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

Shi-Jin Feng*, Ji-Yun Chang, Hong-Xin Chen

Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China

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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

* Corresponding author.
E-mail address: fsjgly@tongji.edu.cn (S.-J. Feng).

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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

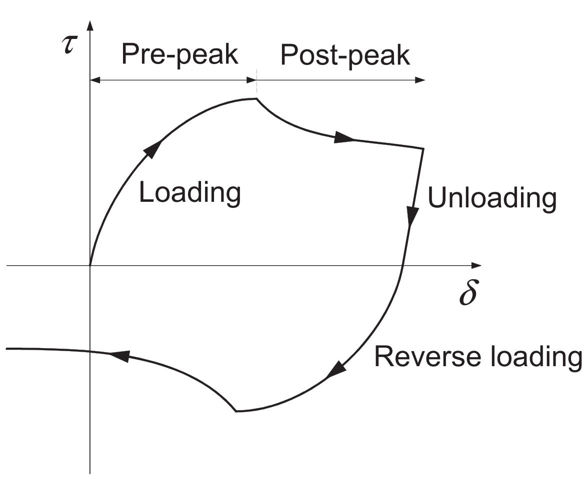

Fig. 1. Relationship between shear stress and relative shear displacement under cyclic load.

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

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