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SEISMIC STABILITY OF BIOREACTOR LANDFILL WITH DECOMPOSITION - A NUMERICAL MODELING

MD Sahadat HOSSAIN[1], Mohamed HAQUE[2] , Syed QASIM[3], and Laureano HOYOS[4]

ABSTRACT

Recently proposed federal regulations have focused increase attention on seismic design of solid waste fills, and have mandated that the solid waste landfills located in the seismic impact zones should be designed to resist the earthquake. About 50% of the continental United States comes under the designated seismic impact zone. Bioreactor landfills are operated to enhance refuse decomposition, gas production, and waste stabilization. Due to the accelerated decomposition and settlement of solid waste, bioreactor landfills are gaining popularity as an alternative to the conventional Subtitle D landfill. When the landfills are operated as bioreactor landfills, accelerated decomposition changes the physical and engineering characteristic of waste, and may affect the dynamic characteristics of waste mass. These changes increase the concern for stability of bioreactor landfills during earthquake. The objective of this paper is to analyze the seismic stability of bioreactor landfills, as a function of time and decomposition. The finite element program PLAXIS is used for the numerical modeling of bioreactor landfill. Based on the analyses, the factor of safety decreased as the solid waste degraded with time in both static and dynamic cases. Also, limit equilibrium GSTABL analysis underestimated the factor of safety values for dynamic analysis. For Case 1 FEM PLAXIS analysis predicted a factor of safety of 1.51, whereas that predicted by GSTABL was only 0.99.

Keywords: landfill; bioreactors; seismic slope stability; decomposition; finite element analysis; limit equilibrium analysis

INTRODUCTION

Disposing municipal solid wastes (MSW) into landfills remains the predominant method of disposal in United States. About 67% of the generated solid waste goes in to the landfills. Many of the recent landfills are located in the vicinity of highly populated areas, this increases the potential hazard associated with the slope failure of a municipal solid waste (MSW) landfill (Haque and Hossain, 2006). Due to this considerable attention has been focused on studying the stability characteristics of these landfills (Singh and Murphy, 1990; Anderson et al., 1992; Seed and Bonaparte, 1992; Rathje et.al, 1998; and Kavazanjian et al., 2000). About 50% of the continental United States comes under the designated seismic impact zone. A seismic impact zone is defined in the regulations as the area with a ten percent or greater probability that the maximum horizontal acceleration in lithified material will exceed 0.1 g in 250 years (Repetto and Bray, 1992). Therefore the newly proposed federal regulations have focused increase attention on seismic design of solid waste fills. They have mandated that the solid waste landfills located in the seismic impact zones should be designed to resist the earthquake.

A bioreactor landfill accelerates the decomposition and stabilization of solid waste by recirculating the leachate. Unlike the conventional landfills that are designed and operated to minimize contact between water and solid waste, the operation of a bioreactor relies on the addition of liquids to increase the moisture content of the solid waste to the optimum level for decomposition. A

[1]Assistant Professor, Department of Civil and Environmental Engineering, University of Texas at Arlington, TX 76019, email: hossain@uta.edu
[2]Graduate Student, Department of Civil and Environmental Engineering, University of Texas at Arlington, TX 76019, email: msa_889@yahoo.com
[3] Professor, Department of Civil and Environmental Engineering, University of Texas at Arlington, TX 76019, email: Qasim@uta.edu
[4]Associate Professor, Department of Civil and Environmental Engineering, University of Texas at Arlington, TX 76019, email: hoyos@uta.edu

typical bioreactor will re-circulate all of its leachate and may require the addition of liquids for its operation (SCS Engineers, 2005). Increase in the MSW moisture content creates a more favorable environment for the biological decomposition of organic matter in the landfill, and therefore accelerates the decomposition of refuse (Townsend et al., 1995). The accelerated decomposition of the refuse in bioreactors also considerably changes the geotechnical characteristics of the waste in the landfill, and thereby increases the concern for waste seismic stability. Every documented landfill stability problem has had wet conditions of the waste as one of the factors that contributed to the failure (SCS Engineers, 2005).

The time difference between placement of MSW at bottom of landfill and at top of landfill may be between 15 to 35 years depending on the active filling period of landfill. Therefore, the levels of decomposition of MSW between these two parts of the landfill are expected to be different (Gabr et al., 2000). Based on the insitu tests, Matasovic and Kavazanjian (1998) also showed that the values of Poisson's ratio at deeper portions of the landfill were greater than those located closer to the surface. This observation confirms that MSW is degraded more at bottom compared to the top. Therefore, considering properties to be uniform throughout the bioreactor landfill is not a reasonable assumption, and would lead to erroneous result during stability analysis.

The objective of this paper is to analyze the dynamic stability of bioreactor landfill. Considering the degree of decomposition, a seismic slope stability analysis was performed using finite element model (FEM) PLAXIS. Also, the results from the finite element program PLAXIS were also compared with the results from limit equilibrium program STABL.

SOLID WASTE PROPERTIES

Unit weight of solid waste is considered to be an important factor in estimating the static and seismic stability of landfills. It is directly influenced by the type of waste, degree of decomposition, degree of compaction, volume of daily cover, compaction degree, quantity of leachate produced, and the depth from which sample is taken. Kavazanjian (2003) reported that the MSW unit weights in bioreactor and leachate recirculation landfills are likely to be significantly higher than those in conventional landfills, with values sometimes approaching or exceeding 127 lb/ft^3 at depths. Field testing in saturated-waste zones at Operating Industries, Inc (OII) landfill yielded unit weight values as high as 135 lb/ft^3 (Matasovic and Kavazanjian, 1998). The results from laboratory tests conducted on generated samples also indicated an increase in unit weight from 70 lb/ft^3 to 90 lb/ft^3 as the waste degrades.

Landfills can be subjected to undrained cyclic loads due to earthquakes; the dynamic response under such loads depends to a large extent on the cyclic stress-strain characteristics of the MSW in shear. A key material property necessary to evaluate dynamic response of MSW is shear modulus (G), which relates shear stresses to shear strains. Normalized shear modulus reduction and material damping relationships for MSW have been recommended by various researchers (e.g. Idriss et al. 1995, Matasovic and Kavazanjian, 1998, Augello et al. 1998, Elgamal et al. 2004). Augello et al (1998) developed the strain dependent modulus reduction and damping curves from the back-analysis of MSW dynamic properties from OII landfill in Southern California. Moreover most of these researchers did not make clear a distinction between the age of the waste and its degree of decomposition. Recently Zekkos et al. (2006) had classified the waste samples into three categories based on their particle sizes. However, Zekkos et al. (2006) did not consider the degree of decomposition of MSW with time. With decomposition, the fibrous nature of the material gets broken down (Haque and Hossain, 2006).

Shear strength is perhaps the single most important mechanical property of solid waste in landfill engineering (Kavazanjian, 2003). MSW shear strength parameters reported in literature vary widely with friction angle of as low as 10° to as high as 53°, and cohesion values varying from 0 to 67 kPa. Kavazanjian, et al. (1995) suggested to use a cohesion of 24 kPa at low confining pressure (below 37 kPa), and at high confining pressure (larger than 37 kPa) a friction angle of 33 degrees. However, most of these researchers neglected the effect of degree of decomposition of MSW with time. Hossain (2002) estimated the shear strength parameters of solid waste based on the degree of decomposition using direct shear test. The author correlated the degree of decomposition of the waste to cellulose plus hemicellulose to lignin ratio [(C+H)/L]. Hossain (2002) found that at the initial stage of decomposition, when (C+H)/L ratio is 1.29 the friction angle was 32º. However at a fully decomposed state (i.e., when (C+H)/L is 0.25) the friction angle was 24º. Permeability is influenced by the degree of decomposition, aging, and sample depth. Existing literatures (Oweiss et al., 1990) had noted as the unit weight of the waste mass increases the permeability decreases, these values ranged from 10^{-4} to 10^{-7} m/s.

SEISMIC STABILITY ANALYSIS

This paper analyses the seismic stability of bioreactor landfill using two-dimensional finite element program (FEM) program PLAXIS. Analyses was also performed using limit equilibrium analysis STABL. Finally the results from FEM PLAXIS were compared with those obtained from limit equilibrium program STABL.

1. Finite Element Modeling

The finite element program PLAXIS has been adopted for evaluating the seismic stability of bioreactor landfill. The cross-section utilized for the numerical model is presented in Figure 1. The bioreactor landfill is modeled as a two dimensional plane strain model.

Mesh Generation and Boundary Conditions

The finite element mesh for the modeling has been generated into 4 layers, representing each stage of decomposition. The 15 nodded triangle elements were used in the modeling. The powerful 15-node element provides an accurate calculation of stresses and failure loads (PLAXIS, 2002). In earthquake problems the dynamic loading source is usually applied along the bottom of the model resulting to shear waves that propagate upwards. Earthquakes are modeled by means of a prescribed displacement in PLAXIS. The two vertical boundaries were set as absorbent boundaries, whereas the bottom boundary is set to a prescribed displacement. The foundation soil was considered to be stiff soil and its stability is not considered in this analysis, therefore the bottom boundary is fixed. The slope stability analysis for the bioreactor landfill was evaluated at 3H:1V slope (Figure 1).

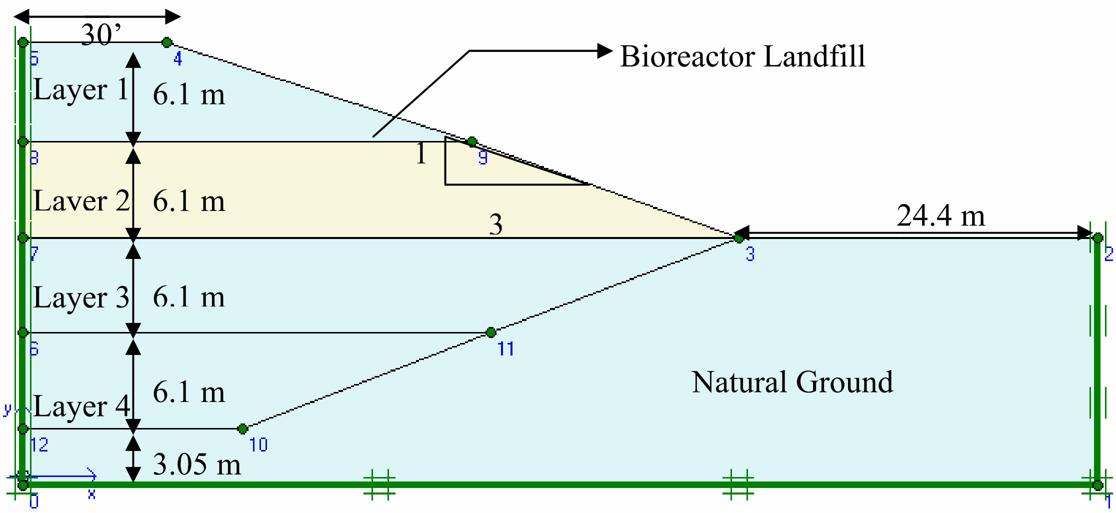


Figure 1 Cross-section utilized for the numerical model

Material Model

The Mohr-Coulomb model was used for this analysis. This model involves five parameters, namely Young's modulus, E, Poisson's ratio, υ, the cohesion, *c*, the friction angle, ϕ, and the dilatancy angle,

ψ . In this case dilatency angle was assumed to be zero, since it is close to zero for clay and for sands with friction angle less than 30°. Material damping in a soil is generally caused by its viscous properties, friction and the development of plasticity. The standard setting in PLAXIS assumes no Rayleigh damping. However, damping can be introduced in the material data sets for soils and interfaces (PLAXIS, 2002).

Material Parameters

The parameters used in the FEM analysis for the different phases of decomposition are presented in Table 1. Some of the important waste properties evaluated are unit weight, shear strength, stiffness, permeability and damping characteristics. The rationale behind the selection of these values is explained in the following sections.

The unit weight values used in the analysis are presented in Table 1. These values are obtained by compacting the generated MSW samples from the bioreactor cells into five layers using the modified proctor method. Unit weights increased from 70 lb/ft^3 to 90 lb/ft^3 as the waste degrades. The increase in unit was attributed to degradation, as the waste degrades, larger particles in the MSW are broken down into smaller ones; this reduces the voids and increases the mass of the solid waste per unit volume. Zekkos et al., (2006) reported similarly, as the larger fibrous fraction of the solid waste as having a lower particle unit weight than the smaller particle fraction. This is also justified by the observation of higher unit weight values reported by Kavazanjian (2003) at depths, where the waste mass would be at an advanced stage of decomposition.

PLAXIS uses alternative stiffness moduli, such as shear modulus, G, and the oedometer modulus, E_{oed}. These stiffness moduli relate to Young's modulus according to Hooke's law of isotropic elasticity, which involves Poisson's ratio. Shear modulus values are estimated from the resonant column tests conducted on generated samples (Hossain et al. 2007). The shear modulus (G) values used in the analysis are presented in Table 1. As the material degraded the shear modulus reduction curves shifted to the left and the threshold strain decreased (Hossain et al., 2007). Hossain et al. (2007) observed that the small-strain shear modulus in Phase I was 2,077 kN/m^2, and it increased to 217,175 kN/m^2 in Phase IV. These changes are due to the breakdown of fibrous nature of solid waste particles as it degrades. The increase in the value of shear modulus can be attributed to the increase in unit weight of Phase IV specimen, and due to degradation and the increase in the shear wave velocity of specimen (Hossain et al. 2007).

Damping ratio was also affected by the degradation. However the effect of damping ratio was more pronounced only at strains greater than 10^{-2} %. For smaller strains the material damping ratio is not significantly reduced with strain, but remained roughly constant at values of about 6 -8 % (Hossain et al. 2007). The Rayleigh damping coefficients used in the analysis are presented in Table 1. The coefficients were determined from the following relationship, and at two frequencies of vibration (PLAXIS, 2002).

$$\alpha + \beta\omega_i^2 = 2\omega_i\xi_i$$

Where α and β are Rayleigh damping coefficients, ξ_i is the damping ratio, and ω_i is the corresponding frequency.

The shear strength parameters are dependent on variables such as age, composition, and moisture content of the waste. However, only a limited number of researchers (Hossain, 2002, and Landva and Clark, 1990) had made a clear distinction between the degree of decomposition and strength properties. Hossain (2002) estimated the shear strength parameters of solid waste at each of the four stages of decomposition using direct shear test. Based on Hossain (2002) data's the cohesion and friction values to be used in the modeling at different stages of decomposition are selected and shown in Table 1.

Table 1 Parameters for M-C Model in FEM analysis

Material Set	Drainage Condition	Unit weight, γ_{moist}, kN/m^3	Permeability, m/day × 10^{-3}	Poisons ratio	Shear wave velocity v_s, m/sec	Cohesion, c (kN/m^2)	Friction angle, Φ°
Phase I	Drained	11	860	0.25	23.7	0	33
Phase II	Drained	11.8	86	0.40	30.3	0	27
Phase III	Drained	12.6	86	0.42	71.7	0	25
Phase IV	Drained	14.1	8.6	0.45	73.6	0	24
Natural ground	Drained	15.9	1	0.35	11.8	9.6	30

Analysis Type

The calculation in PLAXIS involved two phases. In the first phase dynamic analysis was performed followed by the slope stability analysis using *Phi-c reduction* calculation type at each case of decomposition. Phi-c reduction is an option available in PLAXIS to compute factor of safety. This option can be selected as a separate calculation type in the general tab sheet (PLAXIS, 2002). Dynamic loads are introduced into the model by means of prescribed displacements. In earthquake problems the dynamic loading source is usually applied along the bottom of the model resulting to shear waves that propagates upwards (PLAXIS, 2002). In this analysis the earthquake records from Sakarya earthquake are used. This earthquake had a magnitude of 7.4 occurred in Kocaeli Province of Turkey. The earthquake was a result of lateral movement of North Anatolian Fault. The traced fault rupture length on the ground surface is about 110 km. the right lateral displacement ranges up to 4.9 meters, and average about 2.5 – 3 meters. The acceleration time history of this earthquake is shown in Figure 2, and the dynamic parameters used in the analysis are presented in Table 2. For slope stability analysis in *Phi-c reduction* type of calculation the load advancement number of steps procedure is followed. The incremental multiplier *Msf* is used to specify the increment of the strength reduction of the first calculation step. The strength parameters are reduced successively in each step until all the steps have been performed. The final step should result in a fully developed failure mechanism, if not the calculation must be repeated with a larger number of additional steps. Once the failure mechanism is reached, the factor of safety is given by (PLAXIS, 2002):

$$SF = \frac{available \quad strength}{strength \quad atfailure} = \text{value of } \Sigma Msf \text{ at failure}$$

Table 2 Dynamic parameters used in the modeling

Component	Sakarya Earthquake
Magnitude	7.4
Peak acceleration value (g)	0.376
Duration (sec)	19.4
Frequency (Hz)	0.86
Displacement amplitude (m)	0.762

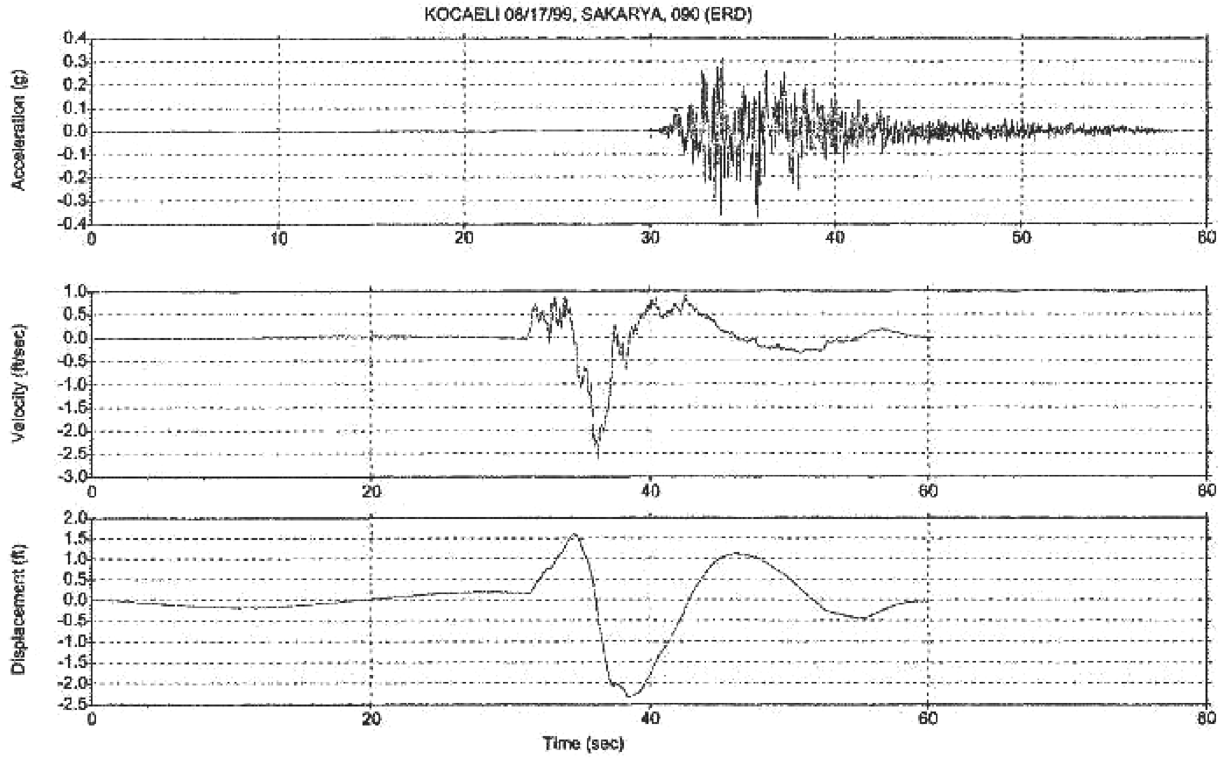


Figure 2 Acceleration-time history of Sakarya Earthquake (Karadeniz, 2003)

Analysis Cases

A closed MSW landfill may not have a single waste age, but rather have different ages associated with various cells within the landfill and their respective stabilization stages (Pohland et al., 1993). The age of waste in MSW landfill can be divided into four stages depending on its degree of decomposition. The four stage of decomposition can be classified as aerobic phase, anaerobic phase, accelerated methane production phase, and decelerated methane production phase. Layers 1 – 4 were assumed to represent the stages of landfilling, and each of these layers is at different stage of decomposition. It is assumed that immediately after landfill closure layer 1 is at initial phase of decomposition, at the same time, it is possible that layer 2, 3, and 4 would be at second, third, and fourth phases of decomposition respectively. With time solid waste layers may advance to next phases of decomposition. Finally after complete stabilization, all the layers would be at the final stage of decomposition. Table 3 shows the phases of decomposition at different cases (i.e., different time periods).

Table 3 Phases of decomposition at different stages

	Layer 1	Layer 2	Layer 3	Layer 4
Case 1	Phase I	Phase II	Phase III	Phase IV
Case 2	Phase II	Phase III	Phase IV	Phase IV
Case 3	Phase III	Phase IV	Phase IV	Phase IV
Case 4	Phase IV	Phase IV	Phase IV	Phase IV

2. Limit Equilibrium GSTABL Slope Stability Analysis

The seismic stability of the slope was analyzed using GSTABL slope stability software. GSTABL with STEDwin is a powerful, comprehensive a 2-dimensional, limit equilibrium slope stability program. GSTABL performs all the slope stability analyses calculations, while the STEDwin provides an extremely user-friendly graphical user interface. The solid waste parameters used in the analysis are shown in Table 4. The basis behind the assumption of these values was discussed in the previous sections. The solid waste parameters, dimensions, and the procedure followed to compute the stability at each case of decomposition in the bioreactor landfill are same as that used in FEM analysis. A pseudostatic seismic coefficient of 0.376 g was used in the analysis for each of the different stages analyzed.

Table 4 Parameters used in GSTABL analysis

Material Set	Unit weight, γ_{moist}, kN/m^3	Cohesion, c (kN/m^2)	Friction angle, Φ°
Phase I	11	0	33
Phase II	11.8	0	27
Phase III	12.6	0	25
Phase IV	14.1	0	24
Natural ground	15.9	9.6	30

RESULTS AND DISCUSSIONS

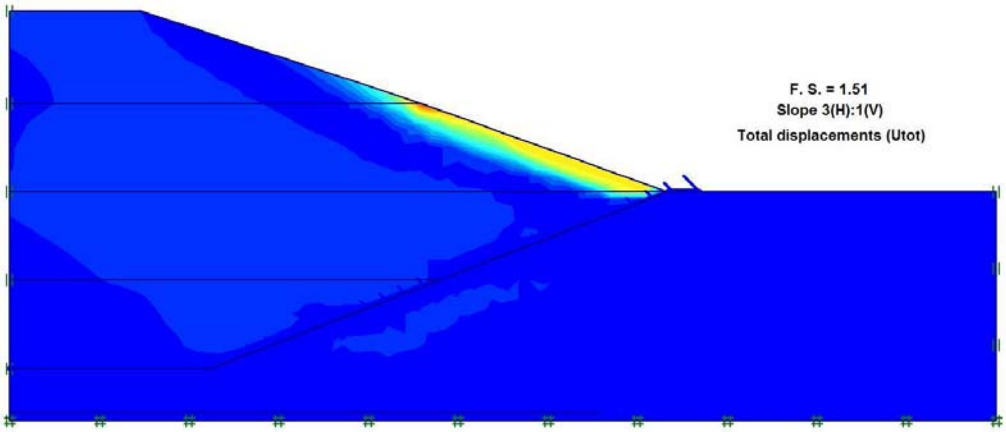
The seismic stability of bioreactors was analyzed by using both finite element program PLAXIS and slope stability software GSTABL. Results from dynamic slope stability analysis in case 1 for a slope of 3:1 are presented in Figure 3. Figure 3 (a) shows the safety factors calculated by the modified Bishop method using GSTABL, and 3 (b) shows the total incremental displacements output from PLAXIS, after the Sakarya station earthquake. It can be observed from Figure 3 that the critical failure surface predicted by PLAXIS and GSTABL are almost the same.

The factors of safety predicted by both FEM and limit equilibrium program GSTABL are presented in Table 5. The factor of safety decreased for both static and seismic cases as the decomposition increased with time. The reduction in factor of safety for dynamic analysis was more pronounced in limit equilibrium program GSTABL than in FEM PLAXIS. In all the cases studied GSTABL overestimated the factor of safety in static analysis and underestimated it in seismic stability analysis.

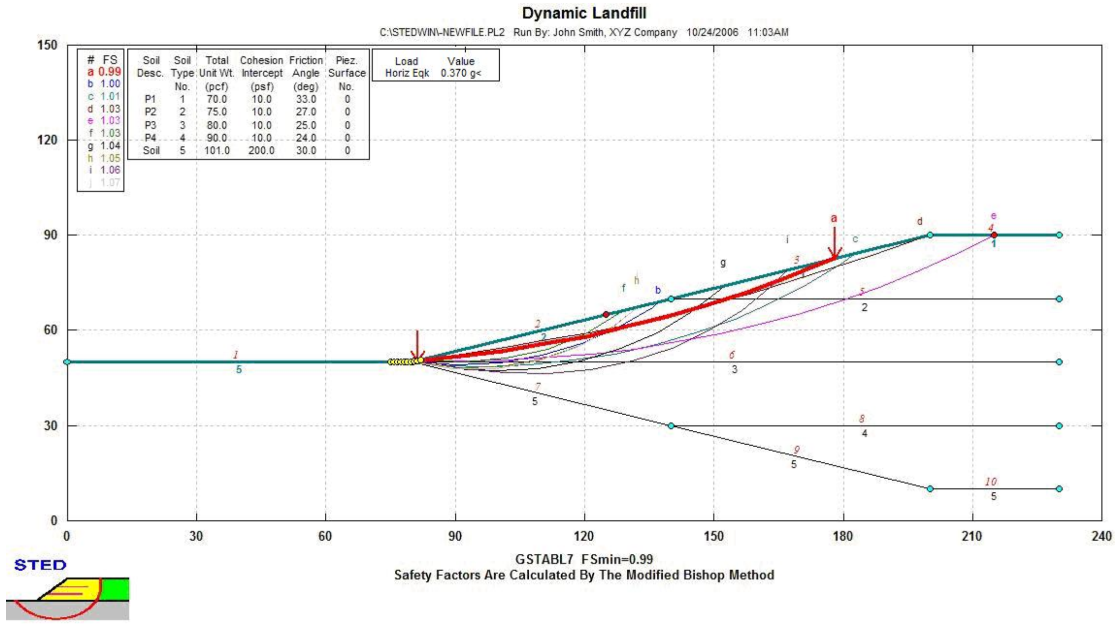
The principal limitation of limit equilibrium methods is that ground deformations are not taken into account (FHWA, 2003). It is assumed that a state of limit equilibrium is achieved instantaneously along the entire failure surface. This assumption eliminates the ability to predict localized failure, progressive failure, and slope movements that may occur even though the global factor of safety may be greater than 1.0. In the dynamic analysis, GSTABL does not include the damping properties of solid waste. Whereas, the laboratory results indicated that the solid waste material induces significant damping. As we can observe from Figure 4 the material damping values significantly reduced the acceleration of the earthquake, and there by increased the factor of safety. These results suggest that the limit equilibrium method overestimates the factor of safety for static analysis and underestimates the factor of safety for dynamic analysis. And it also emphasis the utilization of finite element method and there is a need to go beyond limit equilibrium analysis.

Table 5 Factor of safety from PLAXIS and GSTABL analysis.

Stage	Static		Dynamic	
	PLAXIS	GSTABL	PLAXIS	GSTABL
Stage 1	1.61	1.76	1.51	0.99
Stage 2	1.47	1.54	1.47	0.87
Stage 3	1.42	1.47	1.34	0.82
Stage 4	1.40	1.43	1.33	0.81



(a)



(b)

Figure 3 Results from seismic slope stability analysis in case 1 for a slope of 3:1: (a) total incremental displacements from PLAXIS; (b) safety factors calculated by the modified Bishop method using GSTABL

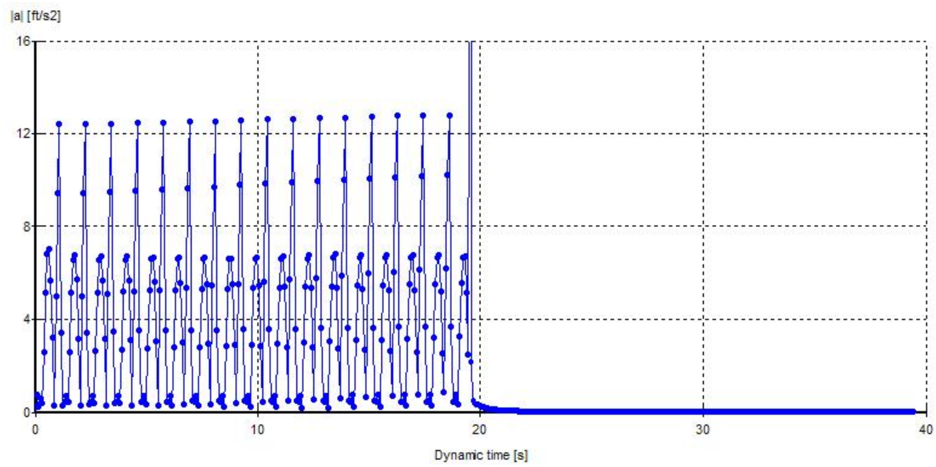


Figure 4 Maximum horizontal acceleration with time.

SUMMARY AND CONCLUSIONS

A bioreactor landfill is operated to enhance refuse decomposition, gas production, and waste stabilization. A major aspect of bioreactor landfill operation is the recirculation of collected leachate back through the refuse mass. The addition of leachate to accelerate the decomposition changes the physical and engineering characteristic of waste and therefore affects the geotechnical characteristics of waste mass.

- The Finite Element Program PLAXIS was used to model and predict the stability of bioreactor landfills, as a function of time and decomposition. Finally the results from finite element program PLAXIS and limit equilibrium program STABL are compared. The results from the analyses are summarized as follows:
- Therefore the seismic stability of bioreactors should be evaluated using the strength characteristics as a function of time and decomposition rather than using average values.
- The factor of safety decreased as the solid waste degraded with time in both static and dynamic analysis.
- Critical failure surface predicted by PLAXIS and GSTABL were very similar. However, PLAXIS predicts the progressive failure pattern, including the plastic points on the slope and considers damping coefficient.
- The factor of safety values for dynamic analysis in Case 1 decreased from 1.51 in FEM PLAXIS analysis to 0.99 in limit equilibrium GSTABL analysis.
- GSTABL did not consider the material damping values and underestimated the seismic stability of solid waste slopes.

These results suggest that the limit equilibrium method overestimates the factor of safety for static analysis and underestimates the factor of safety for dynamic analysis. And it also emphasis the use of finite element method when there is a need to go beyond limit equilibrium analysis.

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