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Research Paper

Required strength of geosynthetic in reinforced soil structures supporting spread footings in three dimensions

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ABSTRACT

Little insight exists into the stability of reinforced slopes supporting spread footings. Existing research is largely focused on idealized, plane strain analyses that do not account for three-dimensional conditions. These conditions are significant because the geometries of both reinforced slopes and footings are three-dimensional in nature. In this study, the stability of reinforced slopes supporting spread footings is analyzed in three dimensions using a limit analysis approach and presented in a series of design charts. To better understand the impact of three-dimensional conditions, a parametric study is conducted to evaluate effects of various design parameters on required reinforcement strength.

1. Introduction

Reinforced earth structures are widely employed as a means of footing support because the application of adequate tensile reinforcement within a soil mass can enable it to retain itself and the added surcharge. The conventional design of reinforced slopes supporting spread footings is primarily dictated by two criteria: (1) slope stability and (2) bearing capacity of reinforced slopes, both of which correspond to different failure kinematics. Most literature that involves reinforced slopes supporting spread footings has focused on the stability at the slope's crest—namely, the bearing capacity of spread footings. Turker et al. [36] conducted a series of experimental bearing capacity tests to investigate the behavior of eccentrically loaded strip footings near a geotextile-reinforced sand slope, finding that ultimate loads decreased with increasing eccentricity owing to a combination of eccentricity and slope. Choudhary et al. [9] analyzed the bearing capacity behavior of strip footing on the reinforced flyash slope and established critical values of geogrid parameters for maximum reinforcing effects. Leshchinsky [20] performed a discontinuity layout optimization (DLO) to demonstrate the relationships among soil strength properties, slope height to footing width ratio, slope angle, and critical collapse mechanism considering the bearing capacity for strip footings placed adjacent to slopes of $c'-\varphi'$ soils. However, little insight exists into the global stability of reinforced slopes supporting discrete spread footings, which is primarily limited to experimental work [6] and analytical studies under plane strain conditions [7]. Most literature observing the behavior of footings atop reinforced structures is limited to walls, consisting of extensive experimental studies [37,2,35,34] and numerical studies [31,19,25,33,17,1,15,30,3]. However, reinforced steep slopes, characterized by a slope of less than 70° [4], are important in the context of serving as integral bridge abutments, which support a bridge deck placed directly atop the reinforced soil mass by means of a concrete spread footing. In addition, previous analyses of reinforced slopes supporting spread footings are based on two-dimensional idealization (i.e., plane strain conditions) that do not account for three-dimensional effects.

Three-dimensional effects are inherent in earth structures, and the stability of spread footings as both slopes (or "walls") and spread footings demonstrate added boundary effects when a slip surface is finite in size. However, it is commonly acknowledged that two-dimensional solutions are conservative when analyzing the stability of straight, homogeneous, reinforced slopes of finite width if end effects are ignored [23,5,22,16,28,24,11,12,10,39]. Few studies have evaluated three-dimensional effects of reinforced earth structures supporting footings. Michalowski [27] analyzed three-dimensional locally loaded slopes based on upper-bound limit analysis, determining the factors of the safety and limit load

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Nomenclature

Notation

$k_t/\gamma H$	required strength of reinforcement (dimensionless)
B	width of reinforced slope
b	width of plane insert
D	energy dissipation rate
H	slope height
l_f	length of footing
n	number of reinforcement layers
Q	weight of footing over unit width
q	weight factor of footing (dimensionless)
S_b	setback of footing
S_v	vertical spacing between reinforcement layers
T_t	minimum required tensile strength per unit width of a single reinforcement layer
W_f	work done rate by footing
W_m	work done rate by soil weight
w_f	width of footing
β	slope angle
γ	soil unit weight
φ	internal angle of friction
ω	angular velocity of rotation

of slopes for drained frictional-cohesive soils assuming a collapse mechanism consisting of rigid-motion prismatic blocks separated by planar velocity discontinuity surfaces. Kalatehjari et al. [18] conducted a small-scale test of a three-dimensional slope under surcharge in the laboratory. The shape of the failure surface was analyzed and compared with the calculated results.

In this study, the required strength of reinforcement for reinforced slopes supporting spread footings are analyzed under three-dimensional conditions using limit analysis (LA). The two-dimensional results are also obtained in this study as a comparative benchmark solution to the three-dimensional results. A parametric analysis studied the effects of the (rigid) footing setback, width, and length as well as soil strength and footing boundary conditions. Selected design charts for reinforced slopes supporting spread footings under both two-dimensional and three-dimensional conditions are presented for convenient evaluation of the stability of reinforced slopes.

2. Limit analysis of three-dimensional reinforced slope stability

Limit analysis has served as an approach for evaluating limit state conditions for a variety of structures within a wide range of complexity. Compared with limit equilibrium (LE) analysis, a well-accepted means in practice of evaluating slope stability and reinforced soil stability for many decades, LA is rigorous in the context of mechanics and does not require assumptions about the formulation of static limit equilibrium (force or moment). Because LA follows rules in mechanics (plasticity) that are more stringent than LE, the LE solution does not necessarily satisfy the rigors of LA analysis. That is, LE mechanisms are not necessarily kinematically admissible [26]. This is not an issue for many slope stability problems (e.g., straightforward geometries, homogenous soil); however, for complex slopes, the identification of a generalized, critical failure mechanism is challenging [21].

The use of LA first requires the establishment of a kinematically admissible collapse mechanism that satisfies boundary conditions under the assumption that the deformation of the soil is perfectly plastic, governed by the normality rule. LA employs a duality of theorems to provide a solution: lower-bound or upper-bound plasticity. In this study, the three-dimensional, kinematically admissible rotational failure mechanism for slopes proposed by Michalowski and Drescher [29] is employed to analyze the reinforcement strength required to maintain the stability of slopes supporting spread footings (Fig. 1). This mechanism was employed because the rotational failure mechanism has been employed in various analytical and numerical models in both two and three dimensions [8,13,14,32] and was also observed in several experimental studies [38,18]. For these reasons, the Michalowski and Drescher [29] mechanism was inferred to be reasonable for this study. More geometric details of the applied mechanism can be found in Michalowski and Drescher [29]. The failure surface is assumed to not penetrate the foundation material (i.e., the foundation soil is competent) and be horizontal; uniaxial reinforcement layers are assumed to contribute the required resistance (horizontal and distributed uniformly), rendering a stable slope. The effects of interface friction, structural effects of facing elements, and effects of vegetation are ignored.

3. Formulations and results

3.1. Verification

For verification, scenarios containing footings of $l_f/H = 0.2$, $\varphi = 34°$, $q = Q/\gamma H = 1.5$, and $S_b/H = 0$, 0.1, 0.25 and 0.5 were analyzed using numerical upper-bound limit analysis applied using finite elements (Optum G2, commercially available software suite). In these scenarios, $H = 5$ m, $\gamma = 20$ kN/m^3, $n = 10$ and the uniform vertical spacing between the reinforcement layers $S_v = 0.5$ m. The numerical results were compared with the analytical results obtained from the aforementioned LA approach under two-dimensional conditions.

The results of T_t (the minimum required tensile strength per unit width of a single reinforcement layer) considered using numerical upper-bound LA demonstrated good agreement with the analytical results shown in Fig. 2. When $S_b/H = 0$, 0.1, 0.25 and 0.5, the maximum differences between the analytical and numerical results are 0.65 kN/m, 0.70 kN/m, 0.90 kN/m and 0.80 kN/m, respectively. The model was created using a reinforced slope of 5 m in height and 10 m in crest length. Because pullout is not a concern in these scenarios, the reinforcement layers are set to be from the face to the back of the slope. A thin (0.2 m) region of elements with minor cohesion (10 kPa) and the same φ as the backfill was applied to the face to prevent numerical issues stemming from shallow failures at the face, which was not considered relevant for comparison (Fig. 3). In the model, 1000 initial triangular elements were applied using mesh adaptivity (3 iterations, 1000 elements) to refine the zone of plasticity (Fig. 4a) after convergence was reached for a given mesh. Fig. 4(b) and (c) illustrates numerical and analytical methods that give similar failure surfaces in addition to similar required geosynthetic strengths.

The two-dimensional results demonstrate good agreement and confidence in the analyses, thus enabling further study under three-dimensional conditions applying similar concepts [10].

3.2. Required tensile strength of reinforcement

Proper design of reinforced soil necessitates that the minimum tensile strength of reinforcements must be greater than the