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Research Paper

Reliability and redundancy of the internal stability of reinforced soil walls

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ABSTRACT

In the present study, a new methodology for reliability assessment of the internal stability of reinforced soil walls, taking into account the highly strength-redundant character of these structures, is suggested. Internal stability is probabilistically modeled as a series configuration and as an r-out-of-m configuration. Consideration of redundancy is formulated based on transitional probabilities and Markov stochastic processes. Following the suggested framework, the updated reliability of the structure, as failure propagates among the different layers of reinforcement, can be quantified. As an illustration of the developed methodology, an example of a reinforced soil wall is analyzed and results are discussed.

1. Introduction

Conventional design methods of reinforced soil walls (also known as mechanically stabilized earth or MSE walls) typically address ultimate limits of resistance with respect to external and internal stability. Particularly with respect to internal stability, design is normally performed against tensile and pull out failure of the reinforcement elements [41,20,19]. In the past, geotechnical design of such walls was traditionally based on implicit consideration of uncertainty, by using empirical, experience-driven, safety factors. Although new design methodologies (EC7, LRFD) deal with geotechnical uncertainty and variability on a more robust way [39,35,36,13], they still do not offer a framework for implementation of reliability analyses in the design process. Therefore, they cannot be used for direct reliability assessment of the geotechnical structure, nor in combination with risk analysis. This is so because (global or partial) safety factors do not actually reflect the probability that a failure may occur [42]. In fact, they can be misleading in regards to this, due to the ambiguity and the non-linearity that generally exists between them and the corresponding level of risk [18,28,43].

In terms of direct reliability assessment of the internal stability of reinforced soil walls, several researchers have performed studies over the last twenty years. Genske et al. [22], Genske et al. [23] used the Hasofer and Lind's method [25] to investigate the reliability of internal stability of geotextiles' reinforced soil walls, assuming a slip surface cutting through the geotextiles. Based on the same method, Miyata et al. [31] briefly discussed an approach that is based on two performance functions, i.e. against rupture and pull out of geosynthetics, and on a slope stability type of analysis. Nonetheless, they do not attempt to obtain a unique measure of the reliability of the structure. Similar approach was followed by Chalermyanont and Benson [16], who analyzed the internal stability using Bishop's simplified method and Monte Carlo simulations (MCS). However, their attempt was based on the assumption that the different modes of failure are independent and mutually exclusive events. Basheer and Najjar [10] used first order Taylor series approximations in order to obtain the mean and variance for the design parameters of a reinforced soil structure, namely the width and length of the reinforcement elements. Similar studies were performed by Basma and Al-Harthy [11] and Basma et al. [12]. Sayed et al. [40] performed reliability analyses of reinforced soil walls for both static and seismic conditions, using three methods: first-order second-moment method, point estimate method, and first-order reliability method. Their system analysis though is based on the assumption of statistically independent failure modes. More recent studies by Basha and Sivakumar Babu [5–9]

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Nomenclature

$[p_{ij}]$	transition probability matrix from a state i to a state j
$[SR]$	performance function defined in terms of safety ratio
$[SR_{POi}]$	performance function defined in terms of safety ratio with respect to pull out failure of an individual reinforcement layer i
$[SR_{Ti}]$	performance function defined in terms of safety ratio with respect to tensile failure of an individual reinforcement layer i
∩	symbol of intersection
Cov[–, –]	covariance of two variables
COV[–]	coefficient of variation of a random variable or a performance function
i	individual layer of reinforcement (i = 1, 2, ..., m) | current state of failure when refers to transitional probabilities p_{ij} (i = 0, 1, 2, ..., m)
j	future state of failure (j = 0, 1, 2, ..., m)
m	total number of reinforcement layers | state of failure on which all m layers have failed (when refers to transitional probabilities)
m + 1	total number of possible states on transition probabilities
$max[PF_i]$	maximum probability of failure per depth
MCS	Monte Carlo simulation
N	number of Monte Carlo realizations
$n_{F,(m-1)i}$	number of realizations of simultaneous failures of i out of m layers given that m – 1 layers have already failed
$n_{F,ij}$	number of Monte Carlo realizations in which j layers fail given that i layers have already failed
$n_{F,mi}$	number of Monte Carlo realizations of simultaneous failures of i out of m layers
$n_{F,POi}$	number of pull out failures on Monte Carlo realizations
$n_{F,Ti}$	number of tensile failures on Monte Carlo realizations
$n_{F,Ti\text{-}POi}$	number of simultaneous pull out and tensile failures on Monte Carlo realizations
P[–]	probability of occurrence of an event
P_F	probability of failure of the wall's internal stability (as one system)
P_{Fcr}	highest probability of failure per depth (among all P_{Fi})
P_{Fi}	probability of failure of an individual layer i
p_{ij}	transition probability from state i to state j
p_{mm}	transition probability from state m to state m
$P_{R,i}$	pull out resistance of each individual reinforcement layer i
r	number of reinforcement layers that shall not fail in order for the structure to remain in operation (on an r-out-of-m system)
R	reliability of the wall's internal stability (as one system)
R_i	reliability of an individual layer i
T	column matrix indicating the profile of probability of failure per depth
T_a	tensile strength of reinforcement element
$T_{max,i}$	maximum tensile force applied on each reinforcement layer i
U	symbol of union
γ_1	unit weight of reinforced soil
γ_2	unit weight of retained soil
μ[–]	mean value of a random variable or a performance function
Π	transition probability matrix
Π_i	transition probability matrix at the state of failure i (i = 0, 1, 2, ..., m)
ρ[–,–]	coefficient of linear correlation between two variables
Σ	summation
σ[–]	standard deviation of a random variable or a performance function
φ_1	friction angle of reinforced soil
φ_2	friction angle of retained soil

investigated in depth the issue of reliability of the internal stability of reinforced soil walls under pseudo-dynamic loads.

Despite the great interest of the above research works, they all avoid to address a very important aspect: the inherent redundancy that characterizes these type of structures. By means of the term redundancy it is meant that in the event of failure of one or more layers of reinforcement, the wall does not necessarily collapse, because the remaining layers assume additional responsibility in terms of loads, even if not as initially intended [13,14,27]. Despite its importance, redundancy is typically an aspect that is ignored by current models. However, provided some modeling simplifications are accepted, stochastic models offer the framework to determine not only the original reliability per layer of reinforcement of a reinforced soil wall, but also the updated reliability given that one or more layers have already failed. In this paper, the development of such a model is elaborately described. Internal stability is approached in two steps using MCS. The framework for consideration of redundancy and propagation of failure is formulated based on transition probabilities and Markov stochastic processes. As an illustration of the developed methodology, an example of a reinforced soil wall is analyzed and relative results are being discussed.

2. Formulation of the probabilistic model

2.1. Performance functions

Internal stability of reinforced soil structures is a multi-component system, with as many components as the number of reinforcement elements. Each component may fail in two different modes, namely in tension and in pull out. In terms of a capacity – demand model and in order to represent limit states of equilibrium, it is convenient to define performance functions by analogy with safety factors, i.e. as safety ratios [*SR*]. So, performance functions with respect to tensile and pull out failure of each individual reinforcement layer *i* (for *i* = 1, 2, ..., *m* where *m* is the total number of reinforcement layers) are expressed by the following equations:

$$[SR_{T_i}] = \frac{T_a}{T_{max,i}} \tag{1}$$

$$[SR_{PO_i}] = \frac{P_{R,i}}{T_{max,i}} \tag{2}$$

where T_a is the tensile strength of the reinforcement elements, $T_{max,i}$ is the maximum tensile force applied on each reinforcement layer *i*, and $P_{R,i}$ is the pull out resistance of each reinforcement layer *i*. In the case of steel strips and steel grids reinforcement, the tensile strength of reinforcement per unit width of reinforcement is given by the following expression, respectively [20]:

$$T_a = 0.55\frac{F_Y A_c}{b} \quad \text{or} \quad T_a = 0.48\frac{F_Y A_c}{b} \tag{3}$$

where b is the gross width of the strip, sheet or grid, F_Y is the yield stress of steel and A_c is the design cross section area of the steel. In the case of geosynthetic reinforcement, the design long-term reinforcement tension load is given by: