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Research Paper

System reliability assessment of soil nail walls

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A B S T R A C T

An analytical model defining soil nail walls' probability of failure with respect to external and internal stability is developed in the present study. Unit weight, shear strength properties and ultimate bond strength along the soil-nail interface are modelled as random variables and computations of reliability are performed using Monte Carlo simulations. The proposed methodology is illustrated through a case example, in order to identify the critical failure modes and the dependency among them. Furthermore, the influence of the random variables' probability distribution function on the probability of failure is examined, as well as the importance of the cross-correlation between them.

1. Introduction

Soil nailing is an in-situ reinforcement technique, whose fundamental principle is to reinforce the ground by passive tension-resisting inclusions. By doing so, an in situ coherent gravity structure is being created, with increased shear strength compared to the original (in situ) soil [16,6,22]. Soil nail walls have been used in civil engineering for more than four decades [21,34]. They have been typically used to stabilize existing slopes or excavations where top-to-bottom construction is beneficial compared to other retaining systems [26]. In terms of ultimate limit states, soil nail walls' design must satisfy three major requirements: external, internal and facing stability. In terms of external stability, the following modes of failure are typically considered in the analysis [7,14,26]: global failure mode, sliding failure mode (that is, shear at the base), and bearing failure mode (i.e. basal heave that may be a concern when a soil nail wall is excavated in fine-grained, soft soils). As far as internal stability is concerned, analysis and design is normally performed against tensile (breakage under tension) and pullout failure of the soil nails. Finally, in terms of potential failure modes at the facing - nail head connection, the most common ones are the so-called flexure failure (due to excessive bending beyond the facing's flexural capacity) and punching shear failure (occurring in the facing around the nails). For permanent structures, design shall also be performed against failure of the headed studs in tension.

Typical design of soil nail walls has been traditionally based on the so-called allowable or working stress design method (ASD or WSD, respectively), on which uncertainties are taken into consideration by using empirical factors of safety [22]. Given the recent development of new design methodologies, such as the Load and Resistance Factor Design (LRFD) in the USA and the Eurocode 7 (EC7) in Europe, a noteworthy effort has been recently devoted to development and calibration of resistance factors for soil nail walls' design. For example, Lazarte [25] calibrated pull out resistance factors using a relevant database. Sivakumar Babu and Singh [39] proposed a procedure to determine reliability-based load and resistance factors for major ultimate limit states, in order to proceed with a LRFD procedure for a soil-nail wall. Their analysis was based on the Hasofer - Lind method. Lin and Liu [30] inspected the effects of different design variables on the resistance factors for soil nail walls against external failures (global and sliding), including soil type, soil shear strength, wall geometry, and nail configurations. They proposed a set of reliability-based resistance factors that can be used in conjunction with LRFD and EC7. Lin et al. [31] performed a similar analysis for soil nail walls in two-layered ground, proposing resistance factors. Based on first-order reliability method (FORM) analyses, a wide range of reliability indices calibrated from traditional WSD was indicated. In addition, the influence of model uncertainty and soil spatial variability on the reliability was investigated.

Despite the above efforts towards the development of resistance factors for soil nail wall design, LRFD and/or EC7 design methodologies still do not provide to the practitioner a frame for direct implementation of probabilistic and reliability analyses in the design process. In other words, these methods still remain deterministic, in the sense that they cannot be used for direct reliability assessment of the soil nail wall, nor in combination with risk analysis (on which consequences of a failure would have been taken into consideration). The reason behind this is that global or partial factors neither reflect the probability that a failure may occur [40], nor they are linearly connected to the

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corresponding level of risk [10,23,43,28]. Another inconvenience of the deterministic approach is that the analysis is not based on an overall estimate of the wall's safety, but only on partial estimates of the safety relative to the individual modes of failure. So, the analysis does not provide an overall integrated measure of safety, but several measures (as many as the failure modes under consideration).

Probabilistic analysis offers the tools to tackle the above shortcomings by explicitly accounting for sources of uncertainty in the computation of the reliability. Each mode of failure can be analyzed individually and then corresponding components' reliabilities can be computed. But more importantly, and provided some modelling simplifications are accepted, an overall measure of reliability of the soil nail wall can be assessed. The key advantage of the system modelling approach is that it provides a single index for quantifying the structure's overall reliability, instead of partial and unrelated components' reliabilities. This greatly facilitates the use of reliability as a criterion of design optimization and decision support. Despite the above advantages, limited work has been reported so far in the literature of direct probabilistic frameworks for soil nail walls. Yuan et al. [42] carried out reliability analysis for soil nailed walls considering one parabolic failure mode. Cohesion, friction angle and degree of mobilization of friction resistance between the nails and surrounding soil were taken as random variables. Sivakumar Babu and Singh [37,38] performed reliability analyses by means of the Hasofer - Lind method, in order to study the influence of variability of in-situ soil properties (cohesion c, friction angle φ and unit weight γ) on the stability of soil nail walls, for both static and seismic (pseudo-static) conditions. In their study, stability was evaluated for four failure modes: global stability and sliding, in terms of external failure, and tensile and pull out in terms of internal failure. In addition, they investigated the influence of correlation among soil parameters. Based on their study, the friction angle and the correlation between friction and cohesion were found to significantly influence soil nail wall stability. However, their approach does not examine the stability from a system reliability point of view. A system approach is being followed by Li et al. [29] on an application similar to soil nails, that is for anchor-stabilised slopes considering stochastic corrosion of anchors.

In the present work, a system reliability assessment model that takes into consideration the dependency between the soil nail walls' different failure modes is suggested. Analysis is performed using Monte Carlo simulations, considering four random variables (unit weight, friction angle and cohesion of the in situ soil, as well as the bond strength between soil and nails) following assumed probability distributions. The model proceeds with the computation of modal probabilities of failure and coefficients of linear correlation among them, as well as with direct assessment of the system probability of failure. The relevance of common simplifications often encountered in reliability practice, such as the first order bounds, is discussed. For illustrative purposes, an example of a typical soil nail wall is analyzed and relative results are being discussed. In addition, within the context of the present work, comparative analyses for both normal and lognormal distributions are performed and discussion is provided regarding the differences between the two assumptions. Finally, the aspect of cross correlations between the friction angle and the cohesion, as well as between the friction angle and the bond strength is addressed via parametric studies.

2. Formulation of the probabilistic model

2.1. Stability considerations

In the present study, a soil nail wall's external and internal stability under static conditions of loading are being considered following relevant manuals and publications [26,37,27]. External stability is examined through analysis against global and sliding failure modes. Internal stability is examined through analysis of nail's tensile and pullout capacity. It is noted that in cases of soil nail walls constructed in fine-grained soft soils, bearing capacity analysis (also known as basal heave) would have been necessary and could have been included in the model as one of the potential external failure modes. However, this is omitted in the present study, given that soft soils are considered unfavourable for soil nailing applications anyway [26,27]. Analysis against facing failure modes at the facing - nail head connection (flexure failure and punching shear failure) is also omitted in the present study, since focus is given on the major stability issues of the wall, i.e. external and internal failure modes.

2.2. Performance functions

For representing ultimate limit states, performance functions are defined as safety ratios (*SR*) - by analogy with safety factors (*SF*) - for each failure mode considered in the study:

2.2.1. External stability

2.2.1.1. Global stability. Global stability analysis is carried out considering a single-wedge failure mechanism [27]. Failure surface is assumed to be inclined at an angle $\psi = 45^\circ + \varphi/2$ (where φ is the internal friction angle of the retained soil) with respect to horizontal [37], and *SR* with respect to global stability is expressed as the ratio of the sum of the resisting and driving forces, ΣR_G and ΣD_G, which act tangentially to the potential failure plane [26]:

$$[SR_G] = \frac{\sum R_G}{\sum D_G} = \frac{cL_F + [(W_G + Q_T)\cos\psi + T_{EQ}\sin(\psi + \omega)]\tan\varphi}{(W_G + Q_T)\sin\psi - T_{EQ}\cos(\psi + \omega)} \quad (1)$$

where c is the cohesion of the retained soil, L_F is the length of the failure plane, W_G is the weight of the wedge, Q_T is the total surcharge load (in units of force), ω is the nail inclination with respect to the horizontal and T_{EQ} is the equivalent nail force. The equivalent nail force is a resultant force that expresses the contribution of the soil nails to the global stability of the system and is provided in Eq. (2):

$$T_{EQ} = \frac{1}{S_H}\sum_{i=1}^{m} T_{all,i} \quad (2)$$

in which S_H is the soil nail horizontal spacing and T_{all} is the maximum tensile force that can be developed (allowable tensile force) along each individual nail i (for $i = 1, 2, \dots, m$ where m is the total number of nails). According to the FHWA guidelines [27], the allowable tensile force of each nail is given in Eq. (3):

$$T_{all,i} = \min\{R_{T,i}, R_{P,i}\} \quad (3)$$

where $R_{T,i}$ and $R_{P,i}$ are the tensile and pullout capacity of each nail i, respectively.

2.2.1.2. Sliding stability. Sliding stability is assessed by considering the soil nail wall as a rigid block, against which lateral forces generated from the earth pressure are applied [27]. Similarly to the case of global stability, safety ratio with respect to sliding is defined as the ratio of the horizontal resisting to the horizontal driving forces [26,37]:

$$[SR_{SL}] = \frac{\sum R_{SL}}{\sum D_{SL}} = \frac{cB_L + (W_{SL} + Q_T + P_A\sin\beta_{eq})\tan\varphi}{P_A\cos\beta_{eq}} \quad (4)$$

where B_L is the width of the soil nail block, W_{SL} is the weight of the soil nail block, Q_T is the total surcharge load (in units of force), P_A is the active lateral earth force and β_{eq} is the equivalent backslope angle with respect to the horizontal. Fig. 1 presents the equilibrium of forces related to Eqs. (1) and (4).

2.2.2. Internal stability

2.2.2.1. Tensile failure. Safety ratio with respect to tensile failure of each individual nail i (for $i = 1, 2, \dots, m$ where m is the total number of nails) is expressed as the ratio of the tensile capacity of each nail i to the maximum tensile force applied on it: