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Influence of liner system parameters on the permanent earthquake-induced displacements of landfill

Jin-shui Ju[a], Shi-Jin Feng[a, b], Qi-teng Zheng[a, c] * and Xiao-lei Zhang[a, b]

[a] *Department of Geotechnical Engineering, Tongji University, 200092 Shanghai, China*
[b] *Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai 200092, China*
[c] *Shanghai Sheshan National Geophysical Observatory, Shanghai 201602, China*
** Corresponding Author, Email: 08qitengzheng@tongji.edu.cn*

ABSTRACT

As the most commonly used indicator of seismic stability of landfills, the seismically induced sliding displacement is generally predicted as a function that includes slope characteristics and ground motion parameters. However, the displacement also varies with the softening characteristics of the geosynthetic interfaces in the liner system which has barely been considered. To address this issue, this paper conducted the dynamic stability analysis of landfills with interface shear and softening based on ABAQUS. The effects of the main liner system parameters (such as the yield coefficient, the seismic spectral acceleration of the degradation period, the dynamic shear strength, and the residual state shear strength) were studied. The results show that the seismic permanent displacement of the landfill along the interface may vary by as much as 50% with or without the liner interface, and the interface adopting the traditional friction model will underestimate the permanent deformation by more than 20% compared with the damage constitutive model used in this paper. Furthermore, several simplified dynamic analysis methods were compared with the developed model and it is indicated that the interface parameters have a considerable effect on the seismic-induced deformation of landfills.

Keywords: Landfill; Earthquake; Liner system; Slip displacement; Seismic effects; Slope stability.

1 INTRODUCTION

Landfills contain pollutant leachate, landfill gas produced by biochemical reactions, and municipal solid waste. The evaluation of the stability of landfills during earthquakes is important because the failure of such structures may cause great harm to humans and the environment. As the amount of municipal solid waste increases year by year, geosynthetics are playing an increasingly vital role in the containment and pollution control of landfills (Fan & Rowe, 2023). The geosynthetic interfaces in the liner system are potential weak interfaces, and the slippage along the geosynthetic interfaces has become one of the main modes of landfill failure. Koerner and Soong (2000) reported that the failure of landfill along the liner system was characterized by a translational mechanism, and that the failure usually occurred on the discrete boundaries of the liner system. The slope failure at the Kettleman Hills landfill was a case in point (Seed et al., 1990). In addition, the risk of landfill instability along geosynthetic interfaces may be increased under seismic loading, as evidenced by many historical records. For example, severe damage to the liner system was observed at the landfill in the Northridge earthquake, with liner tearing and significant permanent sliding deformation of the liner system. Dynamic loads can generate large shear strains and excessive permanent displacements on geostructures. Therefore, the potential impact of dynamic loading on the geosynthetic interface should not be ignored, nor should the impact of the liner system on the seismic stability of the landfill.

At present, the traditional seismic permanent deformation method of landfills is mainly based on the Newmark method (Newmark, 1965) and its modification methods. Newmark method is based on the following assumptions: (a) the sliding mass is rigid; (b) the mechanical behaviour of sliding resistance is rigid-plastic; (c) the resistance to the upslope is infinite; and (d) the displacement occurs along the slope. To overcome the limitations of these assumptions, scholars have proposed several revision methods, such as the coupling approach of the single degree of freedom (SDOF) system and a shear-resistant interface at the bottom (Kramer & Smith, 1997). This coupling method can simultaneously consider the dynamic response and sliding displacement during solving, but the interface strength at the bottom was assumed constant. Ignoring the softening characteristics of the interface will eventually underestimate the permanent deformation of the structure.

The numerical simulation method is another effective method for landfill dynamic response and the permanent deformation analysis, such as the finite element method and finite difference method. Zania et al. (2008) and Choudhury and Savoikar (2009) focused on the internal instability and failure laws of landfill, but the influence of the liner system is still ignored in their numerical simulations and the interaction of solid waste-liner-foundation cannot be fully studied. The deformation of the liner system was considered in the numerical model of the landfill established by Zania et al. (2010). However, the adopted constitutive model of the liner material was linear elastic, which cannot describe the nonlinear tensile properties of the geosynthetics and the accumulative damage to the liner interface.

Based on the numerical simulation, this paper aims to use a damage constitutive model of the interface to analyse the dynamic response and seismic permanent deformation of the landfill along the interface, and to explore the influence of the presence or absence of liners and the type of liner on the seismic-induced deformation of landfills. The impact and mechanism of the liner strength parameters on the permanent deformation of the landfill are subsequently analysed. Furthermore, the damage constitutive model used in this paper is compared with various prediction models and the characteristics and limitations of these simplified calculation methods are analysed.

2 METHODOLOGY

2.1 Establishment of damage constitutive model of liner interface

The damage model can describe the macroscopic response of the material based on the coupling of the non-damaged state and the fully damaged state (Desai & Ma, 1992). Among them, the non-destructive state means that the material has not been damaged or softened, and the fully damaged state refers to the state where the material cannot withstand any further stress, that is, the limit state. Since the interface of geosynthetics exhibits obvious softening characteristics during static and dynamic shearing, the damage theory is suitable for describing its shearing characteristics.

2.1.1 Non-damaged state equations

The non-destructive state is described by the hypoplastic model. The model has only one boundary surface and a stress point in the stress space, which avoids the complexity of the multi-yield surface model and can reasonably describe the plastic deformation of materials, so it is widely used. For the geosynthetic interface, a nonlinear boundary surface equation (Chang & Feng, 2022) is used as follows:

$$f = \bar{\tau}_{\mathrm{i}}^{2} + \left(\eta - \gamma\right)\bar{\sigma}_{\mathrm{n}}^{q} \tag{1}$$

In the equation, *i* represents the intact state (intact state), τ and σ are the shear stress and normal stress of the boundary surface, γ and q are model parameters, and the expression of η is as follows:

$$\eta = \frac{1}{\frac{1}{\gamma} + \frac{\xi^{\beta}}{\alpha}} \tag{2}$$

where α and β are model parameters, ξ is the cumulative plastic shear displacement, and its expression is as follows:

$$\xi = \int \left(\dot{u}^{\mathrm{p}} \dot{u}^{\mathrm{p}}\right)^{1/2} \tag{3}$$

2.1.2 Fully damaged state equations

For the fully damaged state, a nonlinear strength criterion is adopted in this paper, and its expression is as follows:

$$\tau_{\mathrm{f}} = \mu \sigma_{\mathrm{n}}^{k} \tag{4}$$

where f refers to the complete damage state, and μ and k are the model parameters. If k is taken as 1.0, this nonlinear model degenerates into a Coulomb friction model. However, for the geosynthetic interface studied in this paper, the geosynthetic interface can reach a residual state where no further softening occurs. Therefore, all studies in this paper consider a constant value, and the incremental form of the complete damage state can be written as:

$$\dot{\tau}_{\mathrm{f}} = \mu k \sigma_{\mathrm{n}}^{k-1} \dot{\sigma}_{\mathrm{n}} \tag{5}$$

2.1.3 Coupling of damage

According to the research of Desai et al. (2005), the damage equation was initially defined as:

$$D = \frac{\tau_{\mathrm{i}} - \tau}{\tau_{\mathrm{i}} - \tau_{\mathrm{f}}} \tag{6}$$

Then the macroscopic shear stress at the liner interface can be expressed as:

$$\tau = \left(1 - D\right)\tau_{\mathrm{i}} + D\tau_{\mathrm{f}} \tag{7}$$

The damage equation proposed by Desai et al. (2005) is:

$$D{=}D_{\mathrm{u}}\left[1 - \exp\left(-Y\xi^{Z}\right)\right] \tag{8}$$

where Y and Z are model parameters, and D_u is the ultimate damage coefficient, which can usually be set to a value close to 1, such as 0.99. According to Equation (7), the stress increment vector of the liner interface can be further expressed as:

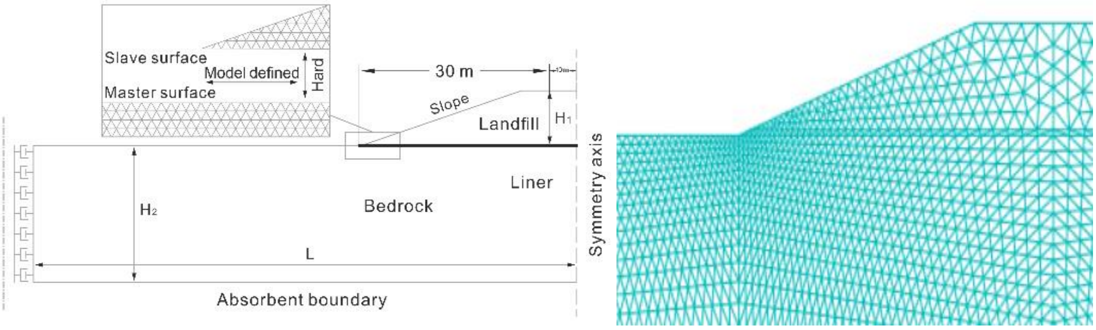
$$\dot{\boldsymbol{\sigma}} = \left(1 - D\right)\boldsymbol{K}_{\mathrm{ep}}\dot{\boldsymbol{u}} + D\boldsymbol{C}_{\mathrm{f}}\dot{\boldsymbol{u}} + \left(\boldsymbol{\sigma}_{\mathrm{f}} - \boldsymbol{\sigma}_{\mathrm{i}}\right)\dot{D} \tag{9}$$

where C_f represents the constitutive matrix of the complete damage state, which can be determined according to formula (5).

The interface damage model proposed in this chapter involves a total of 15 parameters, including 10 parameters in the undamaged state, 2 parameters in the fully damaged state, and 3 parameters in the coupled damage equations. The model has been verified by Chang & Feng (2022), and the calculated results of the model are compared with the results of the uniaxial tensile test and multiaxial tensile test. The results indicate that the adopted model can reasonably describe the damage and softening behavior of the liner system.

2.2 Establishment of Finite Element Numerical Model

The landfill dynamic stability analysis model in this paper mainly considers the damage of the liner interface to simulate the interaction among MSW (municipal solid waste), liner system and foundation (Fig. 1). The geomembrane (GMB) and geosynthetic clay liners (GCL) play the most important roles in the liner system of the landfill. Therefore, in the numerical simulation, for the convenience of solving, secondary elements such as the geotextile protective layer and the leachate drainage layer are omitted.



(a) (b)

Fig. 1. *(a) Geometry diagram of the landfill; (b) details of the finite-element mesh of the model.*

A typical plain landfill was established in ABAQUS with the corresponding parameters listed in Table 1. To prevent the seismic wave from reflecting at the boundary and transmitting the energy back to the landfill, dynamic absorption boundaries were set at the bottom and left sides of the model. In this study, the seismic load was uniformly applied in the form of horizontal acceleration ignoring the vertical seismic load, since the vibration amplitude in the vertical direction is generally subtle.

Table 1. *Geometric parameters, material properties and interface parameters used for seismic analysis of landfill.*

Geometric Parameters		
L/m	*H_1/m*	*H_2/m*
100	20	50
Foundation Parameters		
γ (kN/m^3)	*V_s (m/s)*	*Constitutive relation*
22	100	Linear elastic
GMB Parameters		
Tangent tensile modulus, *E_{ref} (MPa)*	Yield strain, ε_0	Nonlinearity coefficient, a
100	0.15	500
GCL Parameters		
γ (kN/m^3)	Initial shear modulus, *G_0*	Damping ratio, *D*
19	50	$1230(\gamma_d-0.016)^2+0.272$*

Note: GMB and GCL are simulated using rod unit and planar strain unit, respectively. In terms of interface parameters, the interface type simulated in the model is rough surface geomembrane-GCL, and its value ranges refer to Chang et al. (2021).
* Based on the experimental results, the change of damping ratio with shear modulus γ_d is quite different from that of normal soil, therefore the change of damping ratio D is described by the regression equation.

3 ANALYSIS

Methods for generating equivalent sinusoidal pulses from seismic wave databases and using them for dynamic stability analysis have been proposed (Fox & Stark, 2004). To focus on the impact and mechanism of the liner interface rather than the seismic load on the permanent deformation of the landfill, the applied seismic load was simplified as a sinusoid lasting four cycles. The frequency of sinusoidal seismic wave input in the time domain analysis is 1.7 Hz, and the peak acceleration is 0.6g. The dynamic response of the vertical section of the landfill under the seismic load is shown in Fig. 2. The acceleration time histories at the top and middle of the landfill contrast sharply with the sinusoidal excitation at the base. Note that the peaks of acceleration at the bottom interface and inside the landfill have sudden changes rather than a perfect gradual change in the condition without interface (Feng et al., 2021), which reflects the barrier effect of the liner interface on the dynamic load.

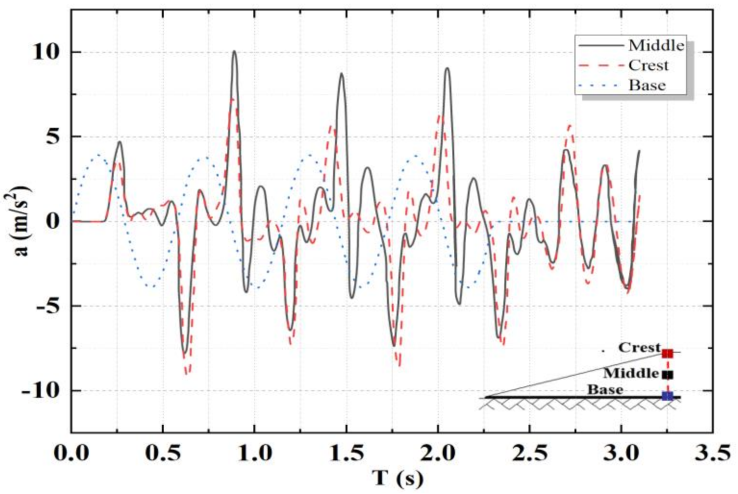


Fig. 2. *Dynamic response distribution of the vertical section on the left side of the landfill.*

The effects of liner interface, interface type, and interface strength parameters on the cumulative slip displacement of the landfill are presented in Fig. 3. The development of slip displacement tends to be stable after the seismic load is applied for 3 seconds. The cumulative process of seismic permanent deformations under four conditions (damaged constitutive model, frictional model, time-history analysis method, and no interface) are compared. It can be found that the development of the progressive displacement is similar across models, whereas ultimate deformation values differ. The liner system shows a significant amplification effect on the permanent seismic deformation of the landfill. The traditional friction interface model underestimates the slip displacement by about 20% due to ignorance of the nonlinear elastoplastic properties and displacement softening properties of the interface. The previous study (Feng et al., 2021) has shown that the frictional model may lead to an overestimation of the acceleration response, especially when the shear strength of the interface is higher.

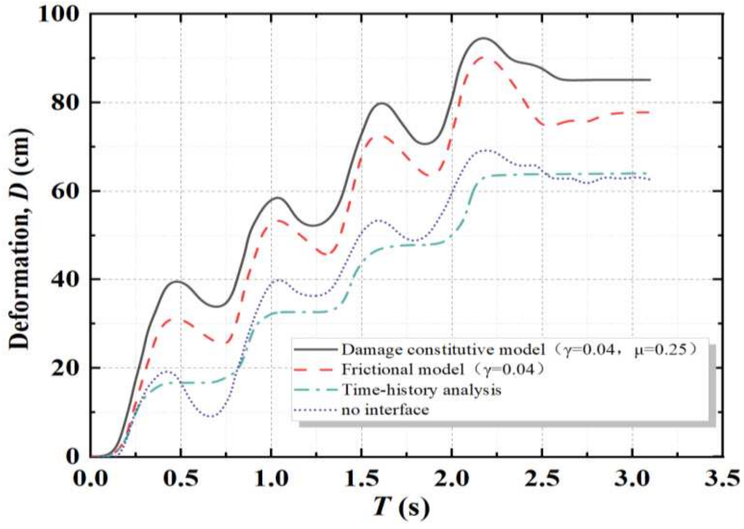


Fig. 3. *The cumulative permanent deformation of different interfaces changes with time.*

It can be found that ignoring the GMB-GCL interface (that is, the no-interface condition shown in the figure) will lead to a significant underestimation of the landfill seismic-induced deformation, which is significantly different from the actual situation. Similarly, the Newmark time-history displacement method also underestimated the permanent deformation by nearly 50%. This is because the Newmark method assumed that the yield acceleration was a constant value while the interface yield strength will significantly decrease as the liner transmits from a non-damaged state to a fully damaged state due to its softening characteristics. Thus, the traditional simplified calculation method may underestimate this part of the cumulative slip displacement.

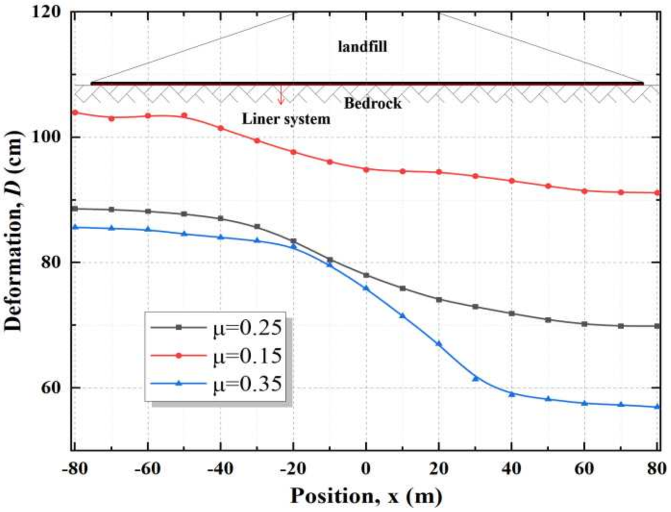


Fig. 4. *Influence of interface residual strength on permanent deformation along the landfill.*

The parameter γ in the undamaged state represents the maximum shear strength that can be achieved at the liner interface, and the shear strength μ in the fully damaged state is another important interface parameter. In this model, μ corresponds to the friction coefficient when the interface is in the residual state. Fig. 4 shows the final slip displacement at different positions of the landfill during the action of seismic sinusoid on the interface with different values of the damage state parameter μ. It can be inferred that higher μ values lead to lower ultimate slip displacements along the liner interface, while a lower damage state parameter results in a more pronounced amplification effect on the permanent deformation displacements in landfills.

4 DISCUSSION

4.1 SODF system analyses

To compare with the permanent deformation of the SDOF system analysis method, the dynamic performance of the sliding body was analysed using the simple model and finite element code proposed by Westermo and Udwadia (1983). The parameters of the SDOF system used are consistent with the corresponding two-dimensional model in this study. The natural frequency of the SDOF model is equal to the eigenfrequency of the corresponding 2D finite element model, and the interface shear strength values of the two models are also the same. The most essential difference between these two methods is that the simplified SODF model analysis cannot provide displacement distribution along the interface. The results calculated by the simple SODF system analysis method and the model adopted in this paper are compared in Table 2.

Table 2. *Comparison of ultimate permanent deformation of landfill between the adopted FEM model and SDOF system model.*

Analysis case	f_{exc}(Hz)	A_y(g)	γ	μ	FEM slip (cm)	SDOF Slip (cm)
Case 1	1.7	0.14	0.04	0.25	14.61	11
Case 2	1.7	0.14	0.04	0.15	44.30	11
Case 3	1.7	0.14	0.04	0.35	12.60	11
Case 4	1.7	0.14	0.25	0.35	8.03	11

The maximum permanent slip displacement values of the landfill under the earthquake action in four cases were calculated (see Fig. 5), and it is found that the SODF analysis method more or less underestimates the permanent deformation along the interface in most cases.

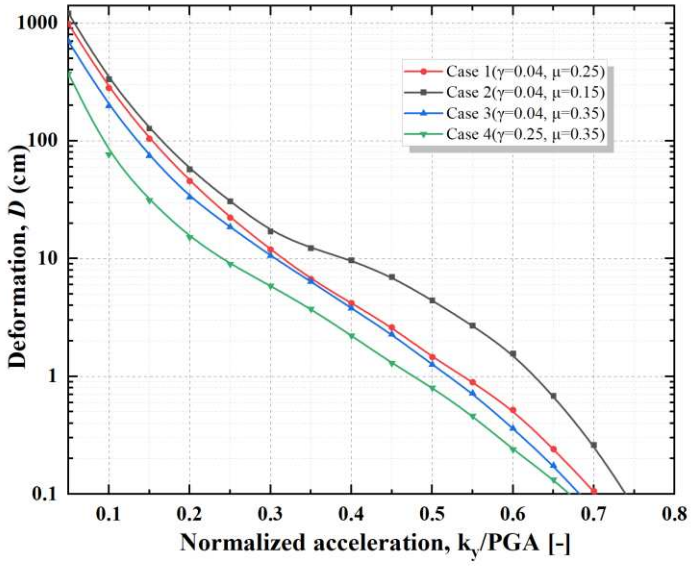


Fig. 5. *Comparison of slip displacement between different coupled strength parameters of the liner system for different ground motion parameters.*

Case 4 with high interface shear strength (non-damage state parameter γ=0.25 and damage state parameter μ=0.35) is a critical situation, where the permanent deformation value obtained by the proposed method is slightly lower than that of the SODF model. However, the interface shear tests showed that the strength parameters of the liner interface are within the ranges of 0.04~0.25 for γ and 0.15~0.35 for μ (Chang et al., 2021). That is, the critical condition corresponds to the optimal shear strength of the liner interface. By summarizing the data in Table 2, it is also evident that the simplified SODF analysis greatly underestimates the displacement along the interface, especially when the interface shear strength is rather low (Case 2).

4.2 Comparison with empirical predictive models

In addition to the dynamic finite element method used in this study, many scholars (Jibson, 2007; Bray et al., 2018; Saygili & Rathje, 2008) have proposed prediction models for estimating the permanent deformation of geo-slopes under earthquakes using basic parameters of seismic waves, which can be used as a supplement to the evaluation of seismic stability in the absence of material parameters. The optimal and least-favourable conditions in this paper (Cases 2 and 4) are compared with the calculation results of three simplified models (see Fig. 6).

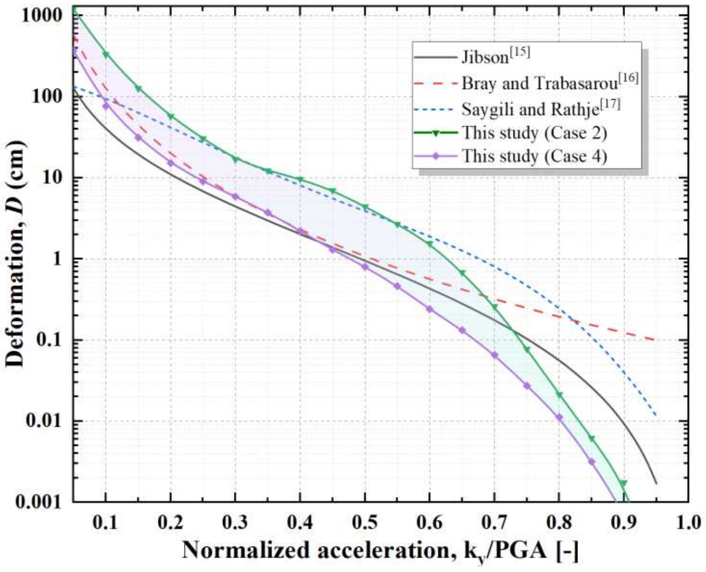


Fig. 6. *Comparison of slip displacement between empirical prediction models with finite element model used in this study for different ground motion parameters.*

It can be found that when the yield acceleration ratio does not exceed 0.4, the Jibson model greatly underestimates the permanent deformation of the landfill. When the yield acceleration ratio is between 0.1 and 0.55, both the Bray and SR (Saygili & Rathje) models are within the deformation range calculated by the model proposed in this paper. In particular, when the yield acceleration ratio is greater than 0.65, the calculated displacement values of all models are less than 1 cm. Displacements smaller than 1 cm are not of engineering significance and can be considered negligible or zero for practical purposes. Therefore, the larger ratio of yield acceleration to peak ground acceleration (k_y/PGA > 0.6) does not need to be the focus of our consideration. It is worth noting that the SR model is close to the upper limit of all the results within the main earthquake intensity range, and the trend is consistent with the adopted model in this study. The values estimated by the SR model are relatively safer, mainly because the model comprehensively considers the coupling effects of various ground motion parameters (peak ground acceleration, peak ground speed, and Arias intensity) and greatly reduces the standard deviation. Therefore, the SR model is recommended as an auxiliary method for evaluating the seismic stability of landfills. Subsequently, based on the SR model, the calculation formula for seismic permanent deformation of landfills containing liner strength parameters has yet to be developed.

5 CONCLUSIONS

The seismic dynamic response and permanent deformation of the landfill are complex dynamic interaction problems of MSW-liner-foundation. Through numerical simulation, the effects of different interface strength parameters on the seismic permanent deformation of landfills were analysed and the applicability of coupled methods and simplified empirical prediction models were also evaluated. The main conclusions are as follows:

(1) In the seismic stability analysis of plain landfills, the influence of the geosynthetic interface should be considered. The seismic stability analysis method of traditional geotechnical structures cannot take the particularity of the structure and materials of the landfill into account and may greatly underestimate the permanent deformation of the landfill.

(2) Compared with the liner interface damage constitutive model used in this paper, the model without interface may significantly overestimate the dynamic response of the landfill while the traditional frictional model will underestimate the seismic permanent deformation of the landfill along the liner system. It is further inferred that the elastic-plastic and dynamic softening characteristics of the liner interface are quite important for the stability analysis of the landfill. For landfill slopes where large slips may occur, more attention should be paid to ensuring sufficient residual shear strength at the weak liner interface.

(3) Caution is required when using simplified dynamic analysis methods for landfill seismic stability assessments. Compared with different simplified prediction models, the estimation results of the SR model, which considers the coupling effects of multiple ground motion parameters, are more secure. However, it is still recommended to introduce liner parameters into the calculation formula for the seismic permanent deformation of landfills. The range of values of different parameters may affect the seismic-induced deformation by more than one order of magnitude, which is as important as ground motion parameters. Furthermore, it is necessary to load and combine complex seismic loads to calculate the standard deviation of interface parameters and combine them with other ground motion parameters in order to predict more accurate and reliable seismic-induced permanent deformation of the landfill.

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