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Seismic analysis of landfill considering the effect of GM-GCL interface within liner

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ABSTRACT

Geomembrane (GM) and geosynthetic clay liner (GCL) are extensively used in liner system which are placed beneath the landfill to isolate waste material from the surrounding environment but the geosynthetics can also be the weak interface, so analysis of seismic response and permanent deformation of landfill should be performed considering the influence of liner interface reasonably. In this study, a displacement-softening nonlinear elastoplastic constitutive model is established to describe the dynamic friction behavior of GM-GCL interface under various normal stress conditions and is validated against experimental results of cyclic shear tests and shaking table tests. Two-dimensional time-domain dynamic finite element analyses of typical above ground landfill incorporating the newly proposed dynamic interface friction model are conducted to provide an insight into the dynamic response and slip displacement along the GM-GCL interface. Neglecting the nonlinear elastoplasticity and displacement-softening property of the geosynthetic interface generally induces significant errors. The liner layer should be designed with full attention to restrict the seismic response and permanent deformation caused by earthquake. Extreme caution is required when using simplified dynamic analysis methods for seismic design or assessment of landfill.

1. Introduction

Landfills are geo-structures for managing municipal solid waste (MSW), which contains contaminant leachate, greenhouse gases, and solid. The failure of a landfill can pose great danger to people and environment. Hence, the stability and serviceability of landfills are substantially important and attract extensive attention. Geosynthetic is widely used in liner system of landfills owing to its favorable anti-seepage performance. However, due to the relatively low shear strength, geosynthetic is often the potential weak interface of a liner system. The failure due to displacement along the geosynthetic interface within the liner system in Kettleman Hills Landfill is a typical example [1]. Moreover, the risk of landfill instability caused by the weak geosynthetic interface may be significantly amplified under seismic load. For example, more serious damage was observed in landfills after the Northridge earthquake, including torn geomembrane and permanent deformation along the liners [2]. Therefore, it is very essential to assess the effect of liner system on the seismic stability of landfills.

Dynamic shear behavior of geosynthetic interface has drawn extensive attention due to its close relation to the stability of landfills [3–7]. Results of shaking table test [3,4] and cyclic direct shear test [5,6] all revealed that friction angle of the geosynthetic interface varied from peak to residual with the development of relative displacement for both dry and wet conditions. Notably, a series of large-scale cyclic shear tests for the interface between geomembrane (GM) and geosynthetic clay liner (GCL) under a very large range of normal stress were conducted by Ross [7] and the test results indicated noteworthy nonlinear elastoplastic feature and displacement-softening property of the geosynthetic interface. Therefore, nonlinearity and displacement-softening are inherent properties of some geosynthetic interfaces (e.g., GM-GCL interface) when subjected to seismic load. Especially, previous studies [8] revealed that failure of GM-GCL interface is the main failure mode in composite liner system under dynamic loads. Hence, the influence of GM-GCL interface on the seismic stability of landfill should be comprehensively investigated.

Traditionally, earthquake-induced displacement of landfill is estimated by Newmark's one-dimensional analytical sliding-block method [9] based on double integration of the relative acceleration time history. To improve the accuracy of Newmark's rigid block model, the rigid sliding block is replaced by lumped mass connected by springs and dashpots [10]. The dynamic response and sliding displacement along the interface can be obtained simultaneously by this method. It is

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noteworthy that these models are not specifically proposed for seismic analysis of landfill and hence the dynamic shear properties of liner system are not considered.

Since liner system can be the weak interface under seismic load, great efforts have been made to investigate the influence of liner system on the response of landfill to earthquake with numerical methods [11–14]. Zania et al. [11] and Feng et al. [12] examined seismic response and base sliding of typical above ground landfill considering the influence of liner interface by setting invariable friction coefficient, which significantly overestimate the dynamic shear strength of liner interface. Arab [13] and Kavazanjian et al. [14] studied earthquake-induced tensile forces and strains of liner systems with a linear elastoplastic friction model. Although the influence of displacement-softening of liner interface was included in these seismic analyses, the assumption that shear stress linearly increases with relative displacement cannot describe the constitutive relation of geosynthetic interface within liner system exactly, which may bring about considerable errors and is adverse to rational seismic design of such geo-structures.

The primary objective of this study is to take the nonlinear elastoplasticity and displacement-softening property of liner interface into account simultaneously and investigate the seismic response and earthquake-induced deformation of landfill. A displacement-softening nonlinear elastoplastic friction model for GM-GCL interface is proposed and verified by the results of cyclic shear test and shaking table test. The seismic response and deformation of landfill are then comprehensively studied using 2D finite element dynamic analysis model where the developed dynamic interface friction model is implemented. Some simplified methods are also adopted for analysis to investigate the possibility of simplifying the seismic analysis of landfill in engineering practice.

2. Methodology

2.1. Development of the dynamic interface friction model

Large-scale cyclic shear tests for the interface between GM and GCL conducted by Ross [7] indicated: (a) dynamic shear behavior of the interface shows typical elastoplastic feature; (b) shear stress of the interface increases nonlinearly with the development of relative displacement during the elastic phase; (c) shear stress decreases with the accumulation of relative displacement during the plastic stage. The relationship between shear stress and relative shear displacement of the GM-GCL interface under cyclic load is illustrated in Fig. 1. The two segments (pre-peak and post-peak) are defined to describe the nonlinear elastic stage and plastic stage during the loading process, respectively. Based on the mechanism revealed by the test results, a new

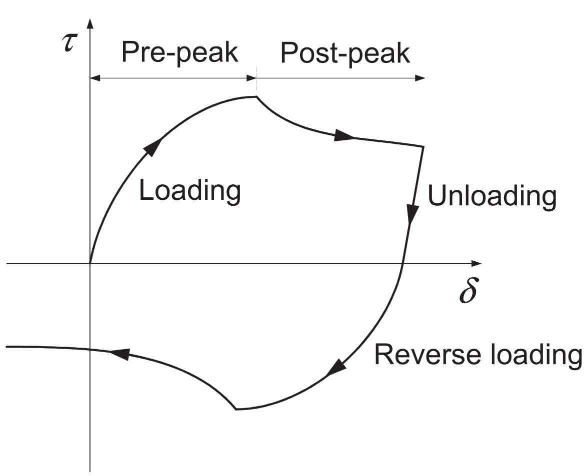

Fig. 1. Relationship between shear stress and relative shear displacement under cyclic load.

displacement-softening nonlinear elastoplastic friction model for GM-GCL interface is developed.

During the elastic stage of every cycle, the dynamic shear property of the interface is characterized by shear stiffness, which can be expressed as

$$\tau = K\,\delta \tag{1}$$

where τ is the shear stress, δ is the relative shear displacement and K is the shear stiffness. To describe the nonlinearity of K shown in the test results [7], the equation proposed by Reddy et al. [15] is improved as follows:

$$K = \left(1 - R_f \frac{\tau}{\sigma\mu}\right)^2 \left(\frac{\sigma}{p_a}\right)^n K_0 \tag{2}$$

where σ is the normal stress; μ is the friction coefficient; R_f is the failure ratio which is derived from the Duncan-Chang model; p_a is the atmospheric pressure to make the normal stress dimensionless; n is an exponent controlling the degree of influence of normal stress on shear stiffness; K_0, which is directly related to material properties, is the basic shear stiffness. μ, n, K_0 can be determined based on test results. The nonlinear elastic characteristics of the GM-GCL interface are addressed by Eq. (2) as the shear stiffness is real-time updated with the development of relative displacement in the elastic stage.

After reaching the peak, notable reduction of shear stress is observed, and the displacement-softening equation is applied to describe such phenomenon. It is assumed that the relation between shear and normal stress obeys the Coulomb criterion for perfect plasticity during the post-peak stage:

$$\tau = \sigma\,\mu \tag{3}$$

where μ is the friction coefficient, which is bounded by peak friction coefficient (μ_p) and residual friction coefficient (μ_r). The degradation of shear strength of the interface can be considered by the reduction of friction coefficient. The degree of reduction can be represented by a residual factor (R) [16]:

$$R = \frac{\mu_p - \mu}{\mu_p - \mu_r} \tag{4}$$

The static shear test results of geosynthetic interface in previous studies [17] indicated that the relationship between residual factor and plastic shear displacement can be described by an exponential curve. Herein, the decay process of friction coefficient under cyclic loading is expressed as follows:

$$R = \left(\frac{\delta - \delta_e}{\delta_p}\right)^k \tag{5}$$

where δ_e is the relative displacement range of elastic phase; δ_p is the relative displacement range of plastic phase; k is the decay exponent. Consequently, combination of Eqs. (4 and 5) results in the variation of friction coefficient with relative displacement, and the whole process is displayed in Fig. 2.

As for the unloading stage, according to the test results [7], the shear stress decreases linearly with relative displacement and the slope varies with normal stress. The following equation is then adopted to describe the variation of shear stiffness:

$$K_{unload} = \left(\frac{\sigma}{p_a}\right)^n K_0 \tag{6}$$

2.2. 2D finite element dynamic analysis method

In the present study, 2D finite element model is established to analyze seismic response and deformation of landfill. As shown in Fig. 3, the numerical model contains two parts, including a typical above ground landfill and foundation, which are assembled together by

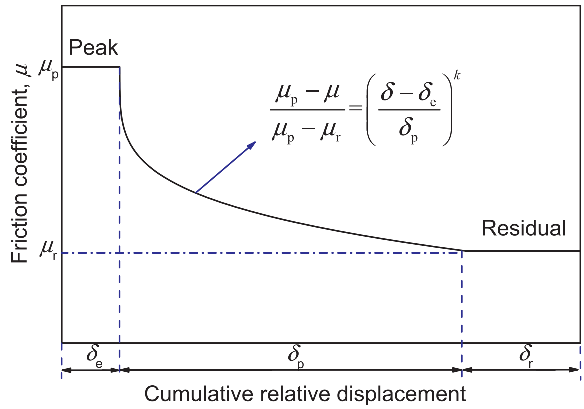

Fig. 2. Relationship between friction coefficient and cumulative relative shear displacement.

specific interaction conditions.

To take the nonlinearity of the waste material into account, equivalent linear viscoelastic constitutive model is used. A corresponding UMAT subroutine where the values of waste stiffness and damping ratio are consistent with the level of shear strain during the calculation is written. Moreover, to simplify effect of site condition, the foundation is modeled with linear elastic material.

The model is discretized utilizing plane-strain elements in finite element code ABAQUS and the element size is set according to the wavelength of interest. Specifically, in case of wave reflection, absorbent boundary is set at the deep bedrock using infinite element, which has proven to be effective for this kind of problem [18].

The GM-GCL interface within liner system of landfill is modeled by defining a pair of master contact surface and slave contact surface (Fig. 3). The contact equations are formulated at each node of slave surface. In sequence, the contact algorithm searches for the closest point on master surface where the slave surface's normal and shear stresses pass through the node on master surface. In this study, the normal contact is set as "hard contact", which means that any separation of the contact surfaces will lead to zero normal stress. Especially, the developed dynamic interface friction model is implemented into the FRIC subroutine as follows. The relative displacement between the contact surfaces is transmitted into it to calculate the frictional stress based on Eqs. (1)–(6), and the result is then sent back to the finite element program to continue the analysis of other parts. In this way, the developed displacement-softening nonlinear elastoplastic relation can be applied to analyze the seismic response and earthquake-induced displacement of landfill in ABAQUS.

As for the dynamic modeling, the accelerations are exerted in horizontal direction on the foundation boundary. Implicit direct time integration according to Hilber et al. [19] is used to solve the equation of motion. Considering convergence issues, time integration parameter is set as −0.333, which means that high frequency response of the geostructure is neglected and convergence can be reached more easily.

3. Verification of the dynamic interface friction model

3.1. Large-scale cyclic shear test

The large-scale cyclic direct shear tests reported by Ross [7] are adopted to test the performance of the proposed model in describing cyclic direct shear behavior of GM-GCL interface. Here, four typical tests are adopted for comparison. Cases with different amplifications (δ_a = 10, 120 mm) and different normal stresses (σ_n = 348, 692 kPa) are simulated. Parameters of the interface friction model are determined through fitting the test results and are summarized in Table 1. The comparison of variation of shear stress with displacement is shown in Fig. 4. The results of the numerical simulation agree with the experimental test results reasonably well.

3.2. Shaking table test

Shaking table test plays an important role in measuring the dynamic shear properties of geosynthetic interface. Considering that the sliding block may show more complicated behavior in an inclined shaking table as a result of the interaction between gravity and dynamic load, the inclined shaking table test conducted by Mendez et al. [20] is adopted for further verification of the interface friction model. In the test, a wood block was placed on geotextile which was glued to an inclined shaking table. Two specific loads were used and two types of motion were observed, which were called "continuous mode" and "stick-slip mode", respectively. The fitting parameters for numerical simulation are summarized in Table 1. Comparison of sliding displacement and acceleration time history is shown in Fig. 5. The "continuous mode" and "stick-slip mode" are both successfully simulated by the present model.

The simulation results of the cyclic shear test prove the ability of the newly developed model to describe relation between shear stress and displacement of GM-GCL interface under dynamic loads. Furthermore, the numerical model of shaking table test can be deemed as a simplified model of landfill. The success of this approach in modeling shaking table tests demonstrates that this method is able to analyze seismic response and earthquake-induced displacement of landfill.

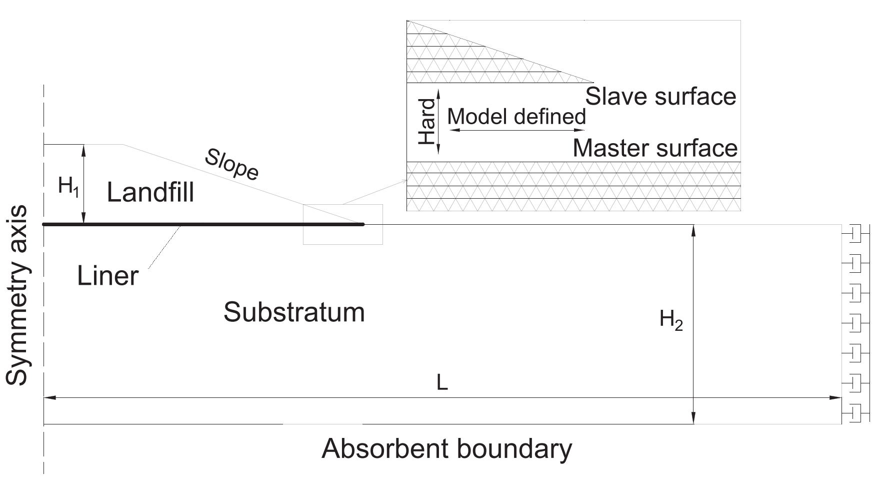

Fig. 3. Finite element model of a typical above ground landfill.

Table 1
Interface parameters used for model verification.

Test type	Interface parameter								Load
	R_f	n	K_0 (kPa)	μ_p	μ_r	k	δ_e (m)	δ_p (m)	
Cyclic direct shear test	0.90	1.0	60,000	0.4	0.08	0.20	0.01	12.00	$\delta = \delta_a \sin(2\pi t)$, displacement-control
Inclined shaking table test	0.90	1.0	60,000	0.35	0.30	0.25	0.01	12.00	From literature [20], acceleration-input

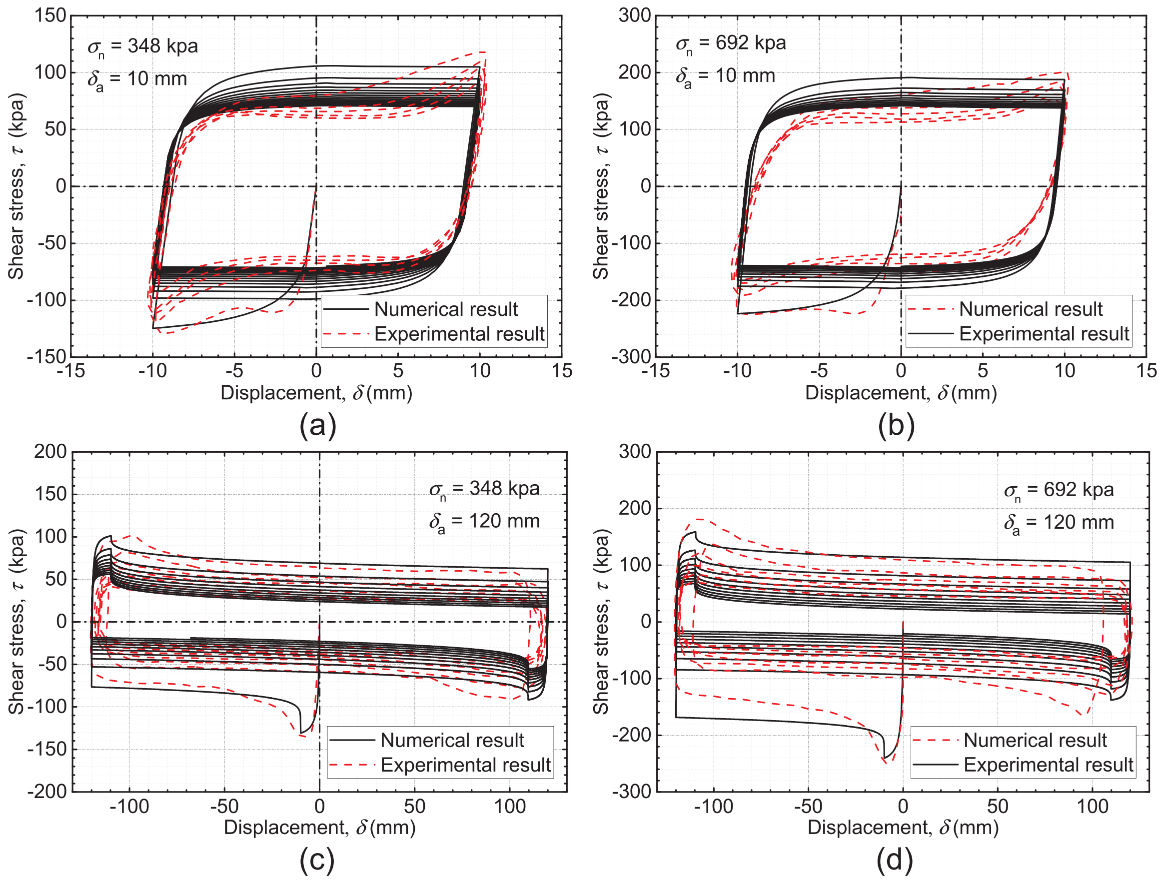

Fig. 4. Comparison of variation of shear stress with displacement between numerical results and cyclic shear test data reported by Ross [7].

4. Seismic analysis of landfill

4.1. Input information

Herein, a finite element model of typical above ground landfill is established in ABAQUS to carry out seismic analysis, and the corresponding geometric parameters shown in Fig. 3 are summarized in Table 2. The mechanical parameters of waste and substratum are based on the available data in literature and the variation of parameters with depth is taken into account as follows.

Published data of the unit weight of MSW [21–24] show significant scatter for different sites (see Fig. 6a). Herein, the typical hyperbolic law proposed by Zekkos et al. [23] is used to determine the variation of unit weight of MSW with depth. Parameters of the hyperbolic model are selected based on mathematical fitting to the published data shown in Fig. 6a. Consequently, the relation between unit weight (γ) and depth (Z) is as follows:

$$\gamma(Z) = 10 + \frac{Z}{2.2 + 0.1Z} \tag{7}$$

Similarly, shear wave velocity of MSW (V_S) from in-situ tests displays significant variance for different sites [25–28] (see Fig. 6b), and in this paper a simplified linear relation is defined as follows:

$$V_S(Z) = 110 + 4.5Z \tag{8}$$

As mentioned before, the nonlinearity of the waste material is involved in UMAT subroutine where waste stiffness and damping ratio vary with shear strain. Concerning shear modulus reduction and damping ratio increase with shear strain, numerous in-situ measurements using various techniques [29,30] and back analyses from seismic records [31] were carried out. Herein, curves of stiffness degradation and damping increase for waste mass proposed by Zekkos et al. [32] through large-scale cyclic triaxial tests are used.

To avoid effect of site condition, the foundation is considered as homogenous bedrock and modeled with linear elastic material, the adopted parameters are summarized in Table 2. Parameter values of dynamic friction model are based on test results [7] and listed in Table 2. Particularly, an empirical relation between initial shear stiffness (K_{ini}) and δ_e is developed from experimental results [7] as follows:

$$K_{ini} = \frac{15\sigma\mu_p}{\delta_e} \tag{9}$$

Moreover, the initial shear stiffness (K_{ini}) in dynamic friction model can be expressed as follows according to Eq. (2):

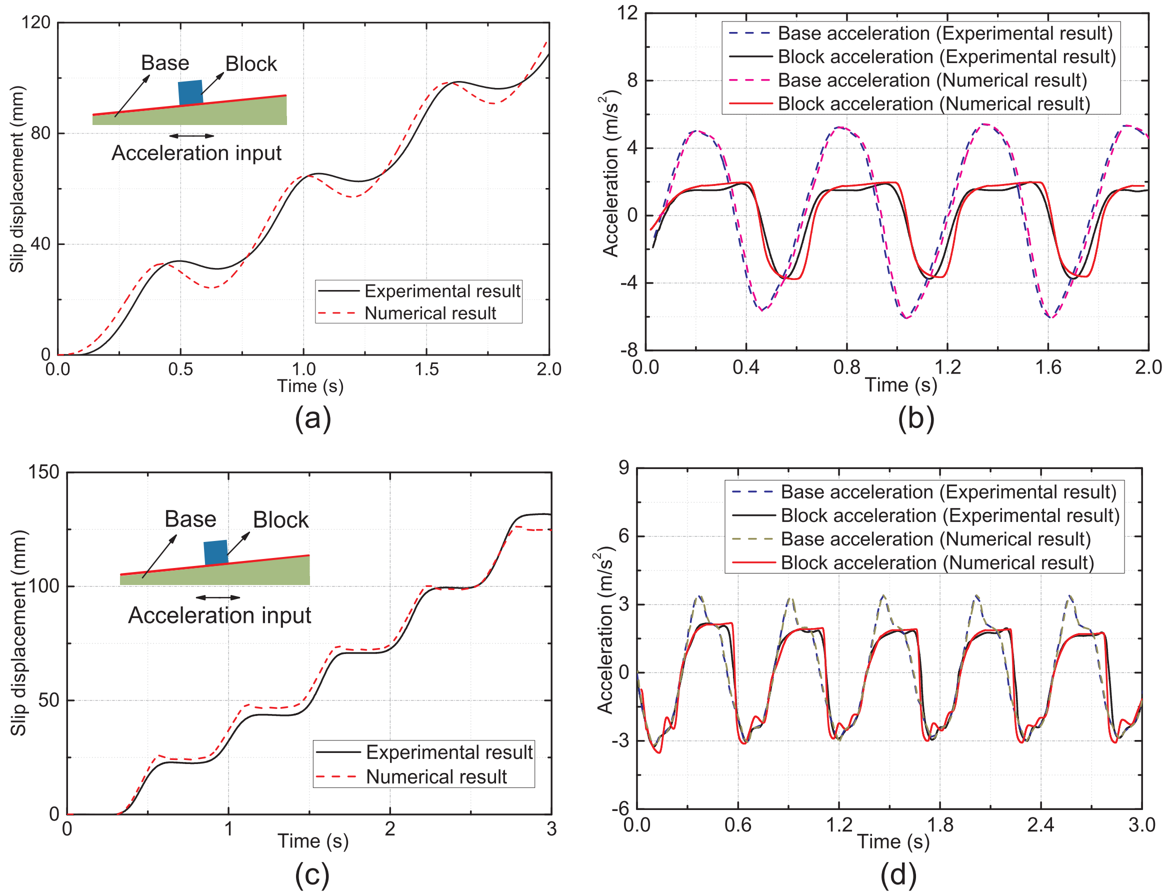

Fig. 5. Comparison between numerical results and inclined shaking table test results reported by Mendez et al. [20]: (a) slip displacement of the continuous mode; (b) acceleration time history of the continuous mode; (c) slip displacement of the stick-slip mode; (d) acceleration time history of the stick-slip mode.

$$K_{ini} = \left(\frac{\sigma}{p_a}\right)^n K_0 \tag{10}$$

Therefore, K_0 varies with δ_e according to Eqs. (9 and 10).

In this study, three typical earthquake loads are adopted for analysis. Apart from the Ricker wavelet with a central frequency of 2.0 Hz, other two acceleration time histories are both realistic earthquake records, and they are all scaled to 0.5 g. Their time history and response spectra are displayed in Fig. 7. Their predominant periods are 0.4, 0.07–0.15 and 0.03 s, respectively, so a large range of predominant period is covered. Time step is 0.01 s because the accelerations in time histories are defined for every 0.01 s.

4.2. Effect of peak friction coefficient (μ_p)

Peak friction coefficient (μ_p) is an important parameter to characterize the dynamic shear property of GM-GCL interface. So the effect of μ_p on seismic response and permanent displacement is firstly analyzed. To eliminate the influence caused by complicated real earthquake record, the landfill is excited by Ricker wavelet consistently.

The response spectra of landfill crest under different interface conditions is displayed in Fig. 8. It is clear that neglecting the GM-GCL interface leads to significant overestimation of seismic response. Even for the peak friction coefficient of 0.5, there still displays obvious difference, which further reveals the necessity of considering geosynthetic interface in seismic analysis of landfill.

Due to no consideration of nonlinear elastoplasticity and

Table 2
Geometric parameters, material properties and interface parameters used for seismic analysis of landfill.

Geometric parameters								
L (m)			H_1 (m)	H_2 (m)		Slope		
200			20	50		1:3		
Material properties								
Material			γ (kN/m^3)	V_S (m/s)		Constitutive model		
Waste			Fig. 6(a)	Fig. 6(b)		Equivalent linear viscoelastic		
Substratum			22	1000		Linear elastic		
Interface parameters								
Section	R_f	n	K_0 (kPa)	μ_p	μ_r	k	δ_e (m)	δ_p (m)
4.2	0.90	1.0	60,000	Analyzed	0.08	0.20	0.01	12.00
4.3	0.90	1.0	Analyzed	0.4	0.08	0.20	Analyzed	12.00
4.4	0.90	1.0	60,000	0.4	Analyzed	0.20	0.01	12.00

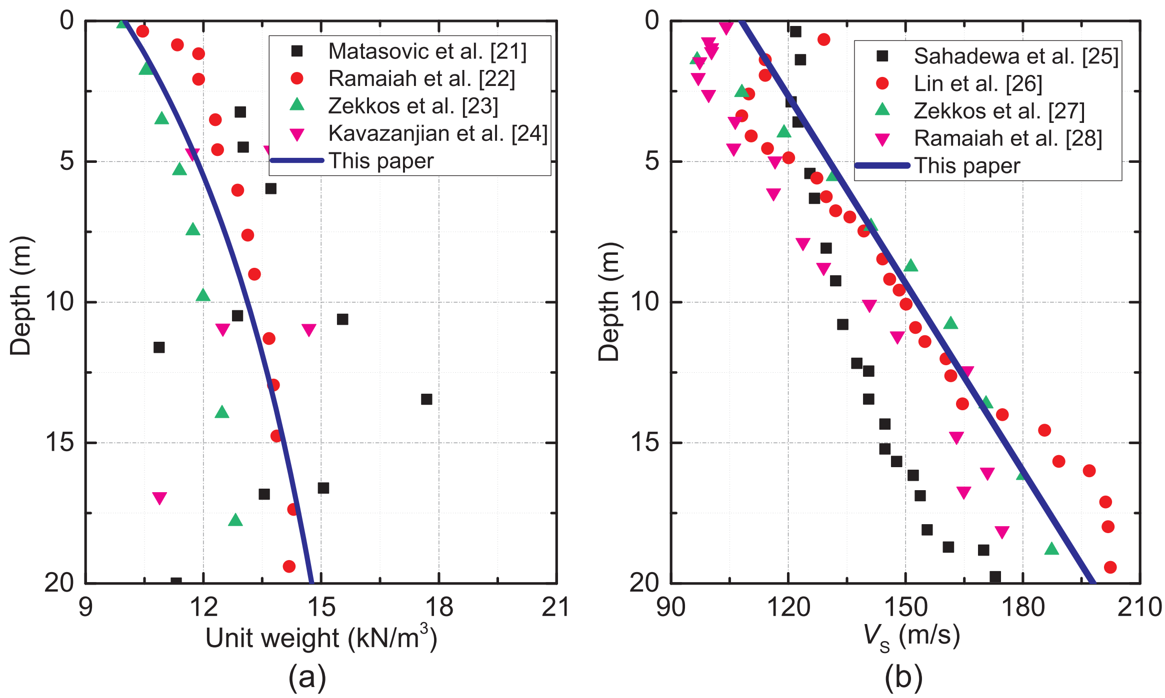

Fig. 6. Mechanical properties of waste in finite-element model: variation of (a) unit weight and (b) shear wave velocity with depth.

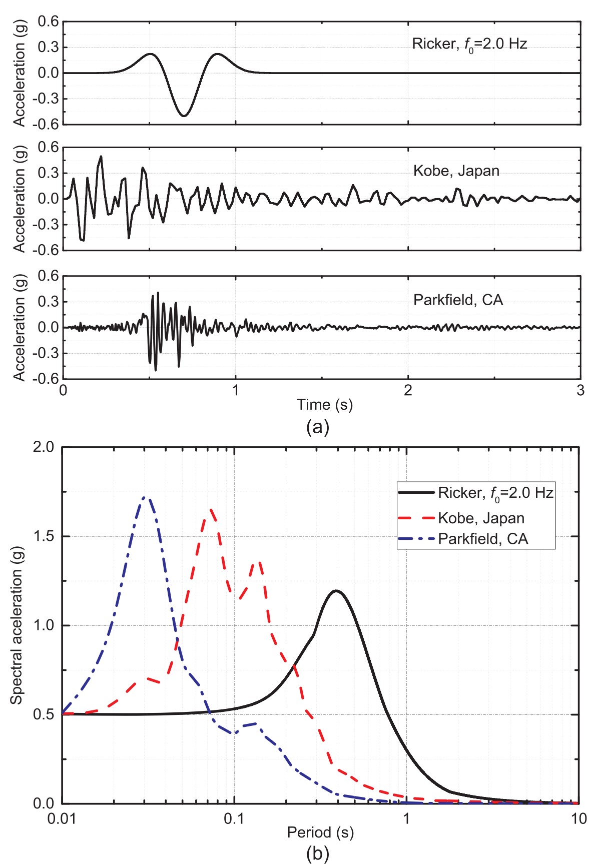

Fig. 7. (a) Acceleration time history and (b) response spectra of three earthquake records used in this study.

displacement-softening property of the interface, overestimation of acceleration response is also caused by constant friction coefficient. The higher the shear strength of the interface, the higher the degree of overestimation. The reason is that higher shear strength of interface means more significant difference between constant friction coefficient and dynamic friction model since the residual friction coefficient is fixed as shown in Table 2. Hence, it is inappropriate to perform numerical seismic analysis of landfill using GM-GCL interface with constant friction coefficient when the shear strength of interface is relatively high.

Fig. 8(a–d) reveals that larger μ_p overall results in higher spectral acceleration, which is due to more dynamic energy transmitted to waste mass through the interface with higher shear strength. Notably, the more intensive acceleration response caused by higher μ_p is adverse to the integrity of cover system and pipes inside the waste for gas collection, which should be treated seriously.

Interestingly, the response spectra are characterized by double peaks in Fig. 8. The second one is caused by the amplification effect of earthquake record because its abscissa value is around the predominant period of the Ricker wavelet (T_p = 0.39 s). The second peak becomes more and more inconspicuous as μ_p decreases, because less energy of excitation is transmitted into the landfill through the interface given lower frictional strength. As for the first one, it is probably related to the natural vibration property of the landfill. According to Kramer [33], the first eigenperiod (T_s) of the landfill is approximately given by

$$T_s = \frac{2.5H_1}{V_S} \tag{11}$$

where H_1 is the height of the landfill and V_S is the shear wave velocity of the waste material. The eigenperiod of the landfill is about 0.30 s. The abscissa value of the first peak is between 0.2 and 0.3 s and is slightly smaller than the eigenperiod of landfill, which reflects the influence of soil-structure interaction when there is geosynthetic interface.

Apart from dynamic response of landfill, earthquake-induced displacement is another important issue for seismic stability analysis. As reported by Seed and Bonaparte [34], the design of landfill is acceptable if the calculated permanent displacement caused by seismic load is not more than 150–300 mm. In this study, absolute value of slip displacement is not concerned and the law of slip displacement along the interface within liner induced by Ricker wavelet is systematically analyzed to investigate the effect of interface condition on seismic

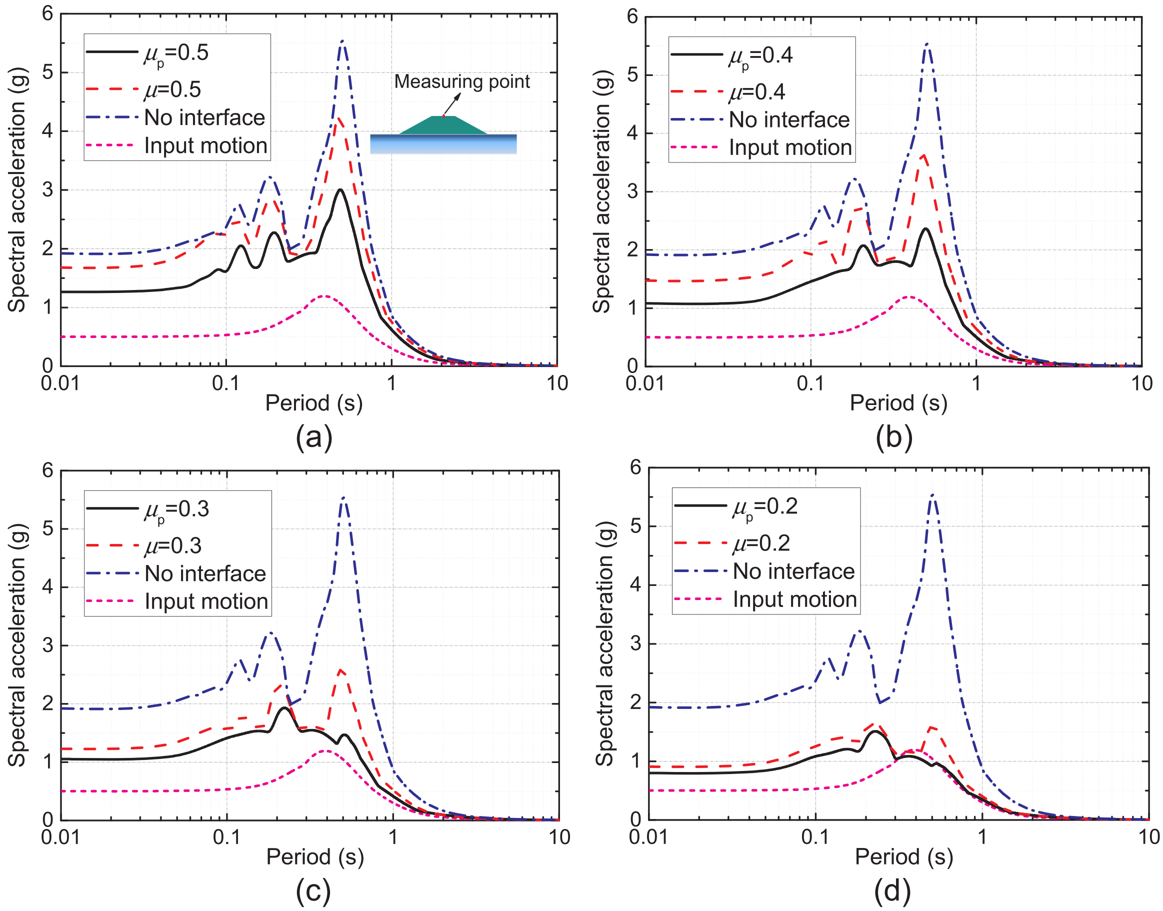

Fig. 8. Acceleration response of landfill to Ricker wavelet: (a) $\mu_p = \mu = 0.5$, (b) $\mu_p = \mu = 0.4$, (c) $\mu_p = \mu = 0.3$, (d) $\mu_p = \mu = 0.2$.

displacement.

The distribution of final displacement along sliding interface for different μ_p is displayed in Fig. 9(a). It is obvious that stronger interface significantly limits the overall slip displacement and deformation. For comparison, results of the interface defined by constant friction coefficient are also displayed in Fig. 9(b). Comparison between Fig. 9(a) and (b) reveals that considering the friction coefficient as a constant will certainly underestimate earthquake-induced displacement and deformation, which is hazardous to safety design of landfill. Therefore, consideration of elastoplasticity and displacement-softening is well recommended in dynamic analysis of landfill.

Based on the above analysis, it can be concluded that increasing shear strength of geosynthetic interface is beneficial to restrict slippage but detrimental to confine dynamic response of waste mass. Restriction of displacement is necessary for overall stability, but high seismic vibration is hazardous to integrity of cover system and pipelines inside landfill. Therefore, rational selection of μ_p is very important for seismic design of landfill.

4.3. Effect of the relative displacement range of elastic phase (δ_e)

δ_e is an essential variable to describe the nonlinear elastoplasticity of the dynamic interface friction model. The effect of δ_e on seismic response of landfill is investigated in this section.

Response spectra of the landfill crest subjected to three earthquake records are displayed in Fig. 10. Increase of δ_e leads to decline of acceleration response consistently. To investigate the reason, time histories of shear stress at middle of the sliding interface are shown in Fig. 11. It is evident that larger δ_e leads to lower final shear stress in every loading cycle, which results in less dynamic energy transmitted into waste mass and lower acceleration response consequently. The phenomenon can also be illustrated by Fig. 1. A larger δ_e means that more relative displacement is needed to reach the peak shear stress.

It is noteworthy that tendencies of spectra lines in Fig. 10 are all similar for different δ_e, but there is a little difference among the abscissa values corresponding to peaks (i.e., predominant periods). This result is attributed to the slightly different hysteresis caused by increasing δ_e, which is clearly shown in Fig. 11. To reach the balance of shear stress along the interface, more time is needed for higher δ_e in each cycle. Therefore, the predominant period of the induced acceleration response shows variance for different δ_e.

Besides, Fig. 10 indicates that Parkfield earthquake leads to the lowest acceleration response at the crest of landfill, though the three earthquake records are all scaled to 0.5 g. Time histories of shear stress at the interface shown in Fig. 11 also reveal that the maximum shear stress at the middle of geosynthetic interface caused by Parkfield is significantly lower than that caused by Ricker wavelet. During the elastic stage, shear stress increases with the accumulation of shear displacement and a certain amount of displacement is required to reach the peak shear strength. When the landfill is subjected to earthquake records with high frequency, shear displacement along the geosynthetic interface in every cycle may be insufficient to reach the peak. Therefore, earthquake with the lowest predominant period (Parkfield, CA) results in the lowest acceleration response.

4.4. Effect of residual friction coefficient (μ_r)

As for the displacement-softening property of the dynamic interface friction model, the residual friction coefficient (μ_r) is the symbol illustrating the amount of softening. In this section, the effect of μ_r on

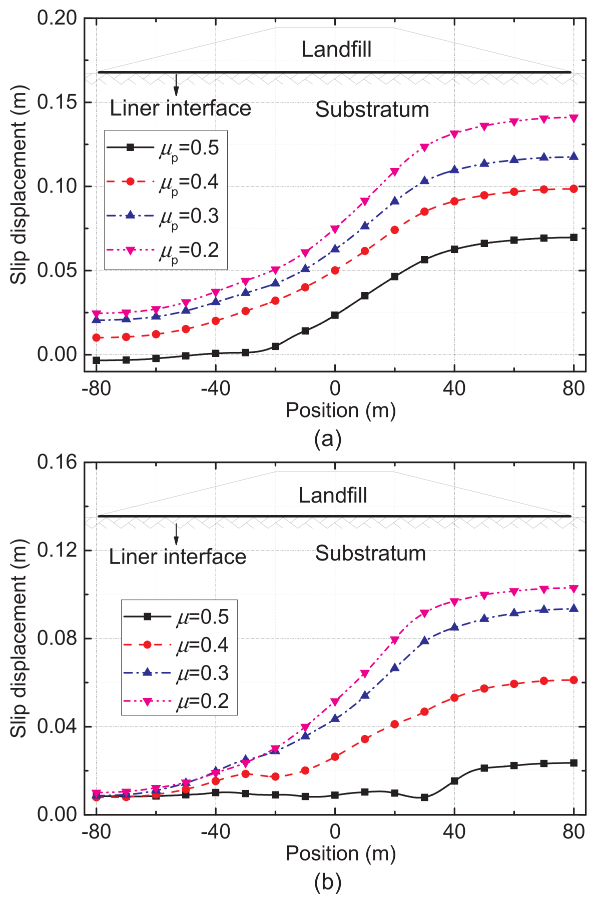

Fig. 9. Distribution of slip displacement along the liner interface for different peak shear strengths of (a) dynamic friction model and (b) constant friction coefficient.

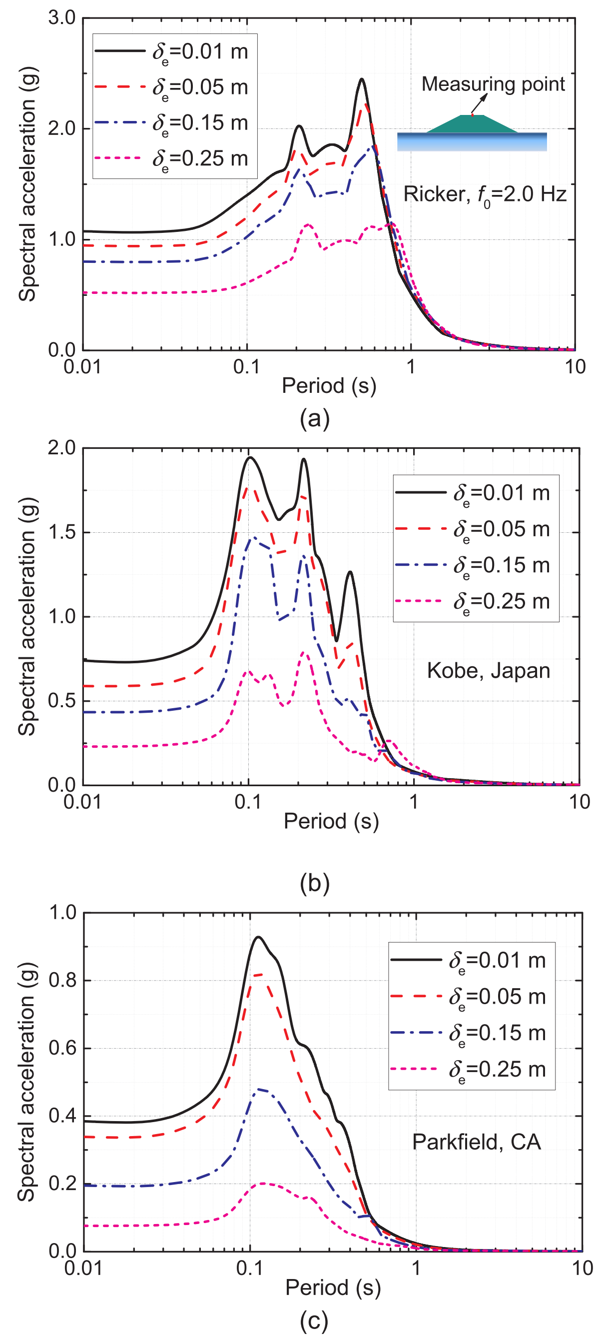

Fig. 10. Acceleration response of landfill with different δ_e of dynamic friction model.

earthquake-induced displacement of landfill is investigated.

Development of slip displacement with different μ_r at three typical positions of the interface is shown in Fig. 12. Higher μ_r results in smaller amount of final slip displacement for all the three points. During the development of slippage, difference caused by different μ_r occurs after a certain amount of relative displacement, which is due to the existence of elastic stage.

Especially, the difference of final displacement for different μ_r is larger at $x = 80$ m than that at the other two points, which is due to the relatively high total displacement at this point. It is easily inferred that larger displacement will make the influence of μ_r more significant. Therefore, increasing the residual shear strength of GM-GCL interface within liner system is more necessary for toe of slope, where vast slippage may occur.

Besides, it is interesting that slip occurs at different time for the three points, which is mainly due to the initial stress condition. Part of shear strength of the interface has been used to restrict outward slip of landfill under gravity. Therefore, peak shear strength of the interface is quickly reached at $x = -80$ m when the bedrock starts to move in positive direction, and slip starts first at this point (at about 0.4 s).

5. Discussion

Generally, numerical modeling is the most accurate method in seismic analysis of landfill and incorporation of displacement-softening nonlinear elastoplastic behavior of geosynthetic interface contributes to more accurate assessment of earthquake-induced slip displacement. Simultaneously, simplified dynamic analysis methods play important role in prompt seismic design and stability assessment of such geo-structures. Hence, the applicability of simplified methods in estimating permanent deformation in landfill is investigated.

5.1. Simplified dynamic analysis methods

As mentioned before, the original Newmark's rigid block model [9] and lumped mass model [10] have been widely used in seismic stability assessment of geo-structures, but they cannot consider the effect of geosynthetic interface. But when it comes to landfill, the dynamic properties of geosynthetic interface within liner system should not be neglected. Therefore, the displacement-softening property of the interface is taken into account in the improved Newmark's rigid block model and lumped mass model, and the softening rule is consistent with that shown in Fig. 2. The elastic process is not included to simplify the calculation. The process of calculation of relative slip displacement with rigid block and lumped mass models considering displacement-

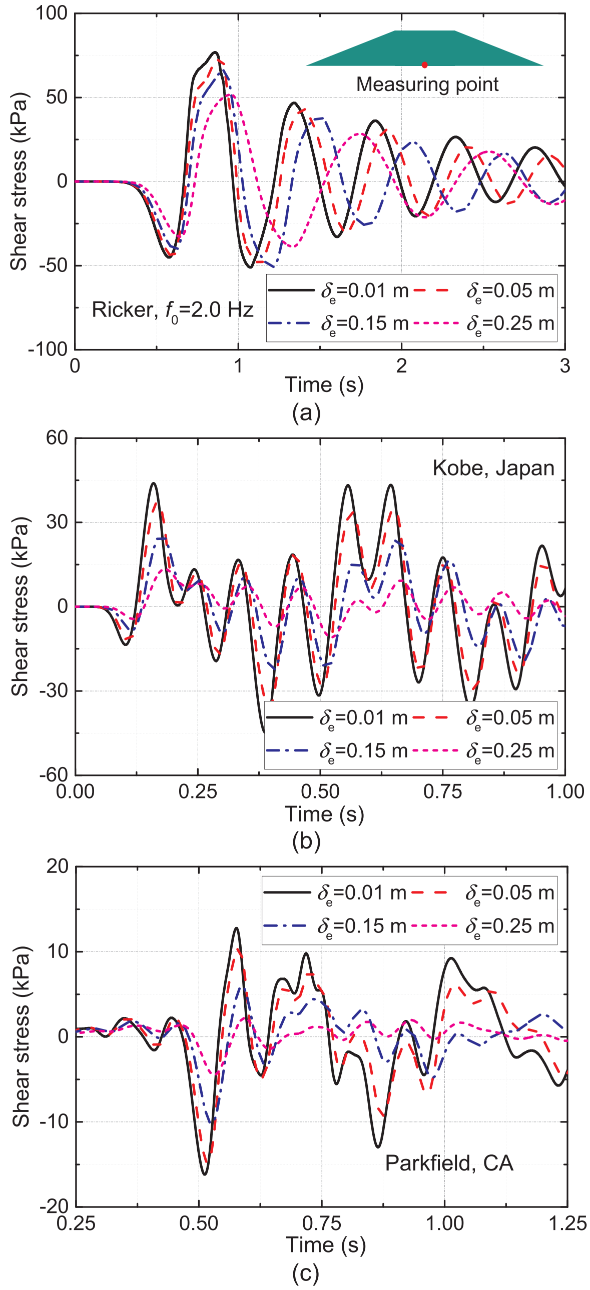

Fig. 11. Development of shear stress at middle of sliding interface with different δ_e of dynamic friction model.

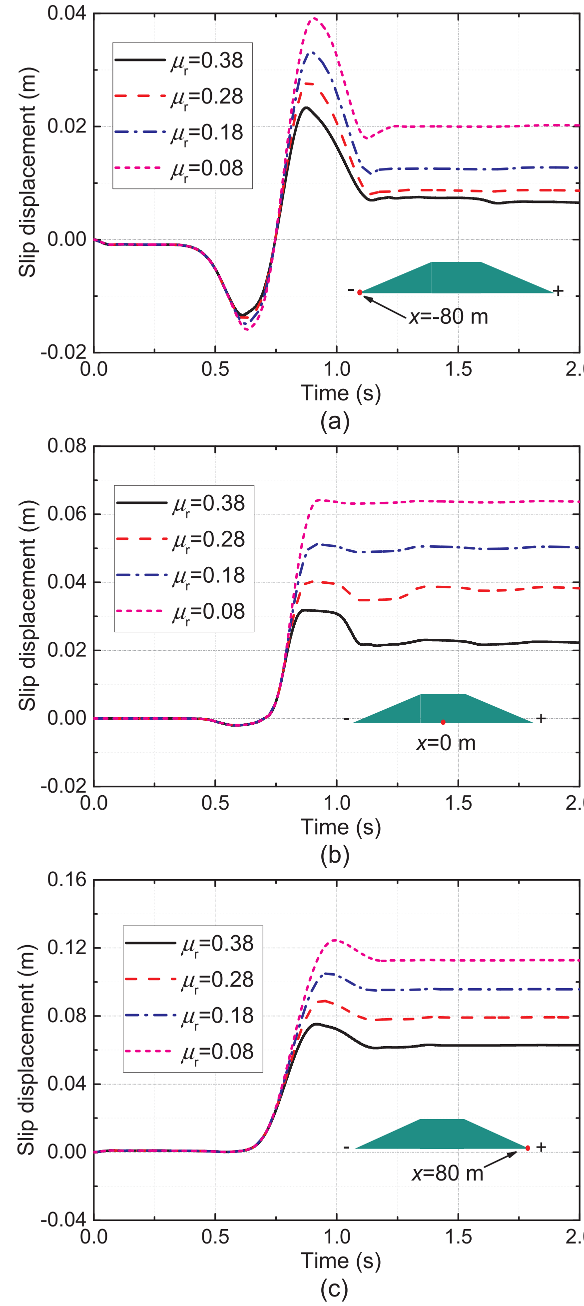

Fig. 12. Development of slip displacement along the liner interface at (a) $x = -80$ m, (b) $x = 0$ m and (c) $x = 80$ m with different μ_r.

softening property of the interface is shown in Fig. 13, where the yield strength of the interface decreases during the sliding periods. Twice integration of the relative acceleration time history enables 1D simplified estimation of earthquake-induced relative displacement of landfill.

In fact, analytical methods require a proper acceleration time history for a specific site. For simplicity in engineering practice, some empirical models were developed to estimate seismic sliding displacement of geo-structures without complex calculation. Hence, empirical methods are also considered in this study and 7 typical ones [35–39] are summarized in Table 3.

5.2. Comparison

In Fig. 14, variation of displacement at three typical points along the liner interface in numerical model, results of the improved rigid block model and lumped mass model with k_y/PGA are displayed. Distinctly, 2D finite element analysis is capable of calculating the distribution of slip displacement along the liner, and slippage of the three points in finite element model indicates that deformation of the landfill increases with the decline of relative dynamic shear strength of the liner interface (i.e., k_y/PGA).

Herein, it is inferred from Fig. 14 that rigid block and lumped mass model are appropriate to estimate slip displacement at middle of the liner interface, and estimation with lumped mass model is commonly conservative for k_y/PGA less than 0.5, especially for Kobe earthquake. Specifically, for landfill subjected to earthquake with low frequency like Ricker wavelet, simplified dynamic analysis is less effective in calculating slip displacement at middle of the liner, which should be taken seriously in engineering practice. Slippage at toes of landfill ($x = -80$ m, $x = 80$ m) is also important for the safety of geo-structure, but

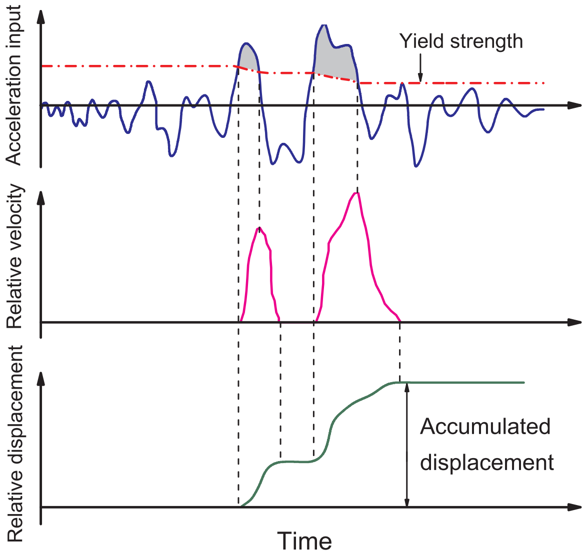

Fig. 13. Newmark sliding block method considering the displacement-softening property.

more correction and assessment are required to estimate earthquake-induced slip displacement in these areas with rigid block and lumped mass models.

The applicability of empirical models is demonstrated by Fig. 15 where results of numerical analysis and empirical models are compared. For slippage at middle of liner ($x = 0$), there displays significant variation. Most of empirical models underestimate slip displacement for Ricker wavelet, while overestimation is common for Parkfield earthquake, which reflects the frequency characteristics of earthquake are of vital importance for empirical estimation. Especially, only results of BT model agree relatively well with those of finite element analysis for all the three earthquake inputs. This proves the necessity of considering characteristics of response spectra of geo-structures in empirical models, such as T_S and S_a $(1.5T_S)$ considered by BT model. As for slippage at $x = 80$ m, no model can well predict the slip displacement for all the three earthquake inputs.

6. Conclusions

Seismic response and earthquake-induced displacement of landfill are complex dynamic soil-structure interaction problems where the geosynthetic interface plays important role. A displacement-softening nonlinear elastoplastic friction model is established to describe the dynamic shear behavior of GM-GCL interface within liner system. The effect of typical parameters on seismic stability of typical above ground landfill is analyzed through numerical modeling. The applicability of simplified 1D analytical models and empirical methods is also evaluated. Some major conclusions are drawn as follows.

(1) Consideration of nonlinear elastoplasticity and displacement-softening property of the geosynthetic interface is indispensable in seismic analysis of above ground landfill, and the assumption of constant friction coefficient generally induces significant errors. Remarkably, when it comes to landfills with different site conditions, more verification and analysis are required for the present model.
(2) Seismic response and permanent displacement of above ground landfill are highly influenced by properties of the geosynthetic interface. The liner layer should be designed with full attention to restrict the response and deformation caused by earthquake.
(3) Improved rigid block model and lumped mass model are appropriate to estimate seismic displacement at the middle of landfill base. But when considering landfill subjected to earthquakes with

Table 3
Summary of empirical equations for earthquake induced slip displacement.

Model	Abbreviation	Parameters	Equation	Standard deviation
Jibson [35]	J-1	k_y/PGA, I_a	$\log D = 0.561 \log I_a - 3.833 \log(k_y/PGA) - 1.474$	$\sigma_{\log D} = 0.616$
Jibson [35]	J-2	k_y/PGA, M	$\log D = -2.710 + \log[(1 - \frac{k_y}{PGA})^{2.335}(\frac{k_y}{PGA})^{-1.478}] + 0.424M$	$\sigma_{\log D} = 0.454$
Bray and Travasarou [36]	BT	k_y, M, T_s, $S_a(1.5T_s)$	$\ln D = -1.1 - 2.83 \ln(k_y) - 0.333(\ln(k_y))^2 + 0.566 \ln(k_y)\ln(S_a(1.5T_s)) + 3.04 \ln(S_a(1.5T_s)) - 0.244(\ln(S_a(1.5T_s)))^2 + 1.5T_s + 0.278(M - 7)$	$\sigma_{\ln D} = 0.67$
Saygili and Rathje [37]	SR-1	k_y, PGA, PGV	$\ln D = -1.56 - 4.58(\frac{k_y}{PGA}) - 20.84(\frac{k_y}{PGA})^2 + 44.75(\frac{k_y}{PGA})^3 - 30.50(\frac{k_y}{PGA})^4 - 0.64 \ln(PGA) + 1.55 \ln(PGV)$	$\sigma_{\ln D} = 0.41 + 0.52(\frac{k_y}{PGA})$
Saygili and Rathje [37]	SR-2	k_y, PGA, PGV, I_a	$\ln D = -0.74 - 4.93(\frac{k_y}{PGA}) - 19.91(\frac{k_y}{PGA})^2 + 43.75(\frac{k_y}{PGA})^3 - 30.12(\frac{k_y}{PGA})^4 - 1.30 \ln(PGA) + 1.04 \ln(PGV) + 0.67 \ln(I_a)$	$\sigma_{\ln D} = 0.20 + 0.79(\frac{k_y}{PGA})$
Rathje and Saygili [38]	RS	k_y, PGA, M	$\ln D = 4.89 - 4.85(\frac{k_y}{PGA}) - 19.64(\frac{k_y}{PGA})^2 + 42.49(\frac{k_y}{PGA})^3 - 29.06(\frac{k_y}{PGA})^4 + 0.72 \ln(PGA) + 0.89(M - 6)$	$\sigma_{\ln D} = 0.732 + 0.789(\frac{k_y}{PGA}) - 0.539(\frac{k_y}{PGA})^2$
Hsieh and Lee [39]	HL	k_y, I_a	$\log D = 0.847 \log I_a - 10.62k_y + 6.587k_y \log(I_a) + 1.84$	$\sigma_{\log D} = 0.295$

Note: k_y = yield coefficient ($= \mu_p$); T_s = initial fundamental period of the sliding mass (s); PGA = peak ground acceleration (g); PGV = peak ground velocity (cm/s), I_a = arias intensity of earthquake (m/s); M = magnitude of earthquake; S_a $(1.5T_s)$ = spectral acceleration of the input motion at a period of $1.5T_s$ (g).

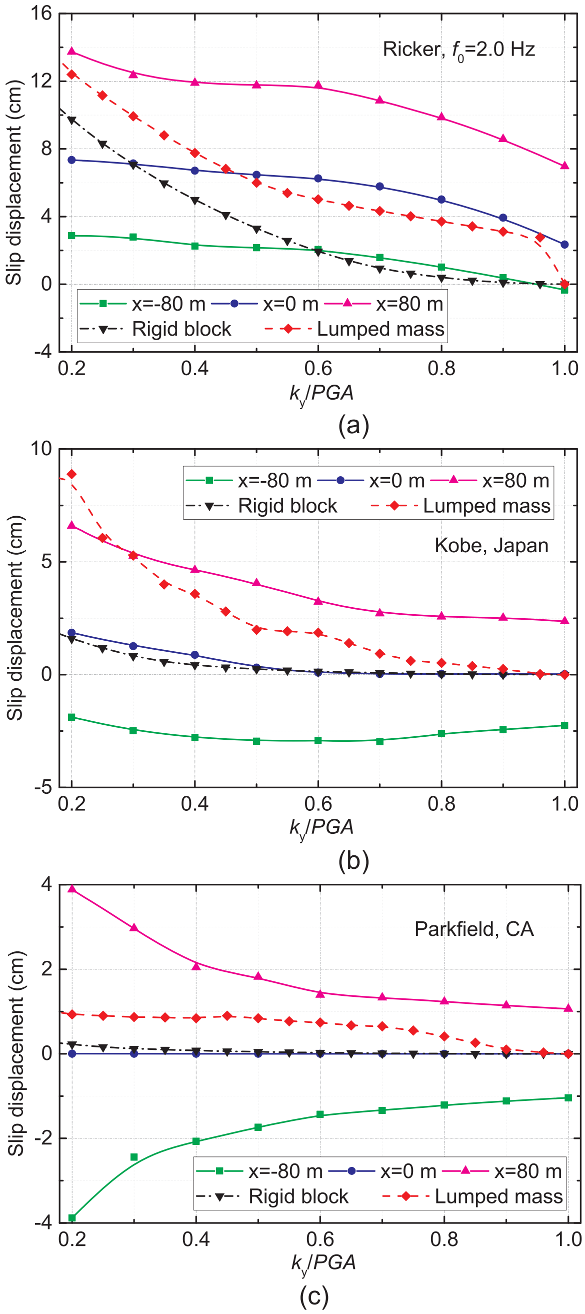

Fig. 14. Comparison of slip displacement for rigid block model, lumped mass model and finite element model for different earthquake records.

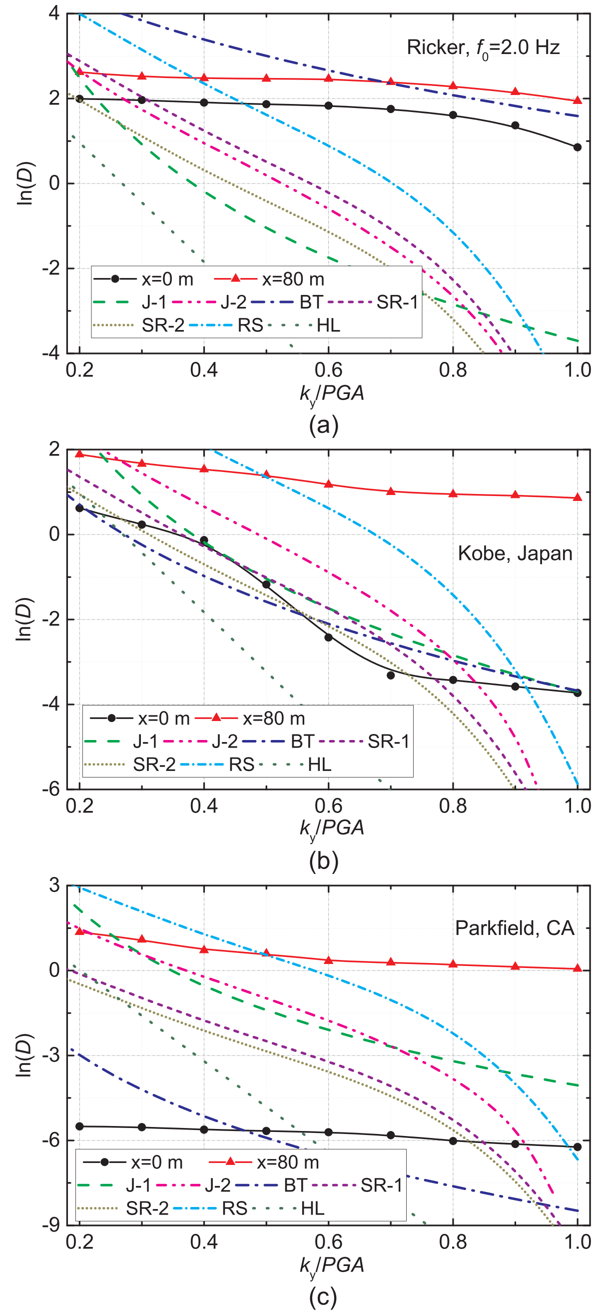

Fig. 15. Comparison of slip displacement between empirical equation and finite element analysis for different earthquake records.

low frequency or slippage at toes of landfill, further improvement of the analytical models is needed. As for empirical models, consideration of characteristics of response spectra of geo-structures is quite important for evaluating the slip displacement.

In conclusion, seismic stability assessment of MSW landfills with potential slippage along liner interface should be performed with careful consideration of the dynamic property of the geosynthetic interface. Furthermore, extreme caution is required when using simplified dynamic analysis methods for seismic design or assessment of landfill.

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