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Research Paper

Probabilistic analysis of responses of cantilever wall-supported excavations in sands considering vertical spatial variability

Sedat Sert [a], Zhe Luo [b,*], Junhua Xiao [c], Wenping Gong [d], C. Hsein Juang [d]

[a] Department of Civil Engineering, Sakarya University, Adapazari 54187, Turkey
[b] Department of Civil Engineering, University of Akron, Akron, OH 44325, USA
[c] Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai 201804, China
[d] Glenn Department of Civil Engineering, Clemson University, Clemson, SC 29634, USA

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ABSTRACT

The influence of vertical spatial variability of sands on the excavation-induced lateral wall deflection and bending moment of excavations supported by cantilever retaining walls is investigated in this paper. Herein, the random finite element method (RFEM) is adopted to explicitly study the effect of one-dimensional spatial variability of internal friction angle of sands on the predicted wall and ground responses. The RFEM analysis consists of three components: (1) finite element method for analyzing lateral wall deflection and bending moment, (2) random field theory implemented with Monte Carlo simulation (MCS), and (3) statistical interpretation of MCS results through confidence intervals. This study reveals the importance of random field modeling in coping with the spatial variability of sands in the problem of supported excavations: (1) neglecting spatial variability of soil property will cause an overestimation of the variation in the predicted wall deflection and bending moment; (2) the estimated probability of failure based on a well-established serviceability limit state may be overestimated or underestimated depending on the chosen limiting lateral wall deflection. This study further investigates the effect of the number of MCS on the confidence intervals of the predicted statistics of the maximum lateral wall deflection and the maximum bending moment. The results also demonstrate that the confidence interval analysis of the predicted statistics of the maximum lateral wall deflection and the maximum bending moment provides a rational tool for interpreting the statistical data from RFEM.

1. Introduction

Cantilever retaining walls as a type of traditional earth retaining structures require simpler construction procedure and are suitable for excavations with depths less than 6 m. This type of earth retaining structures provides unobstructed open excavations and do not involve the installation of tiebacks or struts. In the conventional design of cantilever retaining walls, the design is realized through meeting the minimum required factor of safety [31]. The classical approaches based on Rankine and Coulomb earth pressure theories yield factor of safety against various failure modes such as sliding and overturning [8]. With the advances of geotechnical finite element method (FEM), it has been shown that the wall and ground movements during excavations have considerable influence on the lateral earth pressures [12], which impacts the design of cantilever retaining walls. The soil–structure interaction of the excavations can be rationally captured by the numerical approaches such as FEM.

Recent research on reliability-based design in geotechnical engineering reveals the insufficiency of factor-of-safety-based approaches. Due to the uncertainty in the design soil parameters, a factor of safety greater than the minimum required value may not always guarantee safety. In this regard, probability/reliability-based approaches such as Monte Carlo simulation can reasonably consider the variation in the soil and structural parameters. The reliability-based design is realized through meeting a target reliability index or probability of failure. The relevant research has addressed the reliability and risk assessment of cantilever retaining walls (e.g., [3,20]). Wang [36] proposed a procedure for reliability-based design of embedded sheet pile walls using Monte Carlo simulation. Phoon et al. [25] highlighted the importance of considering model uncertainty for limit equilibrium analysis of cantilever retaining walls in sands and calibrated the model factor using field test data. In addition, the simpler form of reliability-based design (e.g., load and resistance factor design, LRFD) has also been reported in literature. For instance, Goh et al. [13] developed a partial safety factor design method for cantilever retaining walls in granular soils.

* Corresponding author.
E-mail address: zluo@uakron.edu (Z. Luo).

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It is noted that the inherent uncertainty of soil parameters, including their spatial variability, may be modeled with the random field theory [32]. It is illustrated that the probability of failure in some geotechnical problems can be either overestimated or underestimated if the spatial variability is neglected [14]. The influence of spatial variability of soils in geotechnical design has been investigated in various problems such as shallow foundations, gravity retaining walls, seepage of dams, and earth slopes [10,11,15]. However, research on excavations supported by cantilever retaining walls considering spatial variability is rarely reported. To this end, this paper is devoted to studying the effect of vertical spatial variability of soil property on the responses of excavations in sands supported by cantilever retaining walls using random finite element method (RFEM). The RFEM analysis consists of three components: (1) finite element method (FEM) for analyzing lateral wall deflection and bending moment, (2) random field theory [33] implemented with Monte Carlo simulation (MCS), and (3) statistical interpretation of MCS results using confidence intervals.

The excavation-induced excessive wall and soil movement and the failure of supporting system can result in considerable damage to the adjacent infrastructures. Due to the inherent spatial variability of soils, the conventional simplified reliability-based approach cannot deal with a sophisticated geotechnical problem such as excavations. This study investigates the effect of one-dimensional vertical spatial variability on the excavation-induced lateral wall deflection and bending moment of a cantilever retaining wall in sands. It has been reported that the horizontal scale of fluctuation is generally much larger, and its effect is much less significant, compared with the vertical scale of fluctuation [24]. To reduce the computational effort, only the vertical spatial randomness is modeled in this paper, although the procedure in this study can be readily extended to consider both horizontal and vertical spatial randomness. The previous research shows that for some geotechnical problems, the joint spatial effect can be more significant if the two-dimensional spatial randomness is simulated (e.g., [22]). Nevertheless, the vertical spatial variability is more significant in this excavation problem and thus it is the focus of this study.

The RFEM results reveal that the computed statistics of maximum lateral wall deflection and maximum bending moment are significantly influenced by the spatial variability of sands. The critical limiting wall deflection that distinguishes the overestimation of the probability of serviceability failure from the underestimation of this probability is also explored. The confidence interval analysis of the predicted statistics of the maximum lateral wall deflection and maximum bending moment provides a rational tool for interpreting the statistical data from RFEM. The effect of the number of MCS on the confidence interval is also investigated through a hypothetical case study.

2. Finite element method for modeling cantilever retaining walls

The finite element method (FEM) is widely employed to model complex soil–structure interaction problems and it is a common approach for estimating wall deflections induced by excavations. In this study, a commercially available FEM code, PLAXIS [7], is adopted to analyze the excavation-induced maximum lateral wall deflection and maximum bending moment of the walls.

Fig. 1 shows the geometry of the 2-D FEM model for excavations supported by cantilever walls. In this problem, the excavation depth is 5 m and wall length is set to be 10 m to have a sufficient passive pressure to resist the lateral active earth pressure. The plane-strain condition is assumed for this FEM analysis. Only half-width of the excavation is modeled due to its symmetricity.

To minimize the boundary effect on the wall displacements, the left-side boundary is fixed at 50 m away from the centerline and the bottom boundary is set 20 m below the ground surface in all case scenarios. The bottom boundary is restrained from both horizontal and vertical movements, and the left and right-side boundaries are only restrained horizontally. In the previous research on model boundaries for unsupported excavations, Brinkgreve [5] reported that the minimum distance between the retaining wall and the excavated-side boundary is 3–5 times of the embedment depth of the wall; the minimum distance between the retaining wall and the unexcavated-side boundary is 2–3 times of the wall length; the minimum distance between the bottom of the wall and bottom boundary is wall length. The geometry of FEM model as in Fig. 1 follows the aforementioned criteria.

The hardening soil (HS) model is a nonlinear constitutive model for simulating the behavior of soils [27]. For HS model, the failure is still defined by the Mohr–Coulomb (MC) failure criterion. The thrust of the HS model is the hyperbolic relationship between the axial strain and the deviatoric stress [19]. Interested readers are referred to Schanz et al. [27] for more details of the formulation and verification of the HS model. In this study, the stress–strain behavior of sands is modeled using the hardening small strain (HSS) constitutive relationship that considers the small strain effect. The HSS model accounts for the increased stiffness of soils at small strains. At low strain levels most soils exhibit a higher stiffness than at higher strain levels, and this stiffness varies non-linearly with strain. The improved features of the HSS model

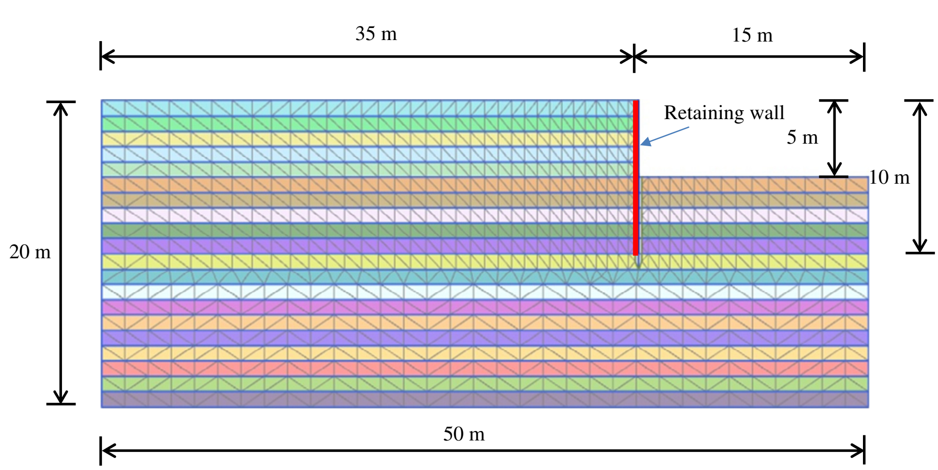

Fig. 1. Geometry of the finite element model of cantilever retaining walls.