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Finite element analyses of two-tier geosynthetic-reinforced soil walls: Comparison involving centrifuge tests and limit equilibrium results

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ABSTRACT

This study presents the procedure and results of the finite element (FE) analyses of a series of centrifuge tests on geosynthetic-reinforced soil (GRS) two-tier wall models with various offset distances. The objectives of this study were to evaluate the applicability of FE for analyzing GRS two-tier walls with various offset distances and to investigate the performance and behavior of GRS two-tier walls in various stress states. The FE simulations were first verified according to the centrifuge test results by comparing the locations of failure surfaces. The FE results were then used to investigate the effective overburden pressure, mobilization and distribution of reinforcement tensile loads, and horizontal deformation at the wall faces. The interaction between two tiers was investigated based on the FE results, which were also used to examine the modeling assumption of reinforcement tensile loads in limit equilibrium (LE) analysis and to evaluate the design methods in current design guidelines. This study demonstrated favorable agreement between FE and the centrifuge model in locating the failure surface. The FE results indicated that as the offset distance increased, the reinforcement tensile load and wall deformation decreased in both the upper and lower tiers, suggesting the attenuation of interaction between the two tiers. The maximum tensile loads of all reinforcement layers at the wall failure predicted using FE analysis and LE method assuming uniform distribution of reinforced tensile loads were comparable. Compared with the FE results, the Federal Highway Administration (FHWA) design guidelines are conservative in determining the effect of overburden pressure, required tensile strength, location of maximum tension line (for designing the reinforcement length), and the critical offset distance. Furthermore, the FHWA design guidelines do not account for the influence of the lower tier on the upper tier that was observed in this study.

1. Introduction

Geosynthetic-reinforced soil (GRS) walls in a tiered configuration are acceptable alternatives to conventional retaining wall systems because of several benefits such as cost, stability and construction constraints, and aesthetics. In addition, drainage swales or ditches can be installed along the toe of each tier to minimize the surficial flow induced erosion and water infiltration induced instability. The current practice in Taiwan is to apply multitier GRS walls with wrap-around facing, each tier typically being 5 m high, to restore slope and roadway failures induced by heavy rainfall during typhoon seasons. A tiered wall is a transitional structure between a single wall and slope (Fig. 1) that can reduce construction costs and increase system stability compared with a single wall. Because of its configuration, the tiers interact and mutually affect each other. The upper and lower tiers interact through the equivalent surcharge from the upper tier acting on the lower tier, and the vertical and lateral deformation of the lower tier influencing the behavior of the upper tier. Consequently, this interaction can cause additional wall deformation and reinforcement loads in both the upper and lower tiers, compared with a wall of the same height as each tier.

Current design methods [10,5,25] for analyzing GRS multitier walls are based on the lateral earth pressure method, an extension of the design method for analyzing single-tier reinforced walls. The design approaches in these guidelines are considered empirical and are geometrically derived based on the relative distance or offset distance, D, between upper and lower tiers. Some studies

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Nomenclature

Basic SI units are given in parentheses

c	cohesion (kPa)
$c_{adjusted}$	adjusted cohesion (kPa)
c_{input}	input cohesion (kPa)
D	offset distance (m)
D_{cr}	critical offset distance (m)
D_{Tmax}	distribution function (dimensionless)
EA	reinforcement stiffness (kN/m)
E_{50}^{ref}	secant modulus (kPa)
E_{oed}^{ref}	tangent modulus for primary oedometer loading (kPa)
E_{ur}^{ref}	unloading–reloading modulus (kPa)
FS	factor of safety (dimensionless)
H	height of two-tiered wall (m)
H_1	height of upper tier (m)
H_2	height of lower tier (m)
K_a	active earth pressure coefficient (dimensionless)
k_r/K_a	normalized lateral earth pressure coefficient (dimensionless)
L_o	reinforcement overlap length (m)
L_1	reinforcement length of upper tier (m)
L_2	reinforcement length of lower tier (m)
m	modulus exponent (dimensionless)
$\max(T_{max})$	maximum reinforcement tensile load (kN/m)
N_g	*g*-level of centrifuge model (dimensionless)
N_f	failure *g*-level of centrifuge model (dimensionless)
N_p	input reinforcement tensile strength (kN/m)
q	equivalent uniform load from the upper tier (kN/m^2)
R_f	failure ratio (dimensionless)
S_v	vertical spacing between layers of reinforcement (m)
T_{max}	maximum reinforcement load in each layer (kN/m)
T_{ult}	confined ultimate tensile strength (kN/m)
x	distance from the wall face (m)
y/H	normalized elevation (dimensionless)
z	depth below the surcharge load (m)
z_i	depth to the *i*th layer of reinforcement (m)
γ	unit weight of backfill soil (kN/m^3)
δ_H	horizontal deformation of wall face (m)
$\delta_{H,max}$	maximum horizontal deformation of wall face (m)
θ	failure plane angle (°)
σ_f	additional vertical stress at the wall face on the *i*th layer of reinforcement caused by upper tier (kN/m^2)
σ_v	effective overburden pressures (kN/m^2)
σ_z	overburden pressure at depth z (kN/m^2)
ν_{ur}	Poisson's ratio for unloading–reloading (dimensionless)
ϕ	peak friction angle (°)
$\phi_{adjusted}$	adjusted peak friction angle (°)
ϕ_{input}	input peak friction angle (°)
ϕ_{ps}	plane strain peak friction angle (°)
ϕ_{tx}	triaxial compression test friction angle (°)
ψ	angle of dilatancy (°)
$\Delta\sigma_v$	additional vertical stress caused by upper tier (kN/m^2)
$\Delta\sigma_{v,i}$	additional vertical stresses from the upper tier acting on the *i*th layer of reinforcement at the maximum tension line (kN/m^2)
$\Delta\sigma_{v,j}$	additional vertical stresses from the upper tier acting on the *j*th layer of reinforcement at the maximum tension line (kN/m^2)
ΣM_{sf}	total multiplier defined in PLAXIS (dimensionless)
ΣT_{max}	summation of maximum reinforcement force for all layers (kN/m)

have questioned using this empirical approach [17]. Moreover, the compound wall designs suggested in the design guidelines are complex and require numerous calculation procedures to determine the maximum tension line and additional vertical stress for internal stability analyses. These guidelines do not fully address the interactive mechanism between two tiers and are based only on the additional vertical stresses from the overlying wall tiers acting on the lower tiers. They do not account for the influence of the lower tier on the upper tier.

An alternative to the lateral earth approach is to use the limit equilibrium (LE) method, which is useful for predicting the failure surface location and for assessing the system stability regarding the factor of safety (FS). However, the limitations of LE in analyzing the reinforced structures require assuming the reinforcement tensile load and its inability to predict deformation [18,9]. Although the LE method is applicable to analyzing multitier walls

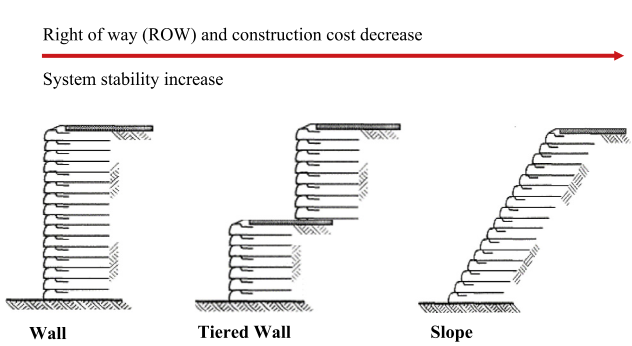

Fig. 1. GRS structures with various configurations.

by comparing its results with those of finite element (FE) analysis [18] and centrifuge tests [24], the modeling assumptions of reinforcement tensile loads require further verification by using the results of measuring physical walls or those of optimally calibrated FE analyses. The FE method has been widely used for modeling reinforced soil structures [35,12,13,15,19,22]. The FE method offers comprehensive information concerning stress, strain, force, and displacement at any location of interest (e.g., at the nodal and Gaussian points). However, the FE method requires comprehensive material characterization and model validation using the measured data from physical walls to produce convincing results. Thus, the FE method combined with experimental test results should be used to investigate the behavior and performance of multitier GRS walls.

Behavior and performance studies of multitier walls are scant, among which multitier walls have been investigated by case studies and field monitoring [20,33,32], full-scale wall tests [37,38], reduced-scale and centrifuge wall tests [36,14], LE analysis [24,17,26,34], and FE analysis [21,36,33,39,38]. Mohamed et al. [24] conducted a thorough review of current design methods and previous studies on multitier walls. Although these studies have addressed crucial issues, most of them have focused on multitier walls with one or two offset distances and lack a comprehensive and consistent comparison of multitier walls with various offset distances. Few studies have quantitatively elaborated on the interactive mechanism discussed at the beginning of this section.

This study conducted a series of FE analyses of twelve GRS two-tier walls with various offset distances and calibrated each FE model according to centrifuge wall models. The objectives of this study were fourfold: (1) to evaluate the FE applicability for analyzing GRS two-tier walls with various offset distances; (2) to