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Effect of soil–structure interaction on the reliability of reinforced concrete bridges

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Abstract In the design of reinforced concrete (RC) bridges, the random and nonlinear behavior of soil may lead to insufficient reliability levels. For this reason, it is necessary to take into account the variability of soil properties which can significantly affect the bridge behavior regarding ultimate and serviceability limit states. This study investigates the failure probability for existing reinforced concrete bridges due to the effects of interaction between the soil and the structure. In this paper, a coupled reliability–mechanical approach is developed to study the effect of soil–structure interaction for RC bridges. The modeling of this interaction is incorporated into the mechanical model of RC continuous beams, by considering nonlinear elastic soil stiffness. The reliability analysis highlights the large importance of soil–structure interaction and shows that the structural safety is highly sensitive to the variability of soil properties, especially when the nonlinear behavior of soil is considered.

1. Introduction

The robustness of reinforced concrete infrastructures is of great importance for safe operation under real conditions. Degradations and loss of capacity lead to reduction of service life, to failure of members and even to collapse of the whole structure. In fact, the loss of capacity may come from the variability of the soil properties which may induce higher bending moments in the structure. For this reason, the variability of soil properties should be taken into account in the analysis and design of the soil–structure system, in order to ensure reliable and economic design. Various studies have been

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conducted on the effect of soil–structure interaction, highlighting its important role in the analysis of structures. Among the large amount of case studies reported in the literature, Zolghadr Jahromi [1] has shown the significant influence of soil–structure interaction on the design and sizing of civil engineering structures. In this regard, the researches conducted by Fenton and Griffiths [2] show the significant effect of soil–structure interaction and its overall importance in the prediction of the response of the coupled system. Elachachi et al. [3,4] considered the effect of soil–structure interaction on embedded pipe networks. Studies on soil–structure interaction considering the effects of soil heterogeneity have been presented by Breysse et al. [5]. The results showed the effect of soil variability on the induced forces in linear mechanical systems. Recently, Jahangir et al. [6] developed analytical model to investigate the effects of the shrinkage of clayey soils on buildings through soil–structure interaction analysis.

As the soil is a material with strong nonlinear and heterogeneous behavior, the studies presented by Frank and Thepot [7] and Viladkar et al. [8] have underlined that the nonlinear effects can alter significantly the stiffness of the soil under the structure foundations. They showed the importance of using nonlinear material models in the analysis of soil–structure interaction. Fontan et al. [9] have studied the soil–structure interaction of reinforced concrete bridges under static loading. This study has shown the complexity of the soil–structure interaction and the need for considering the specific properties of soil and structural stiffness.

The studies in the literature are often devoted to the nominal effect of the interaction between the soil and the structure, and few works consider the effect of variability of soil properties. This variability has a complex character as it results from many sources of uncertainty, on the one hand, and as it varies with space and time, on the other hand. Modeling the uncertainties in soil properties requires statistical analysis of data coming from either laboratory testing or in-situ measurements. The identification of these uncertainties consists in modeling three types of uncertainties: (i) natural variability of the soil (space and time variabilities), (ii) testing and measurement errors, and (iii) model uncertainty (Kulhawy [10], Favre [11]). These uncertainties can be modeled by random fields, which can be succinctly described by a coefficient of variation (COV) and an autocorrelation function, under the assumption of stationarity.

The objective of the present paper is to show and to quantify the importance of soil parameter uncertainties on the redistribution of internal forces in RC structures, as well as their effect on the safety assessment of these structures. In the following research, a reliability–mechanical approach is developed to study the effect of soil–structure interaction. The coupled reliability–mechanical model is applied to assess the failure probability of a real RC bridge by considering variable and non-linear soil properties, in addition to variability in structural resistance and applied load, where soil structure interaction is taken into account. The coupling between the mechanical model and the reliability model is performed by using the well-known First Order Reliability Method (FORM) which is widely explained in reliability textbooks such as Ditlevsen et al. [12], it provides an estimate of the failure probability based on the reliability index. Regarding bridge foundations, the distance between the footings is always larger than the autocorrelation length, allowing us to apply random variable representations. The numerical analysis allows us to evaluate the safety of the RC bridge regarding the soil parameter uncertainties. Furthermore, the obtained results indicate that soil–structure interaction effects and uncertainty of soil parameters should be considered in the reliability assessment of RC structures. This analysis can have significant impact on the design rules of redundant RC structures, especially when large soil uncertainties are involved.

2. Literature review on soil behavior uncertainties

2.1. Different sources of uncertainties

The geotechnical variability is a complex attribute that results from several sources of uncertainties. According to Phoon and Kulhawy [13], the main sources of geotechnical uncertainties are intrinsic variability, measurement errors, and uncertainties of transformation. The first type of the uncertainty which is related to the physical phenomenon is called aleatoric or active and the second one which is related to measurement is called epistemic or passive (Favre [11]). Therefore, soil property statistics that are determined from total variability analyses only can be applied to the specific set of circumstances (site condition, measurement technique, correlation models) for which the design soil properties are derived (Phoon et al. [14]).

2.2. Quantification of uncertainties of soil parameters

This section aims at presenting the values of the coefficient of variation (COV) of the shear strength parameters and the soil elastic properties proposed in the literature. The coefficient of variation of a given uncertain soil parameter is defined as the ratio between its standard deviation and its mean value. Several statistical studies (Phoon and Kulhawy [13], Magnan [15], Harr [16] Cherubini et al. [17] and Duncan [18]) based on in-situ and laboratory tests have proposed intervals for the coefficients of variation (COV) of the soil parameters. Regarding the undrained cohesion (c_u), an interval of the coefficient of variation between 10% and 55% was proposed by most of the authors. Regarding the internal friction angle (φ), the coefficient of variation proposed in the literature lies between 7% and 20%. The coefficient of variation of the Young's modulus (E) is estimated between 2% and 50% (Nour et al. [19], and Baecher and Christian [20]). Concerning the coefficient of variation of Poisson's ratio (v), there is no sufficient information about its interval of variation, leading some authors to suggest that the variability of this parameter in the elastic soil settlement can be neglected, while others proposed a very limited range of variability (Youssef Abdel Massih [21]).

2.3. Modeling of soil uncertainties

The uncertainties of the soil parameters described in the previous section have to be taken into account in any geotechnical probabilistic analysis, with simplified and advanced probabilistic approaches. In these simplified probabilistic approaches, the uncertain soil parameters are modeled as random variables characterized by their probability density functions (PDFs) or their statistical moments (i.e. mean value and standard