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Seismic response of multi-tiered reinforced soil retaining walls

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ABSTRACT

In this study, a validated Finite Element procedure was used to investigate the similarities and differences of seismic performances between single- and multi-tiered reinforced soil walls. Three-tiered walls at a total height of 9 m were analyzed together with vertical walls at the same height. It was found from the Finite Element analyses that the resonant frequency of reinforced soil walls might increase with an increase in the tier-offset. The multi-tiered configuration could considerably reduce the residual lateral facing displacement and the average reinforcement load, and the reinforcement load distribution with height was different from that in vertical walls. With the same reinforcement length and spacing, the multi-tiered walls resulted in smaller reinforcement connection loads with the facing blocks. The study filled the gap of seismic behavior of multi-tiered reinforced soil retaining walls and revealed a few unique dynamic properties of this type of earth structures.

1. Introduction

In recent years, a large number of high geosynthetic-reinforced soil (GRS) retaining walls (higher than 6 m) were built for critical applications in earthquake active areas [1]. Some of these walls may be constructed in multi-tiered configurations. In many available design guidelines for reinforced soil walls [2], only the design of two-tiered walls under static loading is addressed, while in the papers of Leshchinsky and Han [3], Yoo and Jung [4], and Yoo and Kim [5], the responses of multi-tiered walls under static loading were investigated, from which many mechanical aspects of multi-tiered reinforced soil walls were identified. However, at present very limited studies can be found on the seismic response of multi-tiered reinforced soil walls.

The seismic performance of single-tiered GRS retaining walls has been extensively investigated [6–14]. It has been found that generally GRS retaining walls exhibit good seismic performance; however, proper seismic design is still necessary [15], which implies that it is also important to understand the seismic response of multi-tiered reinforced soil walls.

Limit-equilibrium-based approaches have been proposed to analyze the stability of reinforced soil walls and slopes subjected to seismic loading [16,17]. They have also been combined with Newmark's sliding-block theory to predict the permanent displacement of reinforced soil structures [18,19]. The approaches have the advantage of simplicity and are able to locate the failure surface and to calculate the factor of safety provided that a proper coefficient of seismic force is used. However, the approaches cannot predict the distribution of reinforcement load with height as well as the reinforcement-facing connection loads in single- and multi-tiered walls.

Numerical methods have been used successfully to analyze the seismic performance of single-tiered reinforced soil walls [7,9,10,12,14,20–23]. Among the previous studies, both sophisticated and simple constitutive models for soils and geosynthetic reinforcements have been employed. Particularly, Mohr–Coulomb type perfectly plastic models combined with nonlinear elasticity have been used to satisfactorily reproduce the seismic response of reinforced soil structures [20,22]. In this study, a validated Finite Element procedure was used to carry out numerical simulation on the seismic performance of multi-tiered GRS walls. The procedure was based on the one developed by Ling et al. [12] but was modified by using a new approach to model soil–geogrid interfaces. The study focused on revealing the similarity and difference of single- and multi-tiered reinforced soils walls under seismic loading, and hopes to shed light on understanding the seismic behavior of this type of earth structures.

2. Finite element procedure

Plane strain conditions were assumed in this study and the Finite Element simulations were carried out using a modified

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Nomenclature

L	reinforcement length
S_v	reinforcement spacing
g	gravity constant
T_{max}	maximum reinforcement load
Δ_{max}	maximum lateral facing displacement
δ	friction angle of soil–structure interface
s	tier-offset
p'	effective mean stress of soil
q	deviator stress
ε_1	axial strain
ε_v	volumetric strain
σ_1	major principal stress
σ_3	minor principal stress
ϕ_0	reference friction angle of soil at $p'=100$ kPa
$\Delta\phi$	change of friction angle with pressure
M_g	critical state stress ratio in triaxial compression
M_f	model parameter for loading direction vector of sand
G_0	shear modulus parameter
K_0	bulk modulus parameter
α	stress-dilatancy parameter
H_0, k_s, β_{10}, β_0	generalized plasticity model parameters defining loading plastic modulus
H_{u0} and r_u	generalized plasticity model parameters defining unloading plastic modulus
r_d	generalized plasticity model parameter controlling cyclic hardening of soil
r	generalized plasticity model parameter controlling the influence of stress history
J_e	elastic stiffness of geogrid
A and B	intercepts of the bounding lines with the load axis in the tension and compression sides, respectively
$\bar{J}^0_{P+}$ and $\bar{J}^0_{P-}$	slopes of the bounding lines on the tension and compression sides, respectively
h^L_0, h^L_k, h^U_0, and h^U_k	bounding surface model parameters defining the stiffness hardening

version of DIANA-Swandyne II [24,25]. Major components of the procedure are the same as those reported in Ling et al. [12], but the soil–geogrid interface is modeled using a new approach. The original procedure in Ling et al. [12] was validated against a full-scale test for construction behavior and a series of centrifuge shaking table tests for dynamic performance. It has been used to carry out different parametric studies on the dynamic performance of geogrid-reinforced soil retaining walls [14,23]. In the Finite Element procedure, the backfill soil was simulated using a generalized plasticity model for sand [26]; the geogrid reinforcements were modeled using a bounding surface model for geosynthetics [27]; the interfaces between facing blocks and between soil and facing blocks were simulated using thin-layer elements that could close, separate, and slip [24]. The material damping was mostly captured by the hysteresis response of the constitutive models, but small viscous damping coefficient (5%) was also included for the backfill to compensate for the negligible hysteresis of the generalized plasticity model when the soil strain was very small [28]. Due to space limitation, details of the original Finite Element procedure, which can be found in the papers of Ling et al. [12,27] and Ling and Liu [26], are not discussed herein, but the brief introduction of the constitutive models for soil and geosynthetics can be found in Appendices A and B.

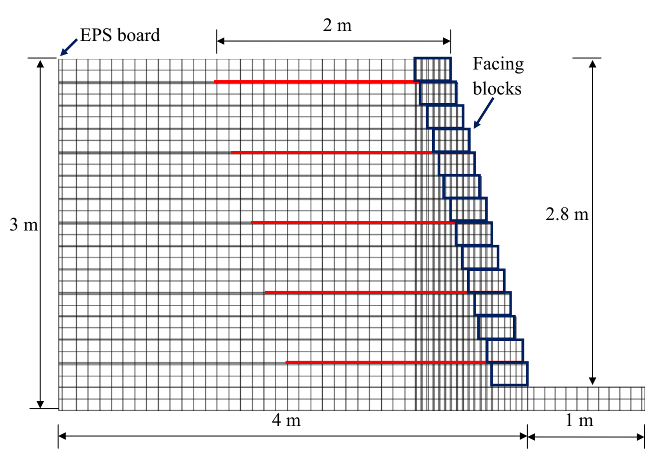

Fig. 1. Finite Element mesh of Wall I of the shaking table tests (Ling et al. [13]).

In the original Finite Element procedure, the geogrid and backfill soil were assumed to be perfectly bonded, considering the large aperture size of many geogrids. However, recent experimental studies on the interaction between granular soil and geogrid showed that the frictional resistance between soil and geogrid was smaller than that of soil [29,30], which could affect the response of reinforced soil walls subjected to strong seismic loading. In the revised Finite Element procedure, ordinary rectangle solid elements were used to model the soil–geogrid interfaces but their thickness was at most 1/10 of their length [31–33]. The generalized plasticity model for sand was used to describe the interface response with strength parameters different from those of the adjacent soil.

In previous studies, besides the no-slip assumption in Ling et al. [12], soil–geogrid interfaces have also been modeled by means of frictional contact [10,11,20], zero-thickness interface elements [34], thin-layer elements assuming Mohr–Coulomb failure criterion [9], and thin-layer elements using special interface models [35]. Ng et al. [36] showed that with a proper constitutive model, thin-layer ordinary rectangle elements could very well describe the cyclic shear behavior of soil–structure interfaces, although special techniques should be adopted in the constitutive model to duplicate the separation and re-closure response. For soil–geogrid interfaces in reinforced soil walls, the shear and slip deformations dominate the response, hence this approach is considered appropriate in this study. By using the generalized plasticity model for sand [26] with the thin-layer solid elements, the nonlinearity, shear strength, normal deformation, and cyclic hysteresis of soil–geogrid interfaces could be properly reproduced.

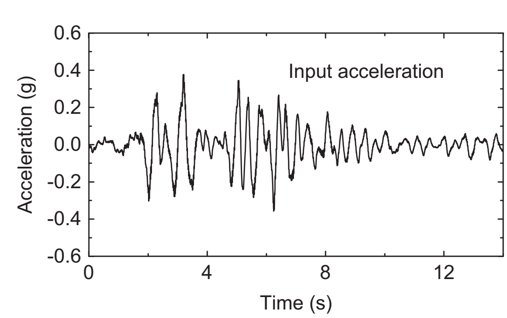

Fig. 2. Input seismic motion at peak acceleration of 0.4 g.