78MPa and 4.94MPa in the geomembrane layer for near-field and far-field records, respectively.

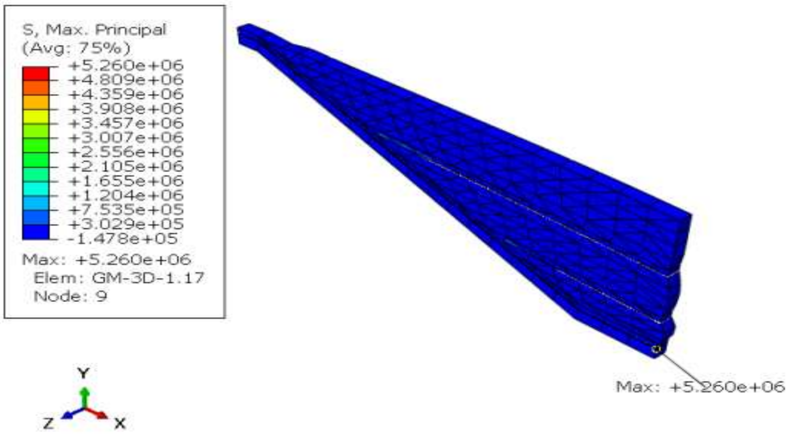

Fig. 10. Maximum S. max created in the landfill wall under earthquake force

The standard uniaxial capacity of geomembrane coating is 1.7 MPa, which is much lower than the maximum observed principal stresses under seismic excitations. As can be seen in Figures 11 and 12, this layer has experienced rupture failure under both near-field and far-field strong ground motions.

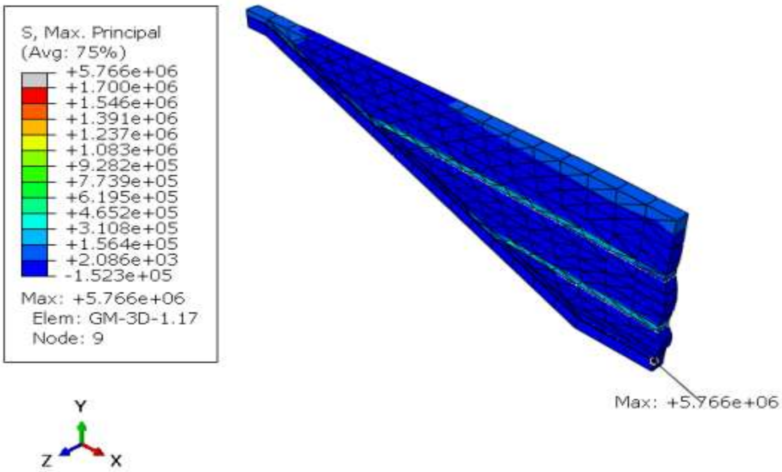

Fig. 11. Application of yield stress and rupture investigation in landfill

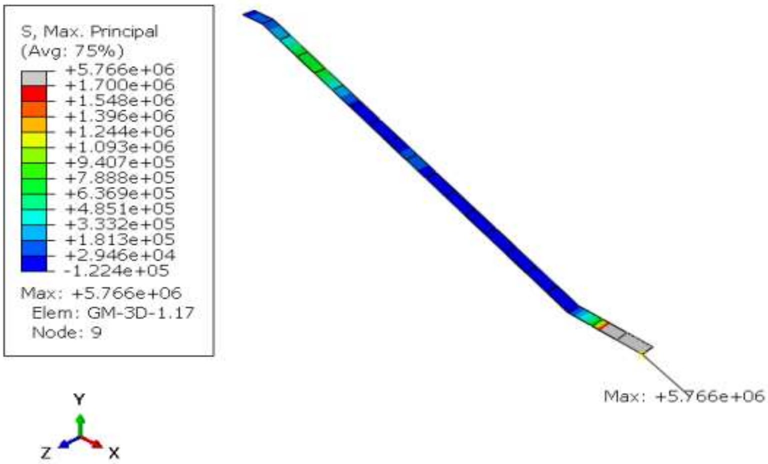

Fig. 12. Rupture in the geomembrane layer under seismic excitations

5. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to investigate the seismic behavior of solid waste landfills under far-field and near-field earthquakes. To this aim, a landfill constructed in the UK was modeled in ABAQUS software and verified with the results of obtained data from instrumentation at the landfill site. Then, by modeling the seismic force, the seismic behavior of solid waste landfill under far-field and near-field earthquakes and its effect on the durability of the landfill wall system were investigated. The results indicated that:

- The extensometers in the middle and at the top of the slope recorded a downward displacement of up to 80 mm, which is very well matched with the FE simulations.
- The maximum displacement of the landfill wall in near-field and far-field earthquakes from the fault showed that the maximum range of displacement of the landfill in earthquakes near the fault is 0.43-0.50 meters and in earthquakes far from the fault is 0.38-3.47 meters.
- The maximum stress in the landfill wall under near-fault and far-fault earthquakes showed that the average maximum stress of the landfill wall in near-fault earthquakes is 5.78 MPa and in far-field earthquakes is 4.94 MPa in the geomembrane section.
- A rupture has been observed in numerical simulations under earthquake excitations in the geomebrane layer.

In this study, the Mohr-Columb behavioral model has been used for soil. It is suggested that in the future studies, more complex models be used.

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