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Research Paper

Numerical evaluation of reinforced slopes with various backfill-reinforcement-drainage systems subject to rainfall infiltration

Kuo-Hsin Yang[a,*], Joseph Ng'ang'a Thuo[b], Vo Duyen Anh Huynh[c], Thanh Son Nguyen[d], Fernando Henrique Martins Portelinha[e]

[a] *Department of Civil Engineering, National Taiwan University (NTU), 1, Sec. 4, Roosevelt Rd., Taipei 106, Taiwan*
[b] *Department of Civil Engineering, Dedan Kimathi University of Technology, Kenya*
[c] *Department of Civil Engineering, The University of Da Nang, Viet Nam*
[d] *Department of Civil and Construction Engineering, National Taiwan University of Science and Technology (Taiwan Tech), Taipei, Taiwan*
[e] *Department of Civil Engineering, Federal University of Sao Carlos, Sao Carlos, Brazil*

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ABSTRACT

This paper presents a numerical study investigating the hydraulic response and stability of geosynthetic-reinforced soil slopes subject to rainfall. A series of numerical simulations of unsaturated slopes with various backfill–reinforcement–drainage systems subject to rainfall infiltration was performed by comprehensively considering the combined effect of backfill (i.e., sand, silt, and silty clay), reinforcement type (i.e., geogrid or nonwoven geotextile), and rainfall intensity (350 and 500 mm/day). The backfills were modeled using three soil–water characteristic curves (SWCCs) representing the general suction range associated with sand, silt, and clay. The influence of sand cushions in improving the stability of reinforced clay slopes was also assessed. The numerical results reveal that the loss of matric suction and development of a capillary barrier effect within clay backfills could have adverse impacts on both the global and local stabilities of the reinforced clay slopes. The contribution of matric suction in enhancing slope stability was initially high for reinforced clay slopes; however, the global stability of the reinforced clay slope substantially decreased due to the loss of matric suction as the rainfall infiltration proceeded. The local instability of the geotextile-reinforced clay slope occurred due to the capillary barrier effect at the geotextile–clay interface. The reinforced marginal soil slopes cannot effectively drain the infiltrating water under torrential rainfall. Free drainage conditions may not be assumed for these slopes if the drainage is not properly considered. Both the global and local factors of safety (FS) of the reinforced sand slope were minimally influenced by the loss of matric suction induced by rainfall infiltration. The required reinforcement tensile strengths for the reinforced silt and clay slopes to maintain $FS = 1.3$ were, respectively, approximately 3 and 4 times larger than that for reinforced sand slopes. Numerical results also indicated that the inclusion of sand cushions, which provide both strength and drainage functions, can effectively enhance the slope stability. An optimal sand cushion thickness of 15 cm (replacing 20% of marginal backfill with sand) was determined in this study.

1. Introduction

Geosynthetic-reinforced soil (GRS) structures are typically composed of four components: soil, reinforcement, facing, and drainage. Each component has various material options that can have different influences on the performance of the GRS structure. Considering backfill types as an example, design guidelines [1,5,12,39] recommend the use of coarse-grained soils as a backfill material within the reinforced zone. However, fine-grained backfill soils (referred to as marginal fills), which are often locally available and provide both economic and sustainability benefits, have gained increasing popularity as an alternative to high-quality granular fills [4,42,45,51,65]. The contrasting merits and demerits of using marginal fills have been reported and discussed.

Positive aspects of using locally available marginal fills are reducing transport costs and minimizing environmental impacts associated with the disposal of excavated soils. In addition, because the backfills are usually compacted within ± 2% of optimum moisture content, the

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* Corresponding author.
E-mail addresses: khyang@ntu.edu.tw (K.-H. Yang), joseph.thuo@dkut.ac.ke (J.N. Thuo), hvdanh@dct.udn.vn (V.D.A. Huynh), sonnt@nuce.edu.vn (T.S. Nguyen), fportelinha@ufscar.br (F.H.M. Portelinha).

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matric suction generated within unsaturated fills could exert favorable effects on reinforced soil structures [30,53,54]. Matric suction plays a crucial role in the interparticle or effective stress state of unsaturated soils [14,19,33,48,54,63]. The presence of suction can increase soil effective stress and thus enhance the performance and stability of reinforced soil structures by increasing soil stiffness and shear strength [13,19,27], increasing soil–reinforcement interface strength [4,41,65], and reducing mobilized reinforcement load [25,46,54].

The key criticism of the use of marginal fills concerns the uncertainty and variation of porewater pressure (PWP) within reinforced zones subjected to various moisture conditions. Some fine-grained soils with a low drainage capacity have been observed to compromise the performance of reinforced soil structures upon rainfall infiltration owing to the development of a positive PWP [8,26,28,32,35,56,61,65]. Despite this fact, studies have demonstrated that the problem of PWP accumulation within marginal fills can be appropriately alleviated by installing sufficient and efficient drainage [10,38,41,44].

In addition to backfill types, the influence of reinforcement types (i.e., geogrid or geotextile) on the performance and stability of reinforced structures has been discussed in the literature. In addition to reinforcement function, nonwoven geotextiles are expected to provide drainage functions to facilitate PWP dissipation within saturated backfills [15,18,41,43,44]. However, studies have reported that, under unsaturated soil conditions, nonwoven geotextiles can retard water flow due to the capillary barrier effect [15,25,36,42,64]. Because of the capillary barrier effect, a measurable amount of water does not flow from the backfill soil to the underlying nonwoven geotextile drain until a critical suction threshold is achieved; hence, nonwoven geotextile may act as a water barrier instead of a drainage material and lead to an increase in PWP in the soils immediately above it. Bouazza et al. [7] and Iryo and Rowe [23] suggested that considerable care is required when selecting nonwoven geotextiles for use within soil structures in order to avoid increased PWP developing.

The preceding discussion explains the dilemma of selecting backfill and reinforcement for GRS structures and describes the complex interaction and mutual influence between backfill–reinforcement–drainage systems in GRS structures. Few studies on the overall evaluation of such systems have been published. Accordingly, this study addressed this concern by performing a series of numerical analyses to investigate the hydraulic response and stability of reinforced slopes subject to rainfall by comprehensively considering the combined effect of backfill (i.e., sand, silt, and silty clay) and reinforcement types (i.e., geogrid or nonwoven geotextile) and rainfall intensity (350 and 500 mm/day). The study findings can facilitate developing improved methodologies for the analysis and design of reinforced soil structures constructed using marginal soils and can provide suitable guidance for selecting an appropriate backfill–reinforcement–drainage system for GRS structures. The specific objectives of this study were as follows: 1. to assess the rainfall-induced suction variation in reinforced slopes with various backfill–reinforcement–drainage systems; 2. to examine the influence of suction variation on both the global and local stability of reinforced slope systems; and 3. to evaluate the required reinforcement tensile strength to achieve a consistent stability level for the reinforced slopes with various backfills under specified rainfall conditions.

This study also assessed the effectiveness of sand cushions, granular soil-layer sandwiching reinforcement and drain layers, in improving the drainage and stability of reinforced marginal soil slopes. Fig. 1 illustrates the application of granular soils as facing drains and sand cushions in a GRS structure in current practice. Studies have demonstrated that the application of sand cushions can accelerate PWP dissipation under saturated conditions [43,44], reduce the capillary barrier effect under unsaturated conditions [51], mitigate the surficial intrusion and long-term clogging in nonwoven geotextiles by fine-grained soils [9,31], enhance pullout resistance [3], and improve the strength and deformation characteristics of reinforced clay by improving the soil–reinforcement interface shear strength [2,52,60]. In this study, the influence of the use of sand cushions in improving the stability of reinforced slopes was assessed, and the contribution of sand cushions resulting from their strength and drainage functions was quantified. The optimal thickness of the sand cushions was also determined.

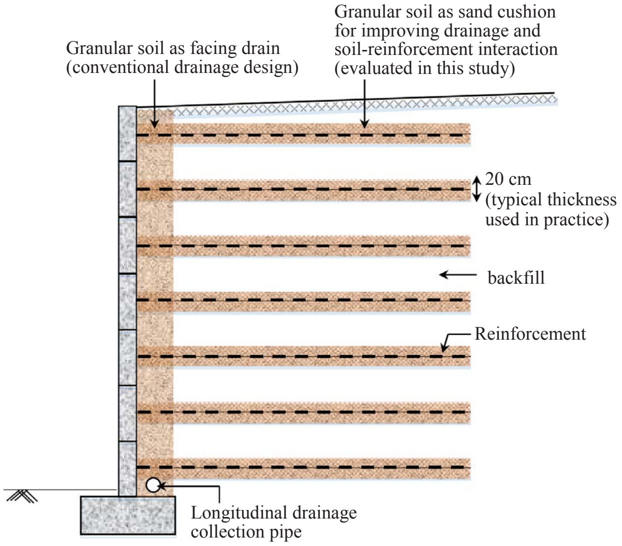

Fig. 1. Illustration of application of granular soils as facing drain and sand cushion in a geosynthetic-reinforced soil structure in current practice.

2. Numerical analysis of reinforced slope

2.1. Numerical model and verification

Numerical analyses were performed to investigate the hydraulic response and stability of reinforced slopes with various soil–reinforcement–drainage systems subject to rainfall. Two-dimensional embankment models (Fig. 2) were developed using SEEP/W and SLOPE/W software [16,17]. The numerical models were established on the basis of the full-scale embankment model tests conducted by the Public Works Research Institute (PWRI), Japan, reported by [25]. The embankments were 3 m high and 6 m long, with a slope of 0.7H:1V (=55°). Four layers of geosynthetic reinforcements were placed with a vertical spacing of 0.75 m. A flow flux was specified as the boundary condition on the top and side slope surfaces of the embankment to model rainfall infiltration.

The validation of the numerical model was reported by the authors in a companion paper [51]. A reasonably good agreement was achieved between the measured and numerical results of PWP distribution within the embankment. In addition, the authors demonstrated that numerical analysis is capable of capturing the capillary barrier effect at the soil–geotextile interface. Notably, this companion paper [51] primarily investigated the influence of the capillary barrier effect on nonwoven geotextile-reinforced soil slopes, whereas the present study comprehensively evaluated the complex interaction and mutual influence among various backfill–reinforcement–drainage systems.

In this study, a series of numerical reinforced slope models with various backfill–reinforcement–drainage systems was established (Fig. 2). Numerical investigation was conducted by considering various types of backfills (sand, silt, and silty clay) and geosynthetic reinforcements (geogrid and nonwoven geotextile). Sand represents a good-quality backfill, and silt and silty clay represent marginal backfills with different fine contents. For modeling geosynthetics, the geogrid provides only the reinforcement function, whereas nonwoven geotextile is equipped with both reinforcement and drainage functions. The 3-mm thick nonwoven geotextile was modeled using six-node triangular elements with prescribed hydraulic properties across the thickness of the